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# MATHEMATICAL MODEL OF ROLLING TUBE BLANK

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The article first presents theoretical bases of blanks rolling where skew rolling ensures differences in wall thickness ± 6 % and in diameter ± 0,5 %. Further in text a mathematical model for tube blank rolling is provided and in connection with that a number of influential factors is taken into account. The elaborated model ensures the optimum manufacture of seamless tubes.

***Key words:*** *seamless tubes, tube blank, mathematical model*

**Matematički model valjanja cijevnice.** U članku su prvo dane teorijske osnove valjanja cijevnice, gdje koso valjanje osigurava razlike debljine stijenke ± 6 % a po promjeru ± 0,5 %. U nastavku je dat matematički model valjanja cijevnice, uzimajući u obzir niz utjecajnih faktora. Razrađeni model osigurava optimizaciju proizvodnje bešavnih cijevi.

***Ključne riječi:*** *bešavne cijevi, cijevanica, matematički model*

## INTRODUCTION

The Manufacture of steel tubes occupies a significant place in the framework of total world rolled steel production and particularly in total steel production (from 6 to 10 %). The development of this production is characterized by a significant improvement of its assortment.

Following factors are influential [1, 2]:
- employment of tubes in geology and oil industry, and tube-oriented transport of different media such as oil, natural gas, water, coal, ore etc;
- employment of tubes in civil engineering for construction of bridges, roof structures and other supports;
- employment of tubes in energetic industry, mechanical engineering, boiler tubes, tubes for chemical industry, automobile industry, shipbuilding industry, reactor technique etc.

This tendency was substantiated by intensive theoretical and experimental researches in the field of tubular production that has resulted in occurrence of new manufacturing processes, heightening of a technical level of pipe shops, expansion of a sort and improvement of the quality of steel tubes.

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The process of production of seamless tubes and rolling mill installation type is characterized by expansion of tube blank (obtained weaving or press-molding) in a tube. The expansion operation institutes sort, productivity, final quality level of commodity and production efficiency.

For the production of hot-rolled seamless tubes, tube rolling mill of installation with self-acting pilger, mandrel mill and three-roll reeling (Assel) mills, have received, the greatest distribution in world. These installations differ in the technological indexes.

The broadest sort have the installations with self-acting and pilger mill. The installations with continuous and three-roll reeling mill are applied to producing tubes with small and angle diameter: thin-wall and heavy-wall tubes [2].

The modern installation with continuous mill (mandrel mill), have top performance. Seamless tube rolling mill installating with three-roll reeling mill ensures deriving tubes of split-hair accuracy, 1,5 to 2,0 times superior than the exactitude of tubes on other installations [3].

During a long time, the process of weaving an ingot or preforming it in a blank was most composite and defining for qualitative and quantitative indexes of different production. Theoretical and experimental researches of deformation, velocity and power parameters of weaving was given [4, 5] the major attention.

In the last decades essentially new processes of screw rolling of tubes are proposed, the new technique of weaving of preforms designed and are created high-performance mill, supplying deriving of tubes quality [6, 2].

The further increase in the effectiveness of production of seamless tubes and improving of their quality requires finding out of the theory and improving of technical process of the expansion of tube blanks in tubes.

## ROLLING OF THE TUBE BLANK

Deformation of metal at expansion happens in the centre of strain derivates by rolls and a tube expander and as a final goal has deriving tubes from tube blanks at the expense of thinning-down of wall, magnification of length and changes of diameter.

At the production of hot-rolled seamless, the expansion of tube blank is carried out in gauges derivates by three rolls with miscellaneous angles of inclination of axes of rolls to the axis of rolling on stationary or floating tube expanders.

Probably, all expedients of an expansion can have, despite of a variety of the realization, common theoretical and technological regularities, the examination of which will allow to find paths for further improving and intensifing of processes of production of seamless tubes.

With this purpose we carry out the systems analysis of present factors of expansion.

The basic distinctive feature of factors of tubes expansion is the different positional relationship of axes of rolls concerning the axis of a tube (conditionally - axis of rolling). The axes of working rolls can be unrolled concerning an axis of preform on a angle $\alpha$, the magnitude of which is from 0° up to 90° (Figure 1.).

