INVESTIGATION OF MOTION OF WATER-CONTAINING SHEET MATERIAL IN-BETWEEN ROTATING PAIR OF ROLLERS

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Abstract: Rolling machines are widely used in technological processes in different branches industries.
Interaction of pair of rollers, covered with elastic material, and water-containing sheet material studied applying general law of dynamics for variable-mass bodies. It was assumed, in the deformation zone the contact curves are parabolas situated symmetrically from the axis which lies on the neutral line of the sheet.
Based on the motion equation of a sheet material with variable mass there was obtained an equation to determine the mass centre. This parameter is used to calculate the rollers pressure and the value of the friction in the deformation zone. Experimentally determined roller jacket - cloth influence to wringing process.
Key words: rollers, water, material, bodies.

1. INTRODUCTION

Mechanical operations have a great influence on quality of the finished leather product, in particular, in its appearance and the amount of obtained area of the leather. By carrying out mechanical operations (wringing, scouring) in proper way the area of output tanned semi finished leather product increases by 6-8% (Burmistrov, 2006, Fomin 2001).
The amount of contained moisture in the semi finished leather product has significant role in keeping the mechanical processes in appropriate progress. After processes: tanning, keeping the semi finished product some time without any treatment, dying and stuffing the semi finished leather contains about 70% moisture. Such a huge amount of moisture negatively effects to the further processes such as: planing, splitting, drying and sticking. The amount of moisture in a semi finished leather product should contain (55-60)%. The low amount, less than 50% moisture of semi finished leather product causes rapidly decrease of the effect of mechanical processes in the following operations. Wrinkles, which occurred after wringing of the semi finished product nearly do not get smoothed (Kaplin, 1999, Kutsidi, 1990).
A moisture removing process from wet semi finished leather product is performed by means of roller wringing machines.
Roller machines are widely used in many industries. The main working part in rolling machines is the roller pair which works in contact with processed semi finished product (Fomin et al., 1994).
The main requirement to roller pairs is maintenance of the uniform pressure in a contact zone of rollers keeping certain force for clipping of processed product (Boyko et al., 1999).
Kinematic and dynamic features of metal rolling in various rollers are well studied assuminng that the law of a dry friction of Amonton, where the friction factor is a constant (Nikolaev, Putnoki, 2009).
There are various approaches in a research of the material clamped rotating rollers and containing liquid components. Investigated (Smirnov and Novikov, 1975) movement of the product clamped between rotating rollers, at a constant friction coefficient in the centre of deformation and without change of weight of considered material.
There are studies of the hydrodynamics of wringing process of textile materials with use of isotropic and layered models, and it is accepted that the liquid movement in them submits to the law of Darsi. While passing in between rollers, the pressed material is deformed, which causes to hydraulic pressure and a liquid movement in the structure. It is confirmed that the liquid movement during wringing is carried out by the rise of the hydrodynamic pressure in a layer of the processed material. The law of hydrodynamic pressure distribution by length of a deformation zone practically does not depend on a kind and properties of a processed material (Kuznetsov, 2000, Boyko et al., 1999).
According the theory of Nissan (Nissan, 1954) the contact zone of work rollers divides in two parts: entrance and exit, where the liquid component removed at exit site. This appearance explained with the removal liquid part under capillary forces at the exit part in contact zone, where the rollers elastic cover absorbs the liquid because its expansion. However, the results of other researchers (Kuznetsov, 2000, Boyko et al., 1999) show opposite, i.e. the liquid components in the semi finished product are

removed at entrance and absorbed by elastic cover at the exit in contact zone. Moreover, the properties of semi finished product and rollers' covers and mechanical parameters of rollers pair has main influence to the moisture removal character.

In the article based on filter equation of Kozeni-Karman and hydrostatic pressure equation of Gaskell developed physic model of the wringing process on rolling devices. As a basis taken a hypothesis about that, where technological process studied as a combination of two simultaneously running and interconnected mechanisms: liquid filtration and movement of liquid film along the semi finished material. Founded on analysis of obtained equation drawn a practical conclusion: that liquid filtration deepness in the material increases proportionally to $\sqrt{R}$ (R – radii of rollers). I.e. increment of rollers radii conduce to more fully removal of liquid components form fibrous material.

Direct application of those theories on studies of semi finished leather products treated in between pair of rollers gives significant error.

