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Modeling residual moisture content of leather

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Abstract. The study is devoted to the analytical description of the residual moisture of leather (semi-finished leather product after dyeing) taking into account the deformation and filtration properties of the semi-finished leather product at this stage. Mathematical models of changes in the removed fluid, hydraulic pressure in the area of leather squeezing, and residual moisture content are determined. 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. A condition was established for obtaining minimum residual moisture during roller squeezing, which allows for an increase in the efficiency of roller squeezing of leather.

1 Introduction

Roller machines for various purposes are widely used in many branches of industry, in particular, in the mechanical processing of semi-finished leather products. Mechanical processing has a great influence on the quality of the finished leather, its appearance, and the yield of leather in area. The moisture content of leather is important for the normal mechanical processing of semi-finished leather products. After tanning and curing, as well as after dyeing and fat-liquoring processes, the semi-finished leather product usually contains about 75% moisture. Such a high moisture content negatively affects subsequent processes. The moisture content in the semi-finished leather product after squeezing should be 55-60%. Low moisture content (less than 50%) of the semi-finished leather product sharply reduces the efficiency of subsequent mechanical processing operations. The wrinkles formed on leather after squeezing are practically not smoothed out [1]. The process of squeezing semi-finished leather products also has an impact on environmental safety since it is directly related to the problem of wastewater utilization in enterprises. Consequently, we can say that the efficiency of roller squeezing of semi-finished leather products is determined by its residual moisture content.

The possibility of developing mathematical models of roller squeezing of wet materials is largely prepared by previously conducted theoretical and experimental studies in various industries [2-19]. An analysis of these studies showed that the development of mathematical

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models of the squeezing process primarily depends on the deformation and filtration properties of the material being processed.

References [20, 21] are devoted to mathematical modeling of the process of squeezing a semi-finished leather product after chrome pressure; these publications present analytical dependencies that determine the deformation and filtration properties of the semi-finished leather product at this stage [22, 23].

This research is devoted to the analytical description of the residual moisture of the semi-finished leather product after dyeing, taking into account the deformation and filtration properties of the semi-finished leather product at this stage.

An analysis of the design of machines for squeezing semi-finished leather after dyeing [1] showed that the roll modules of such machines have a symmetrical appearance.

In the roll module under consideration, a layer of semi-finished leather product after dyeing (leather) with a thickness of δ_1 interacts with pairs of roll with radii R and has an elastic coating made of technical cloth with a thickness of H (Figure 1).

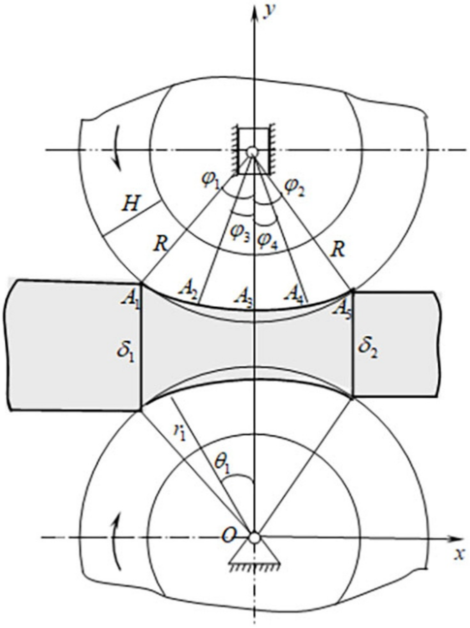

Fig. 1. Scheme of the roll module of leather squeezing machines.

2 Materials and methods

According to previous studies, the main provisions and features of roller squeezing of leather are:

- the hydraulic phenomenon of the roller squeezing process is characterized by the flow of fluid from the leather and cloth into the contact area;
- the contact area consists of four phases. Phase 1 begins when leather or cloth is saturated and ends when both become saturated. Phase 2 begins when both materials are saturated and ends when the external load reaches its maximum. Phase 3 begins when the external load reaches its maximum and ends when the pressure in the pores on the surface of leather becomes negative. Phase 4 begins when the pressure in the

pores on the surface of the skin becomes negative and ends when the external load is removed;

