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Refined model of leather

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Abstract. The structure of finished leather and semi-finished products differ in physical and mechanical parameters. To obtain the properties of elasticity, pliability, and viscosity required in leather production, it is necessary to ensure their values that guarantee the high quality of the resulting product. In this article, a model for finished leather is obtained based on combining the viscoelastic Kelvin model with the deformation-inert Khusanov model and the Bingham–Shvedov viscoplastic model. This model makes it possible to improve the elastic-viscous plastic deformation of a fibrous material (leather). The possibility of clarifying the pattern of change in the deformation curve depending on the time the fibrous material is loaded by a certain force was explored. The aim of refining the deformation curve is that in known models, at the initial moment of loading, deformation occurs instantly up to a certain value, which does not fully describe the real physical process of deformation of the material. Consequently, in the proposed refined model, the deformation is fixedat zero value, which provides a real physical pattern of deformation of the fibrous material. The refined model will serve designers of technological machines to develop parameters of deformation during the mechanical processing of elastic-viscous plastic materials.

1 Introduction

Let us consider well-known publications on rheological models. The study in [1, 2] provides a review of research conducted on leather rheology. Data on the deformation of leather under stress are presented. An analysis of the studies on plasticity and setting and tearing of leather was conducted. The author of that article states that the structure of leather controls its rheological response and points out the fact, that knowledge from other areas of materials science can be very useful in studying the behavior of leather.

In [3], the author developed the model, in which the damping element is replaced by a nonlinear active element. The study examines the deformation of polymers; the creep and stress relaxation modes are described by one defining nonlinear equation.

In [4], a rheological model of a real viscoelastic body was studied considering the presence of an energy barrier. Vertical longitudinal low-amplitude vibrations of a load on a highly oriented polymer material were considered. The resulting rheological model explains the occurrence of beats in a system with one mechanical degree of freedom.

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In [5], two-dimensional stretching of leather was analyzed using a unit that allows independent stretching in two perpendicular directions. In the first approximation, the stress was linearly related to two elastic strain components in perpendicular directions. The influence of such variables as temperature, moisture content of the supplied airflow, airflow velocity, and duration of treatment of fixed leather was determined.

A mathematical model was developed in [6], it describes the rheological properties of footwear materials. The equations previously used to describe the relaxation of forces in footwear materials were considered. A program was developed to automate the calculation and predict force relaxation in footwear materials. This program allows the calculation of forces at a given time, the determination of the adequacy of the experimental dependence on the empirical formula, and the display of the graphical representation of theoretical relaxation curves and experimental values of forces.

The authors of [7] experimentally studied the creep and damage of samples made of genuine leather under deformation. It was established that the microstructure of bovine leather presents a complex layered rete of fibers of different sizes from several to several hundred nanometers in diameter. It was established that leather fibers exhibit nonlinear stress-strain relationships and show viscoelastic behavior. A theoretical model was proposed that describes the basic patterns of behavior under the stretching of leather.

The authors of [8] studied the deformation characteristics of footwear leather materials. The influence of high-frequency plasma treatment on changes in the structural elements of samples made of low-grade natural leather was experimentally determined. The results of the experiment showed an improvement in the elastic properties of leather samples.

Deformation properties of the Wet-blue semi-finished leather product were experimentally determined in [9], based on topographic sections of leather (shoulder, belly, and butt). Mathematical dependences of the deformation of the Wet-blue semi-finished leather product on the pressing force on the topographic sections of shoulder, belly, and butt were obtained. It was established that at the initial stage of loading, the deformation of samples of the Wet-blue leather product increases, and then after its compaction the dependence takes on a linear character.

In [10], a method was developed for determining a parameter – coefficient of deformation inertia of capillary porous materials. An equation for an improved rheological model of leather was derived, expressed through a rheological parameter in the form of a coefficient of deformation inertia. A method for determining a new rheological parameter of the inert resistance of leather to accelerated deformation was described. It consists in determining the immersion force of a conical indenter at a constant velocity and the coefficient that considers the shear zones, and the angle formed by the boundaries of the deformation zone of the material and applying the value of the force.