2. PAIR OF ROLLERS CONTACT ZONE INVESTIGATION

In order to fully investigate the technological wringing process of wet semi finished leather product taking into account movement of removal liquid, it is necessary to know the structure of the semi finished leather product and movement of liquid components in it. Estimation of structure of hides and leathers by microscopic methods let fully understand dermas of different types of animals' hides and happening processes in them during treatments of leather (Mikaelyan, 1979).

During wringing the semi finished leather product between two work rollers the pressure transferred to the product and liquid components removed from the semi finished product on following condition: $V_{liq.} \geq V_{leather}$ where $V_{liq.}$ - speed of liquid components along the semi finished leather product; $V_{leather}$ - movement speed of semi finished leather product between work rollers.

To the movement of liquid components along the semi finished leather product interfered by situated there bunches of collogenic fibers, i.e. capillaries, in the semi finished product's structure of the product under angle $\alpha_{кол}$ against the surface (Mikaelyan, 1979). Thus, with appearance of hydraulic pressure the liquid moves along the capillaries, and rational movement of the liquid depends on contact surface properties of work rollers.

In the process beginning, when one or both ends of capillary are out of contact zone, the hydraulic pressure forces liquid components to the site of noncontact zone on the surface of semi finished leather product. In the case when the both ends of capillary into the contact zone of rollers or one of the ends is in out of contact zone the movement of liquid components take different character. If the surface of rollers covered with water-permeable elastic material, the following movement of liquid components goes through that cover. In the opposite case, the liquid components moves between surfaces of rollers and semi finished leather product. In the latter case in order to fully remove moisture from semi finished leather product it is required high pressure, which can destroy its structure and reduce the quality.

To investigate the removal of the moisture from semi finished leather product between two rollers it is appropriate to use the general law of dynamics for bodies with variable mass. In this case, the amount of moisture contained in the product will vary continuously by time passing. If in the center of deformation at a moment of time t select element with mass M, it is movement can be described with the following equation:

$$\frac{dM}{dt}\overline{V}_c + M\overline{W}_c = \overline{F}^{(c)} \qquad (1)$$

where $\overline{V}_c, \overline{W}_c$ - are speed and acceleration vectors respectively of the mass centre of selected element; $\overline{F}^{(e)}$ is the main vector of the external forces acting on this element. The wringing process of semi finished leather product in between two rollers with equal radii R, set symmetrically against Ox axis (figure 1).

In spite of different approaches of authors in description of running processes in wringing zone, experimental works showed that the deformation line is parabola (Udval, 2004). In this case it was built on base length of central deformation $l = R\sin\alpha + R\sin\gamma$ where α - capture angle; γ - angle counted from a line connecting the roller centres to the exit from the contact zone; h_0, h_1 and h_2 thicknesses of the semi finished leather product in different parts of wringing system at entrance, capture line and exit respectively.

Firstly it is considered the first half of the wringing process of selected element of semi finished leather product, i.e. from the capturing till its maximum pressed line. The deformation curve of rollers' covers in this case in the cross section of the center given as a parabolic equation.

