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NUMERICAL DESIGN OF A HOT-STRETCH-REDUCING PROCESS FOR WELDED TUBES

NUMERIČNO NAČRTOVANJE VROČE RAZTEZNE REDUKCIJE VARJENIH CEVI

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During stretch reducing, steel is submitted to complex stressing and straining processes. This paper gives a ***theoretical model*** of a heat-stretch-reducing process for the relation between the tube diameter and the wall thickness. The design is verified by a determination of the number of revolutions of rolls with every caliber for specific tubes on an industrial mill. The control of the rolled-tube dimensions confirmed the accuracy of the design.

Key words: hot-stretch reducing, welded tubes, numerical model of design, calibrate, coefficient of plastic extension of the steel

Pri raztezni redukciji je jeklo izpostavljeno kompleksni napetostni in deformacijski obremenitvi. V članku je predstavljen teoretičen model procesa vroče raztezne redukcije za razmerje med premerom cevi in debelino njene stene. Načrt je preverjen z določitvijo števila vrtljajev valjev na industrijski valjarni za vsak kaliber za določene dimenzije cevi. Kontrola dimenzij cevi je potrdila natančnost izračuna.

Ključne besede: vroča raztezna redukcija, varjene cevi, numerično načrtovanje, kalibracija, koeficient plastičnega iztezanja

1 INTRODUCTION

With the technology of stretch reducing, previously manufactured tubes are transformed in several passes into tubes with a selected diameter and wall thickness.[1,2,3] In the processing, the tube is submitted to strong compression and tensile stresses during the reduction of the diameter and the decrease of the tube wall with stretching and tensile stressing. Both the types of stressing are mutually dependent, complex and very high.[2,3] The extent of stretching is defined by the coefficient of plastic extension and it is regulated by the number of revolutions of the rolls during every pass.[4] This coefficient is the ratio of the reduction of the tube diameter and wall, and the ratio of the compression and tensile stresses in the tube. The number of passes depends, on the one hand, on the required reductions of the tube diameter and the wall, and on the other hand, on the lowering of the temperature from the first to the last reduction pass. The quality of the processed steel is of great importance, since it determines the temperature range of the processing. For this reason, theoretically, the number of passes of the stretch-reducing mill depends on the total size of the reduction and the decrease of the temperature in all the reducing passes.

The model design of the stretch-reducing parameters, mainly reductions, stretchings, and temperature, is relatively complex and depends on several mutually related parameters. The improper selection of the stretch-reducing parameters leads to deviations between the planned and the obtained tube dimensions and the failure of the tubes' walls and a non-uniform deformation over the tube length may also occur.[5] In comparison to other processes of tube rolling, stretch reducing has some advantages, probably the most important is that it enables the manufacturing of several finished tubes from the same initial tube diameter and wall thickness.[2,9] Also, better accuracy is achieved for the final tube diameter and the wall thickness. And finally, for stretch reducing no internal tool is necessary and welded tubes can be processed without prior removal of the welded beard, while the quality of the tube surface is improved. The technology of stretch reducing is very specific and the number of rolling mills is relatively low. Accordingly, the number of references related to the process is also small. In this work, a ***theoretical model*** of the design of the hot-stretch reducing of tubes is presented, which was used to establish the number and the form of the passes for the industrial rolling of tubes of final diameters in the range ¾ inch to 3 inch from an initial tube of 4 inch.

2 THE PROCESS OF STRETCH REDUCING

The stretch-reducing mill consists of a line of several passes–stands, and as example in Figure 1 a three-stands rolling mill is shown.[3] The number of rolls per caliber is two up to four, with an optimum of three, and any caliber can have an individual drive or all the calibers can have a shared drive. All the calibers have an oval, and only the last one has a circular shape. The rolls are inclined at

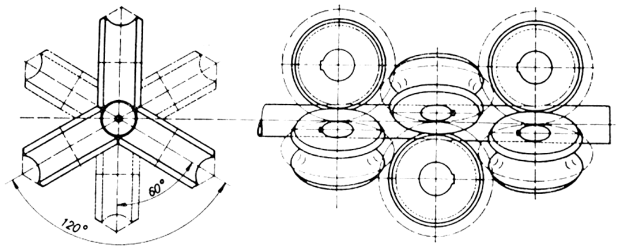

Figure 1: Flow chart of a three-calibers stretch-reducing rolling mill (3)
Slika 1: Pretočna shema trikalibrne raztezne valjarne