The simplest rheological models are also known [11]. These are the Hooke, Newton, Saint-Venant models of real bodies. Hooke's model is represented in the form of a spring. When forces are applied to an ideal body, strain under tension or compression is expressed as $\sigma=\varepsilon E$, where σ is stress, ε is strain, E is the modulus of elasticity. The shear of an ideal body is expressed by $\tau=\gamma G$, where τ is the shear stress of an ideal body, γ is the shear strain of an ideal body, G is the shear modulus of an ideal body.

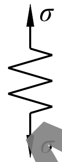
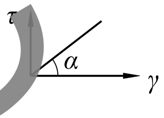
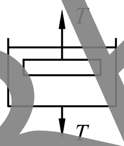
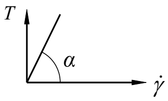
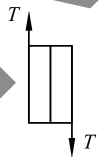
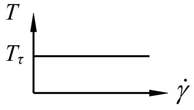
2 Material and method of research

Newton's rheological model of an ideal body is expressed by formula $\tau=\mu$, where τ is the shear stress of an ideal body, μ is the viscosity of an ideal body, is the flow velocity of an ideal body, and formula expresses under tensile or compressive deformation, where σ is the stress of an ideal body at the flow, μ is the viscosity of an ideal body, is the flow rate of an ideal body. Considering the Saint-Venant rheological model, if stress is $\tau<\tau_1$, there is no flow of an ideal body, and if $\tau\geq\tau_1$, then the flow of an ideal body occurs [11].

The first column of the table given below lists the authors who presented the simplest rheological ideal models (Hooke, Newton and Saint-Venant). The second column shows the schematic forms of models. Elasticity is denoted as the deformation of a spring, viscosity of fluid flow is denoted as a piston with holes in the cylinder, and deformation occurs in the form of dry friction when a certain value is exceeded. The third column shows the graphs of flow of these simplest ideal models. The fourth column shows the equations that describe the rheological models of Hooke, Newton and Saint-Venant.

For the Hooke elasticity model, the equations of motion are described by the equations for shear, shear stress is equal to shear strain times the shear modulus, and for compression and tension they are described by the equation stress is equal to strain times the elastic modulus. And for Newton's model, the stress equation is equal to viscosity multiplied by the flow rate or stress equal to viscosity multiplied by the strain rate. And for the Saint-Venant model, the equation for $\tau<\tau_1$ is no deformation; at $\tau\geq\tau_1$ flow [11].

Table 1. Hooke, Newton, and Saint-Venant models of ideal bodies.

Models	Types of models	Graphs of flow
Hooke		
Newton		
Saint-Venant		

Another rheological model is known, $\tau=m_l$, where τ is the deformation stress, ml is the coefficient of deformation inertia of an ideal body and is the acceleration of deformation inertia of an ideal body. The theory of deformation inertia of an ideal body was developed by I.N.Khusanov [12].

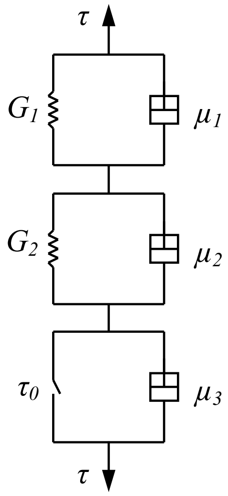


Fig. 1. Scheme of A.G.Burmistrov's rheological model of leather [13–15].

Let us consider the general solution to the rheological equations of the Kelvin-Voigt model sequentially connected with the Shvedov-Bingham model.

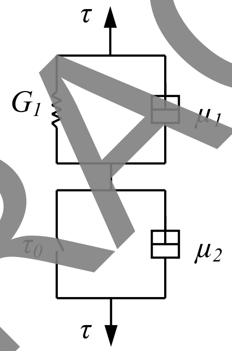


Fig. 2. Scheme of the Kelvin rheological model sequentially connected with the Shvedov-Bingham model.

