Simulation of hydraulic during roller squeezing of leather

Shavkat Khurramov[1*], *Kuvondar* Bektoshev[2], and *Jakhongir* Jonkobilov[3]

[1]Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan
[2]University of Tashkent for Applied Sciences, Tashkent, Uzbekistan
[3]Almalik branch of Tashkent State Technical University, Tashkent, Uzbekistan

Abstract. Mathematical models for the distribution of hydraulic pressure in the area of squeezing leather (semi-finished leather product after chrome tanning) were developed. It was revealed that the graphs of the mathematical models obtained correspond to experimental diagrams plotted when squeezing various wet materials. From the point of view of water filtration, the roll contact zone is divided into four phases. It was established that hydraulic pressure in the first phase increases from zero to a maximum value, then in the second and third phases, it decreases from a maximum value to zero. It was revealed that the hydraulic pressure in the fourth phase, depending on the properties of the cloth used, could take negative values or be equal to zero.

1 Introduction

In many fields of industry, solving the problem of roller pressing is of great practical importance. For example, in the leather industry, the parameters of roller pressing of leather determine the efficiency of production and affect the problem of environmental safety since solving the problem of water removal is impossible without considering the problem of wastewater utilization by enterprises.

To optimize the operation of existing roller squeezing machines and create effective new ones, it is necessary to predict and optimize the main parameters of roller squeezing of leather.

One of the main parameters of roller squeezing of leather is the pressure force of the roller pressing devices.

During the roller squeezing process, under the pressure of the roller pressing devices, the skin is compacted by the rearranging of solid particles and reducing the volume of pores between them; it is accompanied by squeezing out water that fills these pores. Therefore, under squeezing, part of the applied pressure force is perceived by the solid phase and part - by water. The part of the pressure perceived by the solid phase is called compressive pressure, and the part perceived by water is called hydraulic pressure. In this case, the flow of water, and thereby its motion from the material into the roll coating, depends on the distribution of

* Corresponding author: shavkat-xurramov59@mail.ru

hydraulic pressure in the roll squeezing zone. Therefore, the most important stage in roller squeezing of wet materials is to model the distribution of hydraulic pressure.

During the roller squeezing process, the phenomenon of water filtration from wet material occurs together with the phenomenon of contact interaction of the processed material with working rolls. A change in the indices of the first phenomenon affects the change in the indices of the second phenomenon and vice versa. Therefore, solving hydraulic problems of roller squeezing of wet materials without considering the contact interaction of the processed material with working rolls does not allow obtaining reliable parameters of the process of roller squeezing of wet materials.

Compressive pressure is determined based on studying the phenomenon of contact interaction of the processed material with working rolls, i.e. by solving contact problems. References [1-6] are devoted to solving contact problems of roller squeezing of wet materials.

Hydraulic pressure is determined based on studying the phenomenon of water filtration in a deformable non-homogeneous porous medium, i.e. by solving hydraulic problems. References [7-18] are devoted to solving hydraulic problems of roller squeezing of wet materials.

An analysis of literature sources showed that the patterns of hydraulic pressure distribution obtained in theoretical studies do not correspond with experimental diagrams since in analytical studies hydraulic problems are solved without considering contact problems. For example, the theoretical distribution curve of hydraulic pressure (Figure 1, curve 1), obtained in [19], does not correspond with the experimental diagram (Figure 1, curve 2), plotted in [20-22].

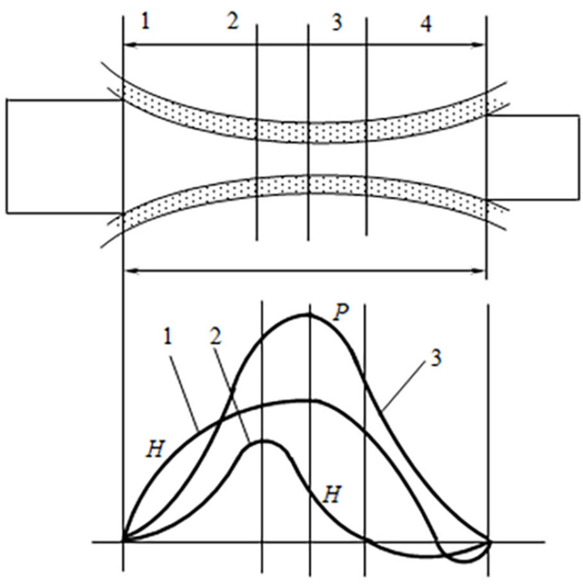

Fig. 1. Hydraulic pressure distribution graphs: 1 - theoretical, 2 – experimental.