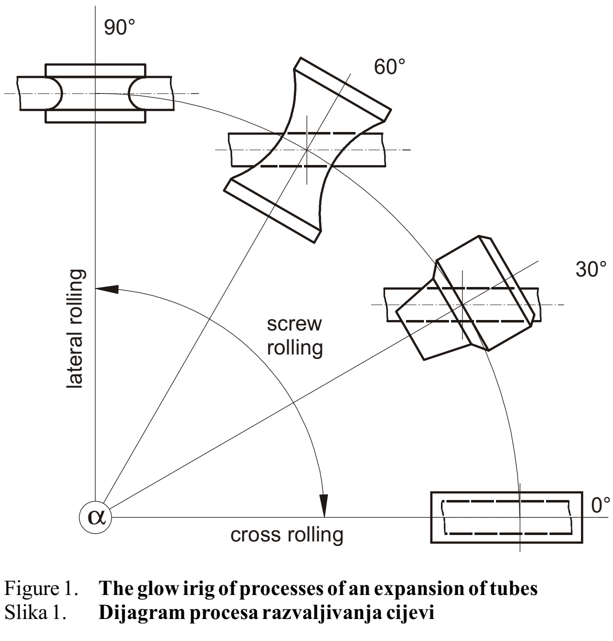


Figure 1. **The glow irig of processes of an expansion of tubes**
Slika 1. **Dijagram procesa razvaljivanja cijevi**

Depending on magnitude of the rotation angle of rolls the shape of calibre (from smooth roll varies at a transversal expansion up to round calibre at longitudinal).

Considering the process of expansion as operating engineering system, we select components of this system (elementary centre of strain) composed from three indivisible devices: the outside and interior instrument and material, deformable between them (Figure 2.).

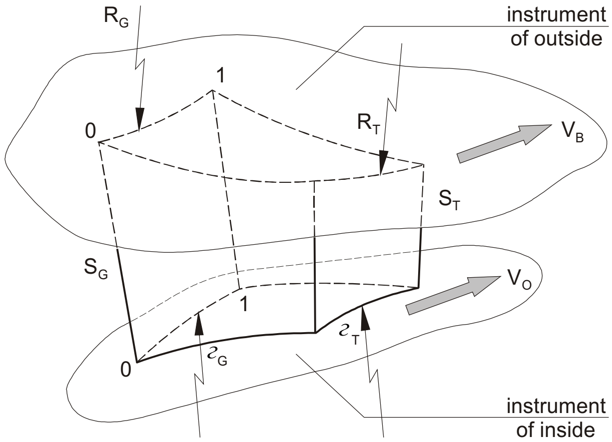


Figure 2. **Components of system - elementary center of a strain**
Slika 2. **Dijelić sustava - elementarni korak deformacije**

Isolated of components of system completely characterizes process of an expansion, having properties targeted to deform a material in convergented space under an operation of a power and velocity field on a contact surface of metal with the instrument.

Besides isolated of components is characteristic system by property by ability to organize new engineering system more high level of complication of devices of the same kind [7].

Considering the idealized model of expansion process, it is possible to define requirements of its architecture, which ensures reaching extreme indications in their plurality. So, for example, for security of complete handling of a head loop of a blank, the uniforms of strain and deriving of tubes of the greatest exactitude have to be created by builders of system - elementary centres of a strain - by(with) the continuous centre displacing lengthways (I) or across (II) of the axis of a blank (Figure 3.a).

The continuous centre of the strain I exists during drawing of tubes, and centre of the strain II - in process of a transversal expansion.

For a realization of actual processes of expansion, the discrete centres of strain, i.e. system of builders II of a level (Figure 3.b, c) are applied.

The discrete centre of strains displacing in an axial direction is applied, for example, at longitudinal rolling of tubes. It is derivates by two or more rolls developing a head loop of a tube in diameter section. Thus the number of the possible discrete centres of strain on perimeter of a tube blank depends on relation of the sizes of a tube blank ($R_G$) and roll ($R_b$) and is contained in:

$$n = \frac{\pi}{\arcsin\left(\frac{R_b}{R_b + R_G}\right)}.$$

However, the irregularity of an altitude strain at longitudinal and transversal, expansion in the discrete centre gives in origin of axial tensile stresses in unyielding leases. The maximum rates of these stresses condition are responsible for failure continuity of metal and restrict magnitude of strain altitude so that a finished stock (tube) bas considerable wall thickness deviation and ovality of sections.