The Kelvin-Voigt model consists of the Hooke model connected in parallel with the Newton model.

$$\tau = G_1\gamma_1 + \mu_1\dot{\gamma}_1 \qquad (1)$$

The Shvedov-Bingham model consists of the Saint-Venant model connected in parallel with the Newton model.

$$\tau = \tau_0 + \mu_2\dot{\gamma}_2 \qquad (2)$$

Let us differentiate the Kelvin-Voigt model (1) and the Shvedov-Bingham model (2) once each and obtain equations (3) and (4).

$$\dot{\tau} = G_1\dot{\gamma}_1 + \mu_1\ddot{\gamma}_1 \qquad (3)$$

$$\dot{\tau} = \mu_2\ddot{\gamma}_2 \qquad (4)$$

Then, equation (3) is divided by viscosity μ_1, and equation (4) is divided by μ_2

$$\frac{\dot{\tau}}{\mu_1} = \frac{G_1}{\mu_1}\dot{\gamma}_1 + \ddot{\gamma}_1 \qquad (5)$$

$$\frac{\dot{\tau}}{\mu_2} = \ddot{\gamma}_2 \qquad (6)$$

We add equations (5) and (6) and obtain the following equation:

$$\left(\frac{1}{\mu_1} + \frac{1}{\mu_2}\right)\dot{\tau} = \frac{G_1}{\mu_1}\dot{\gamma}_1 + \ddot{\gamma} \qquad (7)$$

We multiply equation (7) by µ1/G1 and obtain:

$$\frac{\mu_1}{G_1} \cdot \frac{\mu_1 + \mu_2}{\mu_1 \mu_2}\dot{\tau} = \dot{\gamma}_1 + \frac{\mu_1}{G_1}\ddot{\gamma} \qquad (8)$$

Then we divide the right and left sides of equation (2) by μ_2 and add the right side to the right side of equation (8), and the left side to the left side of equation (8), and obtain equation (9).

$$\frac{\mu_1 + \mu_2}{G_1 \mu_2}\dot{\tau} = \dot{\gamma}_1 + \frac{\mu_1}{G_1}\ddot{\gamma}_1 + \frac{1}{\mu_2}\dot{\tau} = \frac{1}{\mu_2}\tau_0 + \dot{\gamma}_2 \qquad (9)$$

Next, we add up deformations and obtain an equation

$$\frac{\mu_1 + \mu_2}{G_1 \mu_2}\dot{\tau} + \frac{1}{\mu_2}\tau = \dot{\gamma} + \frac{1}{\mu_2}\tau_0 + \frac{\mu_1}{G_1}\ddot{\gamma} \quad (10)$$

Equation (10) is multiplied by μ_2 and an equation that is the general equation for the sequentially connected rheological equations of Kelvin-Voigt and Shvedov-Bingham is obtained

$$\tau + \frac{\mu_1 + \mu_2}{G_1}\dot{\tau} = \tau_0 + \mu_2 \dot{\gamma} + \frac{\mu_1 \mu_2}{G_1}\ddot{\gamma} \qquad (11)$$

Consider the Kelvin-Voigt rheological model connected in parallel with the rheological model of deformation inertia (I.N.Khusanov) [12] and sequentially connected with the Kelvin-Voigt and Shvedov-Bingham models.

$$\tau = G_1 \gamma_1 + \mu_3 \dot{\gamma}_1 + m_l \ddot{\gamma}_1 \qquad (12)$$

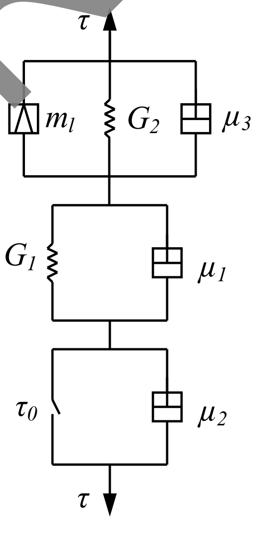


Fig. 3. Scheme of an improved rheological model of leather.