The purpose of this study is to refine the mathematical model of hydraulic pressure obtained in [19], taking into account experimental diagrams of the distribution of hydraulic pressures, the phenomenon of contact interaction of the processed material with working rolls, and the deformation and filtration properties of the semi-finished leather product after chrome tanning [23, 24].

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2 Materials and methods

The process of leather squeezing occurs (as in [19]) in a symmetrical two-roll module, where the leather layer with a thickness of δ_1 interacts with working rolls having radii R and an elastic coating made of technical cloth with a thickness of H (Figure 2).

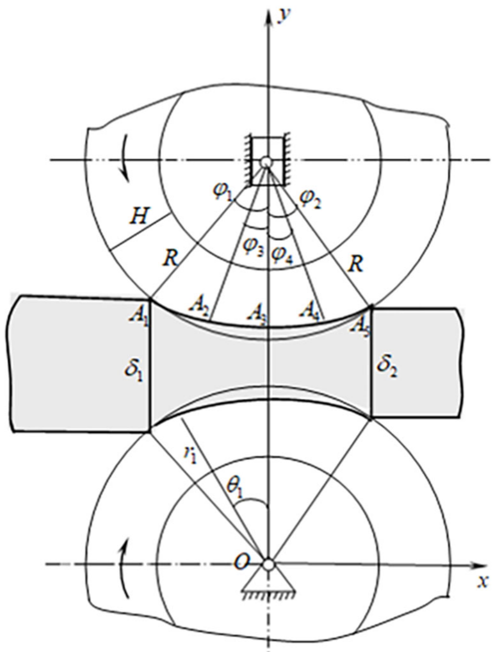

Fig. 2. Diagram of a two-roll module of a squeezing machine.

The basic principles valid for roller squeezing of wet materials, put forward by Wahlström in 1960, is a theory that is widely accepted even today [25]. Wahlström studied the process of removing water in the squeezing zone; he divided this zone into four phases and developed a mathematical model of the residual moisture content of the processed material depending on the uniformity of distribution and maximum hydraulic pressure, flow resistance and re-wetting.

According to [25], phase 1 begins from the moment the leather and cloth are saturated and ends when they become saturated with moisture. At this stage, hydraulic pressure arises and increases to a maximum value (Figure 1, curve 3).

Phase 2 begins when the leather and cloth are saturated. It ends when the external load reaches its maximum.

Phase 3 continues from the point of maximum total pressure to the point of maximum dryness of the skin. At the point of maximum dryness of the skin, hydraulic pressure is zero.

Phase 4 begins when the material layer and the elastic coating of the roll begin to expand, and ends when the external load is removed, that is, when the leather leaves the squeezing zone, resulting in negative hydraulic pressure. At this stage, water flows from the leather to the cloth.

The roll contact curve (of each roll) is divided relative to the line of centers into zones of compression and deformation recovery.

From Figures 1 and 2, it follows that the roll contact curve consists of sections (phases) 1, 2, 3, and 4 [25, 26], corresponding to segments A_1A_2, A_2A_3, A_3A_4, and A_4A_5.

Let the equation of the roll contact curve be given in polar coordinates $r_i = r_i(\theta_i)$, $i = \overline{1,4}$, i – is the index showing the number of the section.

According to Figure 2

$$-\varphi_1 \le \theta_1 \le -\varphi_3, \quad -\varphi_3 \le \theta_2 \le 0, \quad 0 \le \theta_3 \le \varphi_4, \quad \varphi_4 \le \theta_4 \le \varphi_2,$$

where φ_1, φ_2 – are the contact angles, φ_3 – is the angle separating sections 1 and 2 φ_4 – is the angle separating sections 3 and 4.

During the process of leather squeezing, the filtration of liquid from the leather into the roll coating cloth occurs along the polar radius r [19]. Here, it is necessary to take into account changes in the filtration coefficient depending on the direction.

In [26], accepting the working hypothesis about the orthogonality of the maximum and minimum porosity, the applicability of the generalized Darcy law for roller squeezing of an anisotropic medium was stated:

$$\frac{\partial H}{\partial r} = -\vartheta \frac{v}{K}, \tag{1}$$

and the formula for the filtration coefficient depending on the direction was determined as:

$$\frac{1}{K} = \frac{\cos^2\theta}{K_{\max}} + K\frac{\sin^2\theta}{k_{\min}}, \tag{2}$$

where H, v – is the hydraulic pressure and filtration rate along the roll radius; $K_{\max}$ – is the filtration coefficient (maximum) on the axis of ordinates; $K_{\min}$ – is the filtration coefficient (minimum) on the axis of abscissas; ϑ – is the fluid viscosity coefficient.