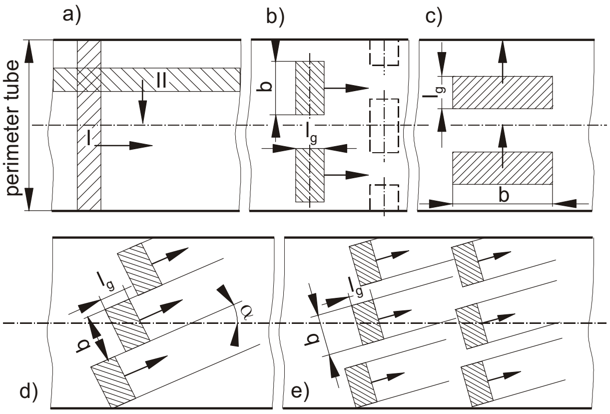


Figure 3. **The circuits of formation of the centre of strain at an expansion**
Slika 3. **Shema stvaranja koraka deformacije ili razvaljivanja**

The uniform and complete handling of a head loop of a blank can be provided only at combination of the discrete centre of strain to a rotational - headway of a blank when the angle between a direction of travel of metal and direct-axis of the tube lays within the limits 0° < $\alpha$ < 90° (screw expansion) (Figure 3.d).

As a feature of process of screw expansion it is necessary to consider that at identical with a longitudinal expansion by magnitude of a velocity term of the instrument, the axial velocity of a tube is less, what results in smaller productivity of process.

At the same time, the magnification of axial velocity at a screw expansion is reached, for example, magnification of the angle of feeding and reallocating of builders of strain in transversal and axial directions.

The structure of process of expansion as a system of the third level is derivates by group of gauges for embodying processes both longitudinal and screw expansion (Figure 3.e).

At a longitudinal expansion each consequent calibre composed of the discrete centres, should create conditions for a strain before undeformed leases of blank. It is carried out in continuous, self-acting and pilger mill. At the same time, each consequent gauge imports the irregularity of strain, that includes necessity of making a great number of single strains. It is bound to heightened energy expenditures and does not ensure split-hair accuracies of finish products. At high deformation ability and broad sort, the screw expansion ensures, in one cage with smaller energy expenditures, of tubes deriving with aberrations on wall thickness ± 6 % and on diameter ± 0,5 %. In most cases ready tubes after reeling mill do not require aftertreatment.

The build-up of batch system of calibres allows considerably to increase a degree of strain, to increase technological flexibility of process of a screw expansion in function of productivity and latitude of a sort. The held systems analysis of processes of an expansion has shown, that most common, rational and perspective is the process of a screw expansion organized in system of discrete calibres, for which designed and the mathematical model of interaction of metal with the instrument in the centre of strain is investigated.

## MATHEMATICAL MODEL OF TUBE BLANK ROLLING

We consider a formulation and method of a solution universal and usable for the analysis of other circuits of a screw expansion, together with longitudinal expansion, with allowance for their features.

The formulation was described by the complex definition of all kinematics' and power parameters of process at the given sizes of blank and tube, outside and interior instrument, plastic properties of metal and requirements of contact abrasion, and, hereinafter, depending on set-up mill and calibration of the instrument, in definition of parameters supplying maximal productivity of process with minimum energy expenditures.

The delivered problem can be resolved under the following circuit:

- definition of functions describing geometry of the centre of strain, surface of contact and private strains;
- definition of functions describing the law of motion of metal, parameters of relative migration on the surface of contact;
- definition of functions describing character of the change of the vectors of normal and shearing stresses on the surface of contact;
- deriving equilibrium equations of forces operating on metal. The resolution will uniquely define the position of neutral sections in the centre of strain.

The actual parameters of interaction are characterized by an angle of screw motion of metal $\gamma$ and angle, defining direction of a vector of relative migration of builders of interaction (metal and roll, metal and tube expander).

Kinematics and energy parameters of processes of a strain of metal by the instrument are instituted by requirements of power interaction on the contact surface and can be described in several ways, the spreadest from which is a method of a standing balance of forces of contact interaction and energy. The majority of the contributors will utillize the first method, the original positions accepted for the analysis of interaction in the present operation.