When two rheological models are connected sequentially, the total stress τ is equal to the stress of the first model τ_1 and the stress of the second model τ_2

$$\tau = \tau_1 = \tau_2 . \qquad (13)$$

The total deformation of two sequentially connected rheological models γ is equal to the sum of the Kelvin-Voigt model deformation γ_1 and the Shvedov-Bingham model deformation γ_2

$$\gamma = \gamma_1 + \gamma_2 \,. \qquad (14)$$

Kelvin-Voigt's rheological model connected in parallel with the rheological model of deformation inertia by I.N.Khusanov has the following form (15):

$$\tau = G_2\gamma_1 + \mu_3\dot{\gamma}_1 + m_l\ddot{\gamma}_1 \qquad (15)$$

$$\tau + \frac{\mu_1 + \mu_2}{G_1}\dot{\tau} = \tau_0 + \mu_2\dot{\gamma}_2 + \frac{\mu_1\mu_2}{G_1}\ddot{\gamma}_2 \,. \qquad (16)$$

It is necessary to find a general solution to equations (15) and (16) in the form of the total stress dependence. The general equation of the Kelvin-Voigt rheological model sequentially connected with the Shvedov-Bingham rheological model is presented in the form of τ of the total deformation γ, the rate of deformation and the acceleration of deformation of leather.

Equation (15) is divided by G_2 and the following derivative is obtained:

$$\frac{\dot{\tau}}{G_2} = \dot{\gamma}_1 + \frac{\mu_3}{G_2}\ddot{\gamma}_1 + \frac{m_l}{G_2}\dddot{\gamma}_1 \qquad (17)$$

Equation (16) is divided by μ_2

$$\frac{\tau}{\mu_2} + \frac{\mu_1 + \mu_2}{G_1\mu_2}\dot{\tau} = \frac{\tau_0}{\mu_2} + \dot{\gamma}_2 + \frac{\mu_1}{G_1}\ddot{\gamma}_2 \qquad (18)$$

Equations (17) and (18) are summed up

$$\frac{\dot{\tau}}{G_2} + \frac{\tau}{\mu_2} + \frac{\mu_1 + \mu_2}{G_1\mu_2}\dot{\tau} - \frac{\tau_0}{\mu_2} = \qquad (19)$$
$$= \dot{\gamma}_1 + \dot{\gamma}_2 + \frac{\mu_3\ddot{\gamma}_1}{G_2} + \frac{\mu_1}{G_1}\ddot{\gamma}_2 + \frac{m_l}{G_2}\dddot{\gamma}_1$$

From expression (18) we take the derivative and obtain the following equation:

$$\frac{\dot{\tau}}{\mu_2} + \frac{\mu_1 + \mu_2}{G_1\mu_2}\ddot{\tau} = \frac{\tau_0}{\mu_2} + \ddot{\gamma}_2 + \frac{\mu_1}{G_1}\dddot{\gamma}_2 \,. \qquad (20)$$

We multiply equation (19) by G_2/m_l and obtain the following equation:

$$\left(\frac{1}{G_2} + \frac{\mu_1 + \mu_2}{\mu_2}\right)\dot{\tau}\frac{G_2}{m_l} + \frac{G_2}{m_l\mu_2}\tau - \frac{G_2}{m_l\mu_2}\tau_0 = \qquad (21)$$
$$= \dot{\gamma}\frac{G_2}{m_l} + \frac{\mu_3}{m_l}\ddot{\gamma}_1 + \frac{G_2\mu_1}{G_1m_l}\ddot{\gamma}_2 + \dddot{\gamma}_1$$

Next, we multiply equation (20) by G_1/μ_1

$$\dot{\tau}\frac{G_1}{\mu_1\mu_2} + \frac{G_1(\mu_1 + \mu_2)}{G_1\mu_1\mu_2}\ddot{\tau} = \frac{G_1}{\mu_1} + \ddot{\gamma}_2 + \dddot{\gamma}_2 \,. \qquad (22)$$

Let us add equations (21) and (22) and write the following equation:

$$\frac{G_2}{m_l\mu_2}(\tau - \tau_0) + \left(\frac{1}{m_l}\frac{\mu_1 + \mu_2}{G_1\mu_2}\frac{G_2}{m_l} + \frac{G_1}{\mu_1\mu_2}\right)\dot{\tau} + \qquad (23)$$
$$+ \frac{\mu_1 + \mu_2}{\mu_1\mu_2}\ddot{\tau} = \frac{G_2}{m_l}\dot{\gamma} + \frac{\mu_3}{m_l}\ddot{\gamma}_1 + \left(\frac{G_2\mu_1}{G_1m_l} + \frac{G_1}{\mu_1}\right)\ddot{\gamma}_2 + \dddot{\gamma}$$