$$y = \frac{h_0 - h_1}{2R^2\sin^2\alpha}x^2 + \frac{h_1}{2} \qquad (2)$$

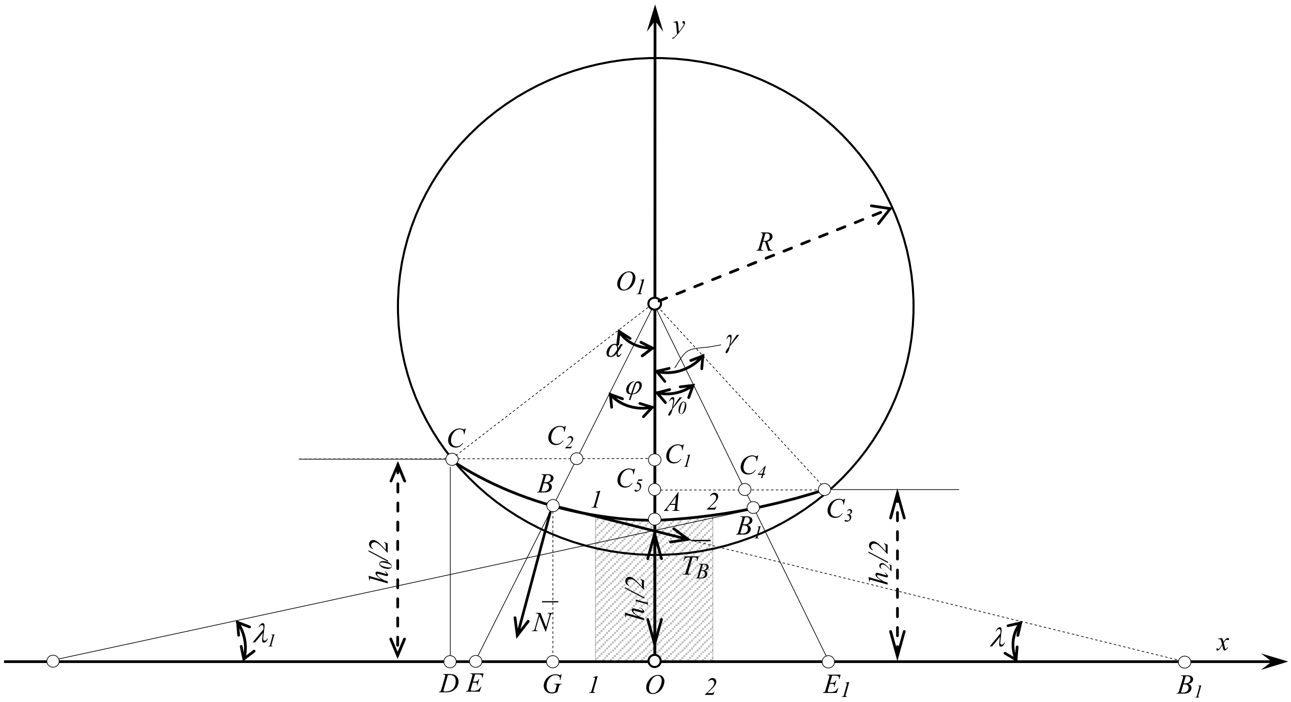

Fig. 1. Schem of roller pair's contact zone

where h_0, h_1 – thicknesses of semi finished leather product at the entrance and at the line connecting the centers of the rollers,

$$\alpha = \arccos\left[1-\frac{1}{R}\left(\frac{1}{2}h_0\varepsilon_M+\delta_0\varepsilon_n\right)\right]$$

- capture angle.

The total volume - V_{tot} of selected element of the product consists of skeleton volume V_{sk}, which in wringing process does not change, volume of pores V_{pore} not filled with a liquid is possible to write as $V_{tot}=V_{sk}+V_{liq.}+V_{pore}$.

Assuming that the liquid components of the considered element in the deformation center start getting removed from instant time $t=t_*$, when V_{pore} equals to null.

At $t=t_*$, a volume of selected element V_{el}, which situated in between two rollers, can be determined from the following:

$$V_{el}=V_{sk}+V_{liq.}=2b\int_{-R\sin\alpha}^{-x_*} y\,dx, \tag{3}$$

where b, $-x_*$- accordingly average width and forward front of the semi finished product.

At constant angular speed ω of rollers the forward front of the semi finished product is defined by the equation

$$-x_*=\frac{1-\sqrt{1+\Gamma tg^2(\alpha-\omega t_*)}}{tg(\alpha-\omega t_*)}\,\frac{R^2\sin^2\alpha}{h_0-h_1}, \tag{4}$$

where

$$\Gamma=\frac{(h_0-h_1)^2}{R^2\sin^2\alpha}\left(1+\frac{2R\cos\alpha}{h_0-h_1}\right).$$

Using equations (2) and (3) we will find

$$V_{el}=\frac{b(R\sin\alpha-x_*)}{3R^2\sin^2\alpha}(h_0-h_1)\left(x_*R\sin\alpha+x_*^2\right)+$$

$$+\left\{(h_0-h_1)\left[R\left(x_*+R\sin\alpha\right)\sin\alpha+x_*^2\right]+\right.$$

$$\left.+3h_1R^2\sin^2\alpha\right. \tag{5}$$

If the investigated element was not deformed for a time interval t_* its volume determined with

$$V_{el}^{(0)}=bh_0\left(R\sin\alpha-x_*\right). \tag{6}$$

Let n_1 is porosity of the semi finished leather product, and ς is its volume humidity, assuming that the liquid completely fills free space of volume V

$$\varsigma V_{el}^{(0)}=n_1V_{el}. \tag{7}$$

From equations (5) - (7) follows that x_* satisfies a quadratic equation

$$x_*^2 + x_* R\sin\alpha +$$

$$+ R^2\left[1 - \frac{3}{h_0 - h_1}\left(\frac{\varsigma h_0}{n_1} - h_1\right)\right]\sin^2\alpha = 0 \quad (8)$$