We consider the process of water filtration in section 1. In this zone, the wet material is compressed and water flows from it into the roll coating along the polar angle.

According to [19], the rate of water filtration along the roll radius in section 1 has the following form:

$$v_1 = -a_1(\theta_1^3 + \varphi_3^3), \tag{4}$$

where $a_1 = \dfrac{2v_l R\cos^2\varphi_1}{3\delta_1(1+m_1\gamma_1)(1+m_1\gamma_1\cos\varphi_1)}$, $m_1 = \dfrac{2n_1H\cos\varphi_1}{n_1^*\delta_1}$, n_1, n_1^* – are the coefficients of hardening of points of cloth and leather under compression, γ_1 – is the ratio of the deformation rate of cloth to the velocity of leather under compression, v_l – is the velocity of leather.

According to formulas (1) - (4), we have

$$\frac{\partial H_1}{\partial r_1} = \vartheta a_1(\theta_1^3 + \varphi_3^3)\left(\frac{\cos^2\theta_1}{K_{\max}} + \frac{\sin^2\theta_1}{K_{\min}}\right)$$

or

$$dH_1 = \vartheta a_1(\theta_1^3 + \varphi_3^3)\left(\frac{\cos^2\theta_1}{K_{\max}} + \frac{\sin^2\theta_1}{K_{\min}}\right)\frac{dr_1}{d\theta_1}d\theta_1. \tag{5}$$

According to [4], we have

$$r_1 = \frac{R}{1+m_1\gamma_1}\left(1+m_1\gamma_1\frac{\cos\varphi_1}{\cos\theta_1}\right), \quad \frac{dr_1}{d\theta_1} = \frac{m_1\gamma_1 R}{1+m_1\gamma_1}\cos\varphi_1\frac{\sin\theta_1}{\cos^2\theta_1}.$$

Substituting $\frac{dr_1}{d\theta_1}$ into expressions (5), and accepting the following assumptions: $\cos^2\theta_1 \approx 1-\theta_1^2$, $\sin\theta_1 \approx \theta_1$, we obtain:

$$dH_1 = c_1\left(\frac{1-\theta_1^2}{K_{\max}} + \frac{\theta_1^2}{K_{\min}}\right)\frac{(\varphi_3^3+\theta_3^3)\theta_1}{1-\theta_1^2}d\theta_1, \tag{6}$$

where $c_1 = \frac{2v_l \vartheta R^2 m_1\gamma_1\cos^3\varphi_1}{3\delta_1(1+m_1\gamma_1)^2(1+m_1\gamma_1\cos\varphi_1)}$.

Integrating (6), expanding the logarithmic functions in a series, and limiting ourselves to terms up to the fifth power with respect to θ_1, we have

$$H_1 = \frac{c_1}{10K_{\max}}(2\theta_1^5 + 5\varphi_3^3\theta_1^2) + C_1. \tag{7}$$

Having determined constant integration C_1 by condition $H_1(-\varphi_1)=0$, we have:

$$H_1 = \frac{c_1}{10K_{\max}}(2(\theta_1^5+\varphi_1^5) - 5\varphi_3^3(\varphi_1^2-\theta_1^2)), \tag{8}$$

From here, we find that

$$H_{\max} = H_1(-\varphi_3) = \frac{c_1}{10K_{\max}}(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 3\varphi_3^5). \tag{9}$$

From expressions (8) and (9), we obtain:

$$H_1 = H_{\max}\frac{2(\varphi_1^5+\theta_1^5)-5\varphi_3^3(\varphi_1^2-\theta_1^2)}{2\varphi_1^5-5\varphi_3^3\varphi_1^2+3\varphi_3^5},\ -\varphi_1 \le \theta_1 \le -\varphi_3\ . \tag{10}$$

Thus, the hydraulic pressure in section 1 increases from zero to the maximum value determined by formula (9).

Similarly to formula (7), for section 2 we have:

$$H_2 = \frac{c_1}{10K_{\max}}(2\theta_2^5 + 5\varphi_3^3\theta_2^2) + C_2. \tag{11}$$

Having determined constant integration C_2 by condition $H_1(-\varphi_3) = H_{\max}$, we have:

$$H_2 = H_{\max}\frac{2(\varphi_1^5+\theta_2^5)-5\varphi_3^3(\varphi_1^2-\theta_2^2)}{2\varphi_1^5-5\varphi_3^3\varphi_1^2+3\varphi_3^5},\ -\varphi_3 \le \theta_2 \le 0. \tag{12}$$

From here, we find that

$$H_2(0) = H_{\max}\frac{2\varphi_1^5-5\varphi_3^3\varphi_1^2}{2\varphi_1^5-5\varphi_3^3\varphi_1^2+3\varphi_3^5}. \tag{13}$$

Thus, in section 2, the hydraulic pressure decreases from the maximum value determined by formula (9) to the value determined by formula (13).