- in the contact area, the flow of fluid from leather to cloth (or vice versa) occurs through the roll contact curves;
- the flow of fluid in the roll contact area creates hydraulic (hydrodynamic) pressure, distributed along the contact curve of each roll. At the point of the contact curve, where the fluid flows from leather to the roller coating, the hydraulic pressure has a positive value otherwise, it is negative;
- the specific pressure of each roll is balanced by the equivalent pressure of leather and cloth caused by the action of pressure (compressive and hydraulic). The sum of compressive and hydraulic pressure in all sections, both in leather and in cloth, is equal to the roll pressure;
- the flow of fluid in leather and in cloth obeys Darcy's law;
- leather and cloth in the contact area can be considered as a two-phase medium consisting of solid particles and fluid filling the pores between them since before entering the contact area they are saturated with fluid from a water wedge.

We divide the roll contact curve (of each roll) relative to the line of centers into zones of compression and deformation recovery.

The roll contact curve (of each roll) consists of sections (phases) 1, 2, 3, and 4 [24, 25], corresponding to sections 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 an index indicating the number of the section.

According to Figure 2

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

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.

3 Results

The shape of the roll contact curve depends on the properties of leather and the pliability of the cloth.

In [26], experimental data were obtained characterizing quantitative and qualitative changes in the elastic and viscoplastic properties of leather under its processing and changes in the moduli of elasticity and viscosity were determined at individual stages of tanning production. According to the results of this study, for the deformation characteristics of leather (semi-finished leather product after dyeing), the Kelvin–Voigt rheological model can be taken:

$$\sigma_1^* = E_1^* \varepsilon_1^* + \mu_1^* \frac{d\varepsilon_1^*}{dt} \tag{1}$$

where $\sigma_1^*, \varepsilon_1^*, E_1^*, \mu_1^*$ – are the stresses, strains, moduli of elasticity and viscosity of leather under compression.

According to [27], a similar model can be taken for the deformation characteristics of cloth:

$$\sigma_1 = E_1 \varepsilon_{1.} + \mu_1 \frac{d\varepsilon_1}{dt}, \tag{2}$$

where $\sigma_1, \varepsilon_1, E_1, \mu_1$ – are the stresses, strains, moduli of elasticity and viscosity of the cloth under compression.

When the Kelvin–Voigt rheological models specify the deformation characteristics of the contacting bodies, the shape of the roll contact curve of the compression zone of the roll module of the leather squeezing machine under consideration, has the following form [27]:

$$\begin{cases} r_1 = \dfrac{R}{1+m_1\gamma_1}\left(1+m_1\gamma_1\dfrac{\cos\varphi_1)}{\cos\theta_1}\right), & -\varphi_1 \le \theta_1 \le -\varphi_3, \\ r_2 = \dfrac{R}{1+m_1\gamma_1}\left(1+m_1\gamma_1\dfrac{\cos\varphi_1}{\cos\theta_2}\right), & -\varphi_3 \le \theta_2 \le 0, \end{cases} \tag{3}$$

where $m_1 = \dfrac{2H\cos\varphi_1}{\delta_1}$, $\gamma_1 = \dfrac{E_1\varphi_1 + \mu_1\omega}{E_1^*\varphi_1 + \mu_1^*\omega}$, $\omega -$ is the angular velocity of the roll.

We determine the patterns of change in the removed fluid in the considered roll module. These patterns make it possible to model the residual moisture of leather.

The effect of squeezing moisture out of wet materials is determined by the amount of fluid removed. Its quantity is determined by the flow rate through the roll contact curves and depends on the deformation of leather and the rate of fluid filtration [28].

During the process of leather squeezing, the filtration of fluid from leather into the cloth of the roll occurs along the polar radius r [28].

As is known [28], the amount of removed fluid flowing along the roll contact curve (polar radius) can be determined by the following expression:

$$dG = B\rho v_r dh,$$

where $B-$ is the width of the leather layer; $\rho-$ is the fluid density; v_r- is the moisture filtration rate in direction r.