Generally, if the geometrical parameters of builders of the centre of strain are known and there are other forces affixe to metal, except for forces of contact interaction, the equilibrium equations look like this:

$$\iint_F p l_p r \mathrm{dF} + \iint_F t l_t r \mathrm{dF} = 0$$

$$\iint_F p m_p \mathrm{dF} + \iint_F t m_t \mathrm{dF} = 0$$

$$\iint_F p n_p \mathrm{dF} + \iint_F t n_t \mathrm{dF} = R$$

where:

- $F$ - surface of contact of metal with working rolls,
- $p$, $t$ - normal and tangential contact stresses in a viewed point of contact,
- $l$, $m$, $n$ - direction cosines, defining the position of vectors $\overline{p}$ and $\overline{t}$ concerning principal directions of processes - horizontal, axial and radial according to the index,
- $r$ - radius arresting a position of a viewed point in a selected frame.

The first two equations feature an equilibrium of contact forces in terms of rotation and axial movement at a free screw expansion of a tube, the third equation institutes the same effect $R$ of all forces of contact interaction in a radial direction, balance working rolls and other structural members of a cage reefer mill.

The reduced equations allow to define a field of velocities of metal in contact and extra contact bands depending upon requirements deformation at the given shape, positional relationship and kinematics' of the working instrument - rolls and tube expander, and also energy of performance of expansion process.

The integrated functions of the equations of static's are rather complicated in the shape and structure. For each point of contact, they create variable and interdependent physical performances of deformable metal (circuit of a tension, degree and strain rate of a material at sectional temperature), geometrical and deformation performances of a contact band (shape both positional relationship of rolls and metal, boundary of a contact band, definiendums not only requirements of a contingence of metal with rolls, and also kinematics' and power factors of process (direction of relative migration and requirements of abrasion in a contact band, interaction contact and extra contact of bands etc.). At finding out a mathematical model of process of rolling structure of integrated functions and general opportunity of their definition in a major degree depends on accepted receptions of formalising and system of allowances. Therefore, the first analysis stage of requirements of interaction during a screw expansion of tubes is the dependent of functions of link of principal parameters and estimation of a correctness of allowances, accepted at it. The second stage is described by finding out of a method of solution for the equations of static's, as the parameters, defining fields of velocities of metal, that go into integrated functions in an implicit aspect, and the complication of functions eliminates deriving quadratures. The third and last stage consists in the analysis of the influencing of different technology factors on kinematic both power parameters of process and optimisation of requirements deformation.

At finding out a mathematical model of process of a screw expansion of tubes in three-roll reeling mill the series of allowances are accepted.

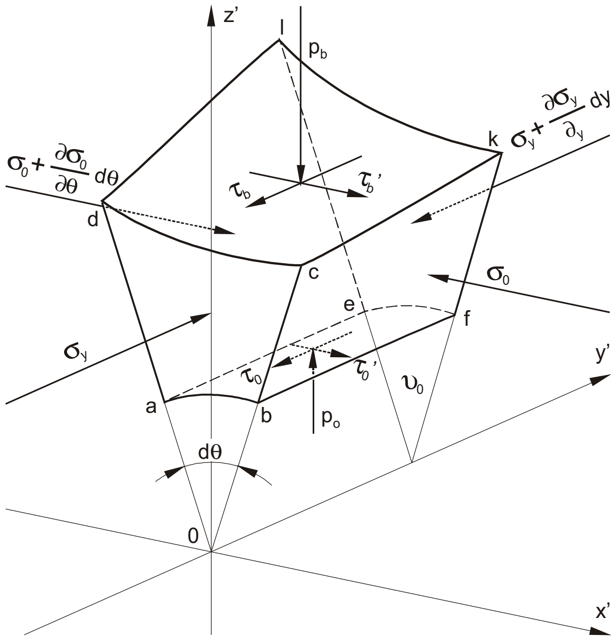


Figure 4. **The force diagram operating in the center of rstrain on a isolated device**

Slika 4. **Shema sila koje djeluju u koraku deformacije na izdvojenom elementu**

In bands with reduction of metal in longitudinal and transversal sections of the centre of strain the contact stresses on the order are less, than in a band of plastic deformation and the extent of a band with reduction in steady-stated process is many times less than extent of a band of deformation of metal on wall thickness. In this connection, the influencing of a band with reduction on the analysis of tight - strained state is left out [2].