Since that $x_* > 0$, from (8) it is found that

$$x_* = \frac{R\sin\alpha}{2}\left\{\sqrt{1 + 4\left[\frac{3}{h_0 - h_1}\left(\frac{\varsigma h_0}{n_1} - h_1\right) - 1\right]} - 1\right\} \quad (9)$$

From (9) it is clear that the inequality should be executed

$$\sqrt{1 + 4\left[\frac{3}{h_0 - h_1}\left(\frac{\varsigma h_0}{n_1} - h_1\right) - 1\right]} > 1 \quad (10)$$

The relation $\frac{\varsigma}{n_1}$ should be ≤ 1, and its bottom border is defined from (10). As a result the following received $\frac{h_0 + 2h_1}{3h_0} \le \frac{\varsigma}{n_1} \le 1$.

The mass centre of any element, being in this area, lies on an axis. *Ox* and it will be defined from the equation

$$x_c = \frac{1}{S}\int_{(S)} x\,ds = \frac{1}{S}\int_{(S)} x\,dx\,dy =$$

$$= \frac{1}{S}\int_{-x_1}^{-x_2} x\,dx \int_{-y(x)}^{y(x)} dy = \frac{2}{S}\int_{-x_1}^{-x_2} x\,y(x)\,dx \quad (11)$$

where *(-x₁)* and *(-x₂)* - the left and right border of a considered element respectively; *S* - the area of cross-section of the element with a plane *of Oxy,* which is defined using the equation (2)

$$S = 2\int_{-x_1}^{-x_2}\left(\frac{h_0 - h_1}{2R^2\sin^2\alpha}x^2 + \frac{h_1}{2}\right)dx =$$

$$= \frac{h_0 - h_1}{3R^2\sin^2\alpha}\left(x_1^3 - x_2^3\right) + h_1(x_1 - x_2) \quad (12)$$

Integrating the equation (11) and substituting *S* value from (12), it is obtained:

$$x_c = -\frac{3}{4}(x_1 + x_2)\times$$

$$\times\frac{(h_0 - h_1)\left(x_1^2 + x_2^2\right) + 2h_1R^2\sin^2\alpha}{(h_0 - h_1)\left(x_1^2 + x_1x_2 + x_2^2\right) + 3h_1R^2\sin^2\alpha} \quad (13)$$

Applying $x_1 = R\sin\alpha$ and $x_2 = x_*$, the considered element at this instant time $t = t_*$ it will be completely filled by a liquid where the mass centre will be defined using equation (13)

$$x_c = -\frac{3}{4}\left(R\sin\alpha + x_*\right)\times$$

$$\times\frac{(h_0 - h_1)x_*^2 + (h_0 + h_1)R^2\sin^2\alpha}{(h_0 - h_1)\left(R\sin\alpha + x_*\right)x_* + (h_0 + 2h_1)R^2\sin^2\alpha}.$$

The volume of a considered element at instant time $t = t_*$ calculated with $V_{el} = bS$.

Since $V_{pore} = 0$, the mass of this element will consist of mass of semi finished leather product skeleton $M_{sk} = \rho_{sk}(1 - n_1)bS$ and from mass of a liquid, $M_{liq.} = \rho_{liq.}n_1bS$, where and ρ_{sk} and $\rho_{liq.}$- densities of the skeleton and the liquid respectively, i.e. mass of the element $M_{el} = M_{sk} + M_{liq.} = bS\left[\rho_{sk}(1 - n_1) + \rho_{liq.}n_1\right]$, where S is defined from equation (12) at $X_1 = R\sin\alpha, \quad x_2 = x_*$

$$S = \frac{R\sin\alpha - x_*}{3R^2\sin^2\alpha}\left[(h_0 - h_1)x_*\left(R\sin\alpha + x_*\right) + \right.$$

$$\left. + (h_0 + 2h_1)R^2\sin^2\alpha\right].$$

On the next step the considered element investigated when $-R\sin\alpha \le x \le -x_*$ at instant time $t = t_*$.