Similarly to formula (7), for section 3 we have:

$$H_3 = \frac{c_2}{10K_{\max}}(2\theta_3^5 + 5\varphi_4^3\theta_3^2) + C_3, \tag{14}$$

where $c_2 = \frac{2v_l \vartheta R^2 m_2\gamma_2\cos^3\varphi_2}{3\delta_1(1+m_2\gamma_2)^2(1+m_2\gamma_2\cos\varphi_2)}$, $m_2 = \frac{2n_2 H\cos\varphi_2}{n_2^*\delta_2}$, n_2, n_2^* – are the coefficients of hardening of points of the cloth and leather under recovery, γ_1 – is the ratio of the deformation rate of the cloth to the velocity of leather under recovery.

Having determined constant integration C_3 by condition $H_3(\varphi_4) = 0$, we have:

$$H_3 = \frac{c_2}{10K_{\max}}(2\theta_3^5 - 5\varphi_4^3\theta_4^2 + 3\varphi_4^5), \quad 0 \le \theta_3 \le \varphi_4. \tag{15}$$

From here, we find that

$$H_3(0) = \frac{3c_2\varphi_4^5}{10K_{\max}}. \tag{16}$$

Thus, the hydraulic pressure in section 3 decreases from the value determined by formula (16) to zero.

Considering condition $H_2(0) = H_3(0)$, from equalities (13) and (16), it follows that

$$\frac{c_2}{10K_{\max}} = H_{\max}\frac{2\varphi_1^5 - 5\varphi_3^3\varphi_1^2}{3(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 3\varphi_3^5)\varphi_4^5}.$$

Then from equality (15) we obtain

$$H_3 = H_{\max}\frac{(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2)(3\varphi_4^5 + 2\theta_3^5 - 5\varphi_4^3\theta_3^2)}{3(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 3\varphi_3^5)\varphi_4^5}, \quad 0 \le \theta_3 \le \varphi_4. \tag{17}$$

Similarly to the last formula, for section 4 we have:

$$H_4 = H_{\max}\frac{(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2)(3\varphi_4^5 + 2\theta_4^5 - 5\varphi_4^3\theta_4^2)}{3(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 3\varphi_3^5)\varphi_4^5}, \quad \varphi_4 \le \theta_3 \le \varphi_2. \tag{18}$$

The elastic coating of the roller (a cloth) is a necessary component of the two-roll module of the machine for squeezing leather [26, 27]. The cloth provides a porous structure into which water can drain from the skin and it should retain this moisture content in the section where the skin is deformed. Therefore, the lengths of the phases depend on the properties of the technical cloth used to cover the rolls. At the same time, by choosing a cloth, we can prevent the outflow of water from the cloth to the leather. In this case, throughout the entire length of phase 4, the hydraulic pressure is zero. This allows the residual moisture of leather to decrease, that is, it leads to an increase in the efficiency of roller squeezing of leather.

Let the cloth be selected in such a way that in phase 4 the reverse water absorption from the cloth by the leather does not occur. In this case, throughout section 4 the hydraulic pressure is zero, that is, equality $H_4(\theta_4) = 0$, where $\varphi_4 \le \theta_3 \le \varphi_2$ satisfied.

3 Results

Mathematical models for the distribution of hydraulic pressure in the area of squeezing leather (semi-finished leather product after chrome tanning) were determined. The graphs of the mathematical models obtained correspond to experimental diagrams obtained by squeezing various wet materials. The study of the squeezing process based on these models makes it possible to determine with sufficient accuracy the appropriate parameters for roller squeezing of leather, necessary for the rational design and operation of squeezing machines.

4 Conclusions

From the point of view of fluid motion, the roll contact zone (a squeezing area) is divided into four sections (phases). Analysis of the mathematical models obtained showed that the hydrodynamic pressure at the initial point of the roll contact zone is zero. First, in section 1, it increases from zero to the maximum value, determined by formula (9), and then in sections 2 and 3, it decreases from the maximum value, determined by formula (9) to zero. Depending on the properties of the cloth used, the hydraulic pressure in section 4 can take negative values or be equal to zero.

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