Hence, for section 1, the following equality holds:

$$dG_1 = B\rho v_{1r} dh_1, \tag{4}$$

According to [8], the rate of moisture filtration along the roll radius in section 1 has the following form:

$$v_{1r} = a_1(\theta_1^3 + \varphi_3^3), \tag{5}$$

where $a_1 = \dfrac{2v_l R\cos^2\varphi_1}{3\delta_1\,(1+m_1\gamma_1)(1+m_1\gamma_1\cos\varphi_1)}$, $v_l -$ is the velocity of leather.

In this area, the deformation of leather is expressed by the following equality:

$$h_1 = R\cos\varphi_1 - r_1\cos\theta_1.$$

Hence, we have

$$dh_1 = (-r_1'\cos\theta_1 + r_1\sin\theta_1)d\theta_1. \tag{6}$$

From the first equation of system (3), we have:

$$r_1' = \frac{Rm_1\gamma_1\cos\varphi_1}{1+m_1\gamma_1}\frac{\sin\theta_1}{\cos^2\theta_1}. \tag{7}$$

Taking into account the first equation of system (3) and expression (7), from equality (6) we obtain:

$$dh_1 = \frac{R}{1+m_1\gamma_1}\sin\theta_1 d\theta_1 \approx \frac{R}{1+m_1\gamma_1}\theta_1 d\theta_1. \tag{8}$$

According to formulas (4), (5), and (8), we have

$$dG_1 = \frac{\rho BRa_1}{1+m_1\gamma_1}(\theta_1^3 + \varphi_3^3)\theta_1 d\theta_1. \tag{9}$$

After integrating expression (9), we obtain:

$$G_1 = b_1(2\theta_1^5 + 5\varphi_3^3\theta_1^2) + C_1, \quad -\varphi_1 \le \theta_1 \le -\varphi_3, \tag{10}$$

where $b_1 = \dfrac{\rho v_l BR^2 \cos^2 \varphi_1}{15\delta_1 (1+m_1\gamma_1)^2 (1+m_1\gamma_1 \cos\varphi_1)}$

Having determined integration constant C_1 by condition $G_1(-\varphi_1) = 0$, we have:

$$G_1 = b_1(2(\theta_1^5 + \varphi_1^5) - 5\varphi_3^3(\varphi_1^2 - \theta_1^2)). \tag{11}$$

Formula (11) determines the patterns of change in the removed fluid flowing along section 1.

The amount of removed fluid flowing in section 1 is determined by the flow rate at point A_2, that is, by moisture $G_1(-\varphi_3)$:

$$G_1(-\varphi_3) = G_1' = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 3\varphi_3^5). \tag{12}$$

Similarly to formula (10), for section 2 we have:

$$G_2 = b_1(2\theta_2^5 + 5\varphi_3^3\theta_2^2) + C_2,$$

Having determined integration constant C_2 by condition $G_2(-\varphi_3) = G_2'$ and taking into account equality $G_1' = G_2'$, we have:

$$G_2 = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2 + 2\theta_2^5 + 5\varphi_3^3\theta_2^2), \quad -\varphi_3 \le \theta_2 \le 0. \tag{13}$$

The amount of removed fluid flowing through the compression zones is determined by the flow rate at point A_3, that is, by moisture $G_2(0)$:

$$G_2(0) = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2). \tag{14}$$

The fluid flow rate at point A_3 determines the amount of water flowing through the compression zones along the roll contact curve from leather to the cloth. Therefore, in this case, condition $G_2(0) > 0,$ must be met; according to it, from equality (14), we find the condition for determining angle φ_3 in the following form:

$$\varphi_3 < 0{,}74\varphi_1. \tag{15}$$

According to [8, 27], for section 3 of the roll contact curve, we have:

$$r_3 = \frac{R}{1+m_2\gamma_2}\left(1 + m_2\gamma_2 \frac{\cos\varphi_2}{\cos\theta_3}\right), \quad 0 \le \theta_3 \le \varphi_4, \tag{16}$$

$$r_3' = \frac{m_2\gamma_2 R}{1+m_2\gamma_2}\cos\varphi_2 \frac{\sin\theta_3}{\cos^2\theta_3}, \tag{17}$$

$$v_{3r} = a_2(\varphi_4^3 - \theta_3^3), \tag{18}$$

$$h_3 = r_3 \cos\theta_3 - r_3(\varphi_4)\cos\varphi_4, \tag{19}$$

where $a_2 = \dfrac{2v_l R\cos^2\varphi_2}{3\delta_2(1+m_2\gamma_2)(1+m_2\gamma_2\cos\varphi_2)}$, $m_2 = \dfrac{2H\cos\varphi_2}{\delta_2}$, $\gamma_2 = \dfrac{E_2\varphi_2 + \mu_2\omega}{E_2^*\varphi_2 + \mu_2^*\omega}$,

$E_2, \mu_2, E_2^*, \mu_2^*$ – are the moduli of elasticity and viscosity of cloth and leather under deformation recovery.