x_* is defined using equation (9), therefore time t_* can be found from (4)

$$t_* = \frac{1}{\omega}\left[\alpha - \right.$$

$$\left. - arctg\frac{2x_*R^2\sin^2\alpha}{\left(R^2\sin^2\alpha - x_*^2\right)(h_0 - h_1) - 2R^3\sin^2(\alpha)\cos(\alpha)}\right].$$

For any instant time the $t_* < t < \frac{\alpha}{\omega}$ front of an element will occupy the position

$$\tilde{x}_2 = \frac{1 - \sqrt{1 + \Gamma tg^2(\alpha - \omega t)}}{tg(\alpha - \omega t)}\cdot\frac{R^2\sin^2\alpha}{h_0 - h_1},$$

and back front

$$\tilde{x}_1 = \frac{1 - \sqrt{1 + \Gamma tg^2[\alpha - \omega(t - t_*)]}}{tg[\alpha - \omega(t - t_*)]}\cdot\frac{R^2\sin^2\alpha}{h_0 - h_1}.$$

Considering that $x_1 = -\tilde{x}_1, \quad x_2 = -\tilde{x}_2$ the mass center's relation with time is obtained using equation (13) function of time

$$x_c = -\frac{3}{4}A_1\left(\sqrt{\frac{\psi_1(t) - 1}{\psi_1(t) + 1}} + \sqrt{\frac{\psi_2(t) - 1}{\psi_2(t) + 1}}\right)\times$$

$$\times\frac{A_2\psi_1(t)\psi_2(t) + h_1[\psi_1(t) + \psi_2(t)] + A_3}{A_7 + A_8} \quad (14)$$

where: $A_1 = \sqrt{1 + \frac{2R\cos\alpha}{h_0 - h_1}} R\sin\alpha,$

$$A_2 = h_0 + 2R\cos\alpha, A_3 = 2h_1 - A_2,$$

$$A_4 = 2A_2 + h_1, \quad A_5 = A_2 - h_1, A_6 = 3h_1 - A_2,$$

$$A_7 = A_4\psi_1(t)\psi_2(t) + A_5\sqrt{\left[\psi_1^2(t) - 1\right]\left[\psi_2^2(t) - 1\right]},$$

$$A_8 = 3h_1\left[\psi_1(t) + \psi_2(t)\right] + A_6,$$

$$\psi_1(t) = \sqrt{1 + \Gamma tg^2(\alpha - \omega t)},$$

$$\psi_2(t) = \sqrt{1 + tg^2\left[\alpha - \omega(t - t_*)\right]}$$

The received value of $x(t)$ will allow to define further rollers pressure N_B and size a friction force T_r of semi finished leather product in the contact zone using equation (1).

3. EXPERIMENTAL WORK

Water-permeable elastic covers – roller jackets either put as sleeves or reel on the cylindrical surface of the rollers. There different types of wringing devices where the water-permeable elastic part passes in between rollers as infinite stripes, feeding and taking of the treated semi finished leather products (Udval, 2005).
In order to study the properties and influence to the wringing process of rollers jacket during industrial exploitation there were performed set of experiments. During exploitation of roller jackets (clothes BM and LASH) subjected in to alternating loadings. As a result of the latter, foul conditions and compaction decreased filtering properties of the jacket.
In order to identify the influence of the change of the jackets on the wringing process of the semi finished leather product there were carried out some measurements and defined the following parameters:
- the change of clipping pressure of the rollers during exploitation to keep required residual moisture of processed semi finished product (figure 2):

$$P = P(t), \text{ at } W_m = const. \qquad (15)$$

where P is a clipping pressure of rollers; t - current time; W_m – moisture of processed semi finished product; the thickness change of the roller jacket during processing (figure 3).

$$\delta = \delta(t) \text{ at } W_в = const. \qquad (16)$$

when: a) $P = const$; b) $P = P(t)$,

-change of filtration properties δ of rollers' jacket at exploitation:

$$k = k(t) \text{ at } W_в = const, \delta = \delta(t) \qquad (17)$$

where k is the permeability coefficient of rollers' jacket.