As much as possible admissible corners of feeding during an expansion of tubes on three-roll reeling mills is restricted to requirements of unsteady processes. For a majority of sort they do not exceed 7 to 7,5°, and the angle of the expansion, as a rule, is selected structurally and its maximal value reaches 4°. At such a set-up of mill the contortion of the geometrical sizes of the centre of strain is unsignificant, and the registration complicates much more, the procedure of calculation, in this connection the contortion of the sizes of the centre can be neglected.

The process of a screw expansion is characterized by availability of one-zonal field of slide of deformable metal in each cross-section of the contact surface. Lengthwise the centre of strain up to carrying on section the metal on the exit. Thus the horizontal stresses in each cross-section of the centre of strain from an entry point of metal in rolls to a point of an exit are diminished in band by keeping ahead and are augmented in band by lagging behind.

For a resolution of a set of equations it is necessary to define a condition of private strains, kinematic parameters of interaction, direction and magnitude of contact stresses, magnitude of a contact surface, and also to fulfil a complex of examinations of expansion process.

At the further theoretical analysis of contact stresses, the method permitting to allow irregularity of metal strain and to receive the bending moment diagram of allocation of contact stresses lengthwise and breadthwise the centre of utilised strain which we have designed.

I select in the centre of a strain mill a screw expansion device, restricted to planes I-I and II-II on the axis OY and angle d$\theta$ in a transverse direction (Figure 4., 5.).

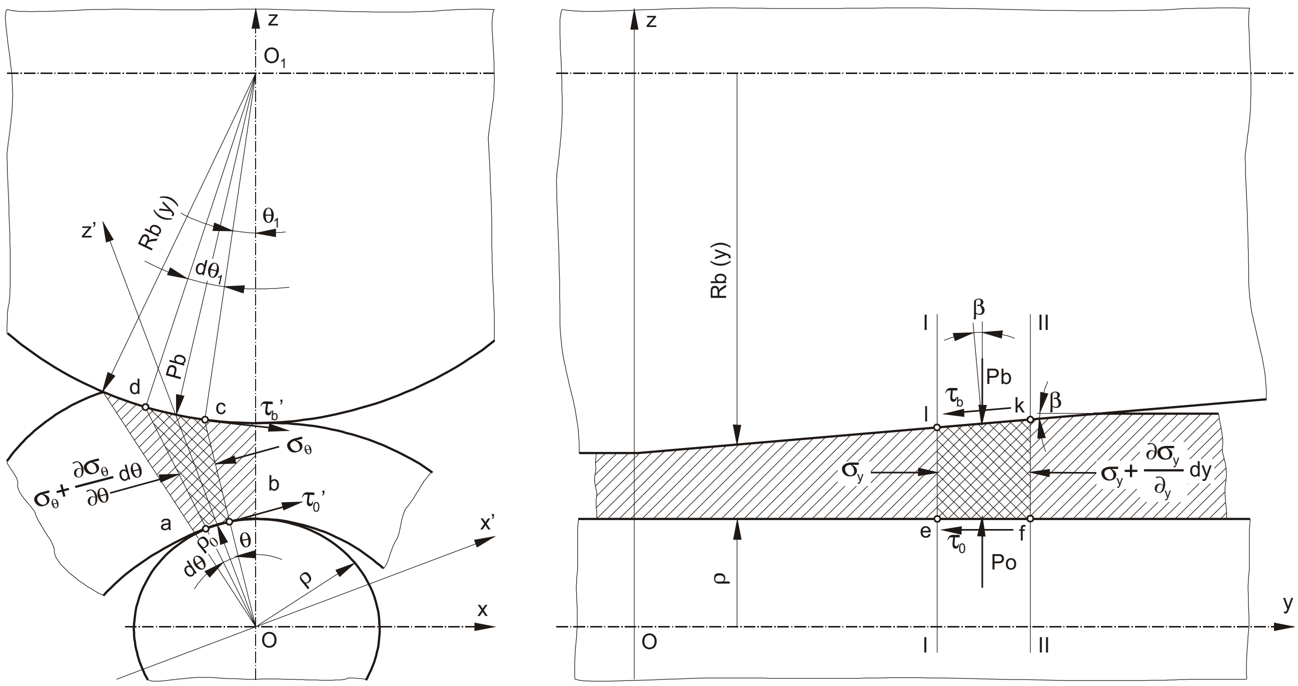


Figure 5. **An equilibrium isolated of a device of a tube**
Slika 5. **Ravnoteža na odvojenom elementu cijevi**