Taking into account expressions (16)-(19), similarly to formula (10) for section 3, we have:

$$G_3 = b_2(5\varphi_4^3\theta_3^2 - 2\theta_3^5) + C_3, \tag{20}$$

where $b_2 = \dfrac{\rho v_l BR^2 \cos^2\varphi_2}{15\delta_2(1+m_2\gamma_2)^2(1+m_2\gamma_2\cos\varphi_2)}.$

According to condition $G_3(0) = G_2(0) = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2)$, we obtain:

$$C_3 = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2).$$

Then we have

$$G_3 = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2) + b_2(5\varphi_4^3\theta_3^2 - 2\theta_3^5), \quad 0 \le \theta_3 \le \varphi_4. \tag{21}$$

The amount of removed fluid flowing through the contact surfaces of the compression zone and sections 3 is determined by moisture content $G_3(\varphi_4)$:

$$G_3(\varphi_4) = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2) + 3b_2\varphi_4^5. \tag{22}$$

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

$$G_4(\varphi_2) = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2) + b_2(5\varphi_4^3\varphi_2^2 - 2\varphi_2^5). \tag{23}$$

At the point determined by angle φ_4, the fluid changes direction. Then in section 4, the fluid flows from leather to the cloth. Therefore, the second term on the right-hand side of equality (23) has a negative value. Considering this, we have the condition for determining angle φ_4:

$$\varphi_4 < 0{,}74\varphi_2. \tag{24}$$

Under roller squeezing of wet materials, choosing an appropriate type of cloth can prevent the reverse absorption of water by leather from the cloth. In this case, along the entire length of section 4, the hydraulic pressure is zero and therefore the amount of fluid removed in section 4 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 chosen in such a way that in section 4 the reverse absorption of water by leather from the cloth does not occur. In this case, throughout section 4 the hydraulic pressure is zero.

Then we obtain:

$$G_{re} = b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2) + 3b_2\varphi_4^5, \ \ \varphi_4 = 0{,}74\varphi_2. \tag{25}$$

With a known amount of fluid removed, the fluid extracted from the wet material under squeezing is determined by the following expression [28]:

$$W_{\text{re}} = \frac{G_{\text{re}}}{\rho B v_l}, \ 100\%. \tag{26}$$

The following equality holds under roller squeezing [28]:

$$W_{res} = W_{\text{in}} - W_{re},$$

where W_{res}, W_{in} are the residual and initial moisture contents of the squeezed material, respectively

The amount of fluid removed from leather during the squeezing process is equal to the sum of the amount of fluid removed through the contact curves of the lower and top rollers. Therefore, from expressions (25) and (26), it follows that the residual moisture content of leather under roller squeezing is determined by the following expression:

$$W_{res} = W_{in} - \frac{2}{\rho B v_l}\left(b_1(2\varphi_1^5 - 5\varphi_3^3\varphi_1^2) + 3b_2\varphi_4^5\right), \ 100\%. \tag{27}$$

4 Conclusions

From the point of view of fluid flow, the contact zone of the rolls (a squeezing area) was divided into four sections (phases).

Mathematical models of changes in the removed fluid, hydraulic pressure in the area of squeezing leather (semi-finished leather product after dyeing), and the residual moisture of leather were determined. The study of the squeezing process based on these models made 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.

A condition was determined for obtaining minimum residual moisture during roller squeezing, which allows for an increase in the efficiency of roller squeezing of leather.