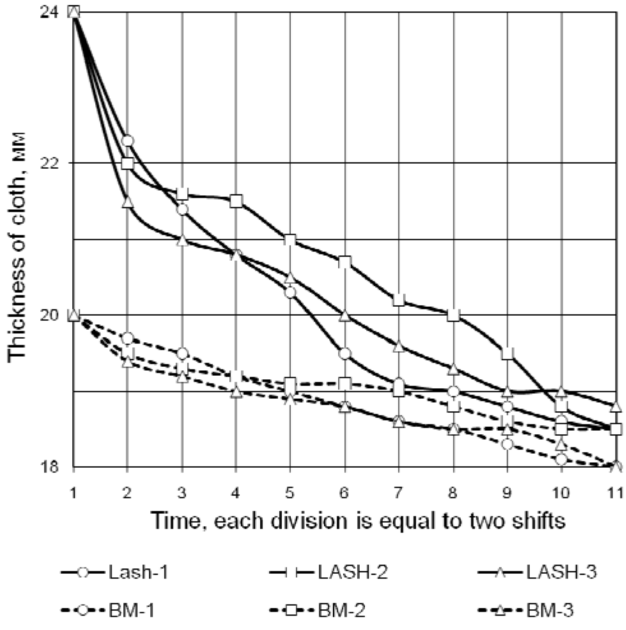

Fig. 2. Schedule changes in the thickness monshon at W = 55%

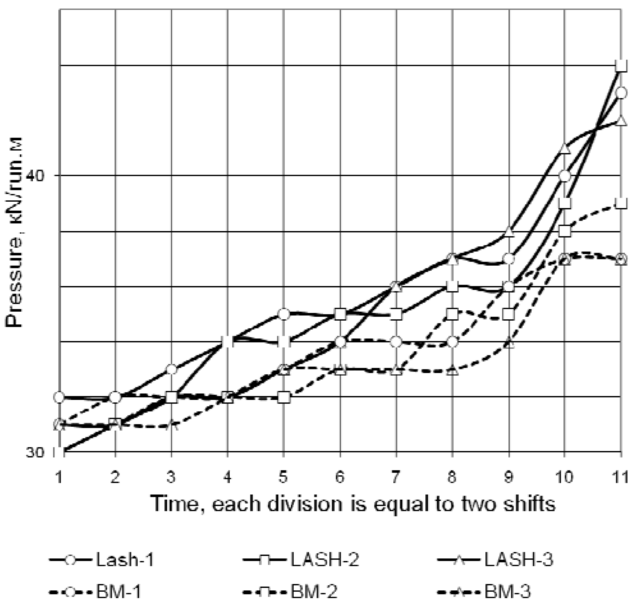

Fig. 3. Schedule of changes in pressure between rolls at W = 55%

As a result of wear and elastic rollers' jackets' pores contamination it is established that the reduction of compressibility and cloth ability to absorb the moisture decreases. Hence, for maintenance of necessary residual moisture in the processed product it is required to increase pressure between rollers.
As a rule, wear, contamination and compression of

the cloth occur almost simultaneously so it is senseless to take off and cleaning from contaminations.
Cleaning of the close done in the case when the rollers jacket strongly contaminated in the first stage of wringing, which helps to restore its properties around (80-90)%.
By replacing roller jackets made from woolen with artificial fibers wear and compression of them in exploitation had changed. This change increased the value of roller cloth cleaning, which is much suitable with artificial fiber jackets.
Now the roller jackets are attended to be cleaned without taking of them from the roller, which cuts extra expenses in those processes. Apart cleaning the jackets without taking off they are required to have certain percentage of moisture in the cloth before rolling semi finished leather products.
The mechanism of moisture removal of fibrous materials based on a capillary structure of roller jackets and processed semi finished product. The capillary structure of the cloth mainly defined with specific pressure, type of yarn, weave of threads and compressibility of the roller jackets. The capillary structure of roller jackets is not studied fully yet.

4. CONCLUSIONS

The obtained expression (14) – determination of the mass center in further works allows to determine the pressure of rollers and friction magnitude in the contact zone of rollers pair using equation of dynamics for variable mass bodies.
In order to remove the moisture from semi finished leather product with high quality – without destroying its structure, the work rollers should be made from porous material or support them with water-permeable elastic covers.
By increasing exploitation time, in order to keep the moisture at the same level in the semi finished product, it is necessary to increase the pressure of roller concerning initial one.
The BM cloth keeps its properties longer than LASH close during exploitation, i.e. the thickness of LASH rapidly decreases in the beginning of the process, where in the case of BM the residual deformation is insignificant. The cloth BM deformed less than LASH one as it is made much dense wool cloth. Moreover, BM is bigger in perimeter than LASH. Consequently, the each point of BM contact less than LASH.

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