advances above the roll in terms of rotation, and after it - lags behind the instrument. Such a character of kinematics' interaction is explained by influencing of exterior bands. Only in that case, when on the whole length of the centre of strain the metal is in a plastic torsion, in each cross-section of bands material is keeping ahead and lagging behind. The availability of one-zonal fields of slide is explained for a band keeping ahead by availability of underpinning forces of interfocal interaction on going into the centre of strain and stretching on escaping it and for a band with lag - underpinning on the input and stretching

Let's designate the areas of edges of a device $F_{abcd}$ through $F_1$; $F_{efkl} = F_2$; $F_{cdlk} = F_3$; $F_{abfe} = F_4$; $F_{adle} = F_5$; $F_{bckf} = F_6$.

The total of projections of forces operating on the axis of isolated device $OX'$:

$$\sum OX' = \sigma_0 F_6 - \left(\sigma_\theta + \frac{\partial \sigma_\theta}{\partial \theta} \mathrm{d}\theta\right) F_5 - $$
$$-\tau_0' F_4 - \tau_b' F_3 \cos(\theta + \theta_1) + p_b F_3 \sin(\theta + \theta_1) = 0.$$

Substituting values of the areas of edges and allowing a requirement of a toughness by the way $p_b - \sigma_\theta = 2k,$ after transformations, an equilibrium equation has been received:

$$\frac{\partial p_b}{\partial \theta} - 2k\frac{1}{S}\frac{\partial S}{\partial \theta} + \tau_0'\frac{r_0}{S} + \tau_b'\frac{1}{S}\frac{\partial S}{\partial \theta}\frac{R_b(y)}{\theta A} = 0.$$

With allowance for equilibrium equation of shearing stresses on edges $F_1$ and $F_2$ after simplification, a differential equilibrium equation has been received:

$$\frac{\partial p_b}{\partial \theta} - 2k\frac{\partial S}{\partial \theta}\ln S + \tau_0'\frac{r_0}{S} + \frac{r_0 + S_b(y)}{S}\tau_b' = 0.$$

Integrating the indicated equation and instituting boundary conditions for bands material keeping ahead and lagging behind defined the values of contact stresses in a band material keeping ahead:

$$\frac{p_b^{on}}{2k} = \xi_1(y) + \ln\frac{S(\theta, y)}{S_k(y)} + f_b'\frac{r_k(y)}{S_k(y)}\theta$$

and band of lag:

$$\frac{p_b^{OT}}{2k} = \xi_0(y) + \ln\frac{S(y,\theta)}{S_0(y)} + f_b'\frac{\varepsilon_k(y)}{S_k(y)}\left[\theta_0(y) - \theta\right].$$

Equating these equations at $\theta = \theta_H(y).$ In neutral section, after transformations have received:

$$\theta_H(y) = \frac{1}{2}\theta_0(y) + \frac{\xi_0(y) - \xi_1(y) - \ln\dfrac{S_0(y)}{S_k(y)}}{2f_b'\dfrac{\varepsilon_k(y)}{S_k(y)}}.$$

In the centre of a strain mill screw rolling it is possible to select except for bands of a complete keeping ahead and lagging behind so-called transitional field, in which the neutral line (boundary of bands), i.e. lease ABCD on the surface of contact having bands keeping ahead and lagging behind (Figure 6.) is posed.

The theoretical analysis allows to introduce character of allocation of normal contact stresses lengthwise and breadthwise the centre of strain.

In our operations [4] more precise solutions for definition of gains taking into account features of strain of metal are obtained for the first time at a longitudinal expansion of tubes in round gauge on a lengthy tube expander.