References

1. G.A. Bahadirov, *The mechanics of the squeezing roll pair* (Tashkent, 2010) p. 156
2. Sh.R. Khurramov, F.S. Khalturaev, IOP Conf.Series: Earth and Environmental Science **614** 012097 (2020). https://www.doi.org/10.1088/1755-1315/614/062097
3. Sh.R. Khurramov, Journal of Physics: Conference Series **1901**, 022115 (2021). https://www.doi.org/10.1088/1742-6596/1901/012115
4. Sh.R. Khurramov, A. Abdukarimov, F.S. Khalturaev, F.Z. Kurbanova, IOP conf. Series Materials Science and Eng. **916** 012051 (2020). https://www.doi.org/10.1088/1757-899X/916/0102051
5. D.C. Chen, Y.M. Elwand, J. of Science and Tech. **11(4),** 235-243 (2002)
6. S. L'Anson, T. Ashword, Tappi J. **70(11),** 1-16 (2000)
7. M. Axelsson, C. Oshlund, H. Vomhoff, S. Svensson, Nordic Pulp and Paper Research J. **21(3)**, 345-402 (2006)
8. Sh.R. Khurramov, F.S, Khalturaev, E3S Web of Conf., **376**, 01053 (2023). https:/doi.org/10.1051/e3sconf/20283760153
9. Y. Yang, D. Linkens, J. Talamantes-Silva, J. of Materials Processing Tech. **152,** 304-315 (2004)
10. S. Abdeikhalek, P. Montmitonnet, N. Legrand, P. Buessler, Int.J.of Mech. Science. **53**, 641-675 (2011)
11. S. Chen, W. Li, X. Li. Int. J. of Mech. Science. **89,** 206-253 (2014)
12. Sh.R. Khurramov, F.Z. Kurbanova, J. AIP Conf. Proc. **2637** (2022). https:/doi.org/10.1063/5.0118674060004
13. Sh.R. Khurramov, F.S. Khalturaev, F.Z. Kurbanova, J. Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti **4(394)**, 159-163 (2021)
14. Sh.R. Khurramov, G.A. Bahadirov, A. Abdukarimov, J. Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti **1(397)**, 242-246 (2022)
15. S. Chen, W. Li, X. Li, Int. J. of Mech. Science. **89,** 118-130 (2014)
16. A. Stefanick, Journal of Achievements in Mater. And Manuf. Eng. **27**, 91-94 (2008)
17. S. Mroz, Journal of Achievements in Mater. And Manuf. Eng. **26**, 186-197 (2008)
18. Sh.R. Khurramov, F.S. Khalturaev, F.Z. Kurbanova, Journal of Physics: Conf. Series **2373(7)**, 072002 (2022). https://www.doi.org/10.1088/0742-6596/2373/072002
19. P. Montmitonnet, Comp.Methods in App. Mech. and Eng. **34,** 342-364 (2007)
20. Sh.R. Khurramov, F.S. Khalturaev, E.S. Buriev, J. AIP Conf. Proceedings **2402** 030038 (2021). https://www.doi.org/10.1063/5.0071265
21. Sh.R. Khurramov, B. Abdurakhmonov, J. AIP Conf. Proc. **2637**, 060003 (2022)
22. A. Amanov, Sh.R. Khurramov, G.A. Bahadirov, A. Abdukarimov, T.Yu. Amanov, Journal of Leather Science and Engineering **3(1),** 1-8 (2021)

23. Sh.R. Khurramov, F.S. Khalturaev, F.Z. Kurbanova, Design and Application for Industry 4.0. Studies in Systems, Decision and Control **342,** 227-240 (2021)
24. V.A. Kuznetsov, N.A. Petrov, V.I. Kartovenko, J. Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Teknologiya Tekstil'noi Promyshlennosti **3**, 67-71 (1984)
25. S. Adanur, Ph.D. *Paper Machine Clothing, Second Editon,* Astenjonsson (2017)
26. A.G. Burmistrov, I. Pol, V.I. Chursin, O.A. Ilyukhina, J. News of Higher Educational Institutions. Light industry technology **3-4**, 40-43 (1992)
27. F.Z. Kurbanova, Dis… Ph.D. Tech. Sci. Namangan (2022)
28. G.K. Kuznetsov, Dis. … Doc. Tech. Sci., Kostroma (1970)