If $\mu_3 = \dfrac{G_2\mu_1^2 + G_1^2 m_l}{G_1\mu_1}$, then we obtain the following equation:

$$\frac{G_2}{m_l\mu_2}(\tau-\tau_0)+\left(\frac{1}{m_l}\frac{\mu_1+\mu_2}{G_1\mu_2}\frac{G_2}{m_l}+\frac{G_1}{\mu_1\mu_2}\right)\dot{\tau}+\frac{\mu_1+\mu_2}{\mu_1\mu_2}\ddot{\tau}= \qquad (24)$$
$$=\frac{G_2}{m_l}\dot{\gamma}+\frac{\mu_3}{m_l}\ddot{\gamma}+\dddot{\gamma}$$

where σ – is the compressive or tensile stress [Pa];
τ – shear stress of leather material, [Pa];
m_l – coefficient of deformation inertness of leather material, [Pa·s^2];
μ_1 – viscosity of leather material, [Pa·s];
μ_2 – viscosity of leather material, [Pa·s];
μ_3 – viscosity of leather material, [Pa·s];
G_1 – modulus of elasticity of leather material, [Pa];
G_2 – modulus of elasticity of leather material, [Pa];
E – modulus of elasticity of solid bodies [Pa];
ε – compressive or tensile strain [(–)];
$\dot{\tau}$ – rate of stress changes in leather material, [Pa/s];
$\ddot{\tau}$ – acceleration of stress changes in leather material, [Pa/s]2;
γ_1 – shear deformation of leather material, [(–)];
γ_2 – shear deformation of leather material, [(–)];
γ_3 – shear deformation of leather material, [(–)];
$\dot{\gamma}$ – rate of shear deformation of leather material, [1/s];
$\ddot{\gamma}$ – acceleration of shear deformation of leather material, [1/s^2];
$\dddot{\gamma}$ – change in the acceleration of shear deformation of leather material, [1/s^3];
τ_0 – shear stress value, after which the leather deforms, [Pa].

The rheological model of leather (24) obtained as a result of the study can be effectively used in the development and design of new effective high-tech equipment for the mechanical processing of fur, leather, and leather fabrics [16–35].

3 Results

An improved rheological model of leather (24) was obtained, which differs from A.G.Burmistrov's model [15] in that the deformation inertia of the material is included in the new rheological model.

The new aspect is that the rheological model of deformation inertia (by I.N.Khusanov) $\tau=m_l$ [12] was added to the improved A.G.Burmistrov's rheological model of leather [15].

Performing measurements in the zone of initial deformation of stresses and strain rates, we obtain the curve shown in Fig. 4. From the curve pattern, it follows that the material under study has a solid structure, that is, the interlacing of leather fibers is compacted, hence the limiting dynamic stress τ changes, taking the values of τ_1, τ_2, …, τ_i, determined by drawing tangents at the points of the curve.

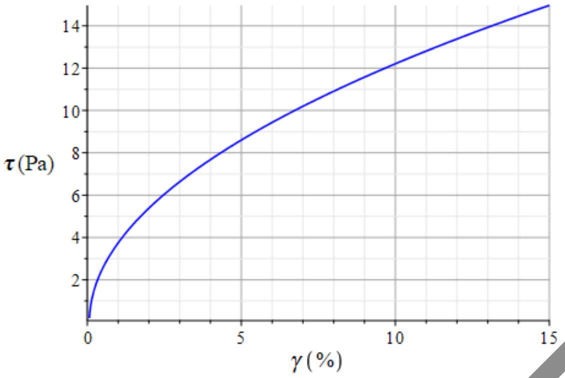


Fig. 4. Graph of dependence of the shear stress (τ) on the change in shear strain of leather material (γ)

Equation (24) is a rheological parametric equation of state of leather, which covers the entire spectrum of ideal bodies of Hooke, Newton, Saint-Venant and I.N.Khusanov (deformation inertia of the material).

4 Conclusion

The resulting rheological model of leather (24), namely, the equation of state relating stress, strain, and time, more accurately describes the physical essence of the behavior of leather than the well-known rheological model by A.G.Burmistrov [15].

The improved rheological model of leather can be used in the development and design of new high-tech equipment for mechanical processing of leather and fur [36–52].

Conflicts of interest

The authors declared no conflict of interest.

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