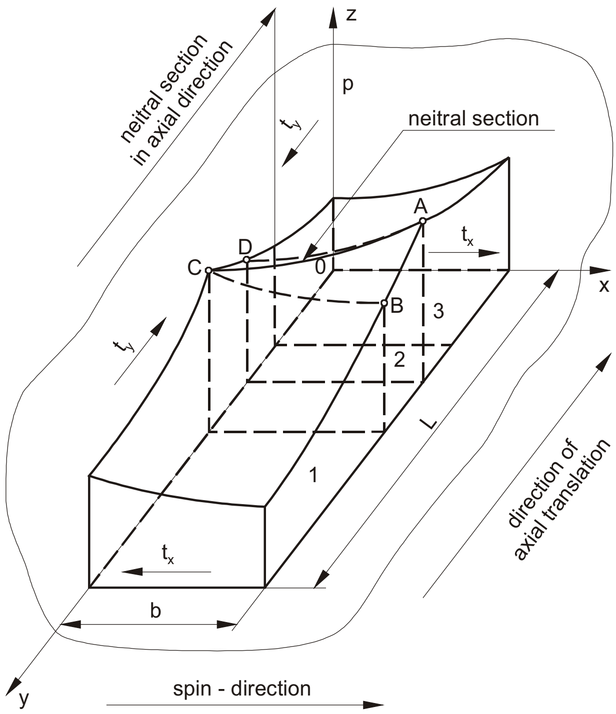


Figure 6. **Allocation of direct stresses lengthwise and breadwise the centre of strain**

Slika 6. **Raspored normalnih naprezanja po dužini i širini koraka deformacije**

Considering the force diagram operating in the centre of strain and equilibrium condition of a device in polar coordinates have been received the equations for definition of normal contact stresses in any point of the centre of strain, which allow to find allocation of direct stresses lengthwise and breadthwise the centre strain depending on the angle $\theta$ [8 - 10].

Normal contact stresses in a band of lagging behind

$$p_{x,\theta} = \beta\sigma_T\left\{\left[1 - \left(\frac{2\theta}{\pi}\right)^2\right] - \left(1 - \frac{f + f_0}{\Delta S}l_D\right)\ln\frac{S_{i,\theta}}{S_{x,\theta}}\right\}$$

in a band keeping ahead

$$p_{x,\theta}' = \beta\sigma_T\left\{\left[1 - \left(\frac{2\theta}{\pi}\right)^2\right] + \left(1 + \frac{f + f_0}{\Delta S}l_D\right)\ln\frac{S_{x,\theta}}{S_{f,\theta}}\right\}.$$

Knowing regularity of allocation of direct stresses in the centre of strain, it is possible to define complete gain on rolls

$$p = 2\int_0^{\frac{\pi}{2}}\int_0^{\frac{x}{H}} p_{x,\theta}' r_x \mathrm{d}x\mathrm{d}\theta + 2\int_0^{\frac{\pi}{2}}\int_{x_H}^{l_D} p_{x,\theta} r_x \mathrm{d}x\mathrm{d}\theta$$

and medial direct stress:

$$p_{med.} = \frac{\beta\sigma_T}{b_{med.}}\left\{\frac{\pi}{3}\left(S_H + \omega\right) - \left(1 - \frac{f + f_0}{\Delta S} l_D\right)\cdot\right.$$
$$\left.\cdot\left[\omega\left(\ln S_H - \frac{S_H}{\Delta S}\ln S_H + \frac{S_k}{\Delta S}\ln S_k\right) + S_{med.} + d_0\right]\right\}$$

where:

$b_{med.}$ - medial breadth of the centre of strain,
$S_i$, $S_f$ - original and final wall thickness,
$\Delta S$ - swaging on wall thickness,
$d_0$ - diameter of tube expander,
$l_D$ - length of the centre of strain,

$$S_{med.} = \frac{S_i + S_f}{2},$$

$\omega = S_i + d_0$,
$f = f_0$ - friction coefficients on contact of metal to rolls and tube expander.

## CONCLUSION

The proposed method has found a further development in operations dedicated to the definition of warping gains at continuous rolling of tubes, reduction, molding and rolling of tubes on a short tube expander.

This theoretical analysis has formed the basis for further improving of the “know-how” of seamless tubes and finding out new high-performance factors of production, including continuous rolling of tubes with containment of a tube expander, rolling of tubes in blocks on a short tube expander, continuous screw rolling, applying screw rolling for operations of calibrations of test leads of tubes both opening-up of test leads of blanks and perform before rolling etc [5, 6].

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