120° and the passes at 60° (**Figure 1**). The number of passes depends on the tube dimensions and the maximum reduction of the tube diameter and wall thickness. To lower the processing temperature and make possible the use of a greater number of passes in the prescribed temperature range, the intercaliber distance must be as small as possible.[2,3,4]

A schematic of the work of the stretch-reducing mill is shown in **Figure 2**. No change of the wall thickness occurs in the first pass, while the reduction of the diameter is 3 % to 5 %. The friction coefficient is negative and has the role of driving the processed tube. In the following two to three passes the diameter reduction is 12 %, the coefficient of plastic extension is below 0.5 and the tube-wall thickness is increased. In the middle passes the diameter reduction is up to 12 %, the extension coefficient is 0.75 and the reduction of the tube diameter and the wall thickness is achieved. In the last two passes the accuracy of the final product is ensured with a diameter reduction of 3 % to 1.5 % and with a constant wall thickness The rate of the processed tube increases from pass to pass.[4,5]

The number of passes, the dimensions of the reduction rolls and the rate of the roll revolutions are given. The calculation model is based on two basic laws: the law of the constancy of the pass rate and of the constancy of volume. When designing the successions of passes on the continuous processing line it is necessary to consider that on the same time, the tube is in several passes. To maintain the continuity of the processing, the same volume of material has to pass through every processing pass. If this continuity is not respected, the movement of the tube may be affected and by greater

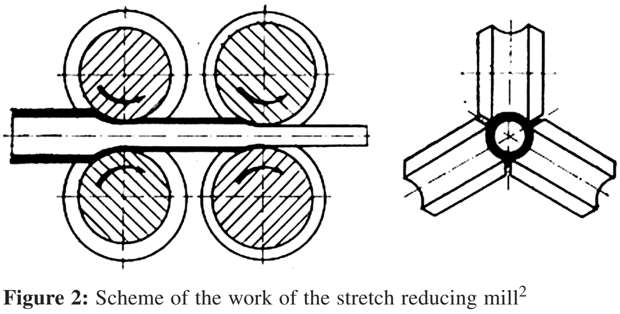

Figure 2: Scheme of the work of the stretch reducing mill[2]
Slika 2: Shema delovanja raztezne valjarne

differences, disturbances or even breaking of the rolling may occur.[2,5,6]

The as-welded tube enters the stretch-reducing mill with an initial outside tube diameter of d_0 and a tube-wall thickness of s_0, which are reduced to the final dimensions of d_n and s_n in a determined number of passes. For the decrease of the tube wall to the required thickness, in relation to the initial, a sufficient tensile stressing (σ_v) is required[2,6,7] it is necessary that for the part of the processed tube between two following passes. For this reason, the rotation rate of the following rolls is greater than that of the precedent, thus ($n_n > \ldots > n_2 > n_1$). The increase in the rotational rate in every pass depends on the reduction of tube diameter and the wall thickness in the pass.

For the simplified design model of the process passes of the tubes, the stretch-reducing equations (1) to (6) are used. For the number of passes n the relations (1) and (2) must be fulfilled, such that:

$$v_{1(1)} = v_{1(2)} = \ldots = v_{1(n)} = const \tag{1}$$

or

$$A_1 \cdot v_{1(1)} = A_2 \cdot v_{1(2)} = \ldots = A_v \cdot v_{1(n)} = C \tag{2}$$

where C is the rolling constant, v_1 is the tube exit rate from the pass and A is the area of the tube section

The circumferential velocity of the rolls is:

$$v_0 = D \cdot \pi \cdot n \tag{3}$$

Because of acceleration, the tube rate v_1 is greater during the pass exit than the circumferential rolls' velocity. For a simplification of the calculation of the passes, the difference is generally neglected and it is assumed that $v_i = v_o$. On the basis of this supposition, the constant C is calculated from equation (4):

$$A_1 \cdot D_1 \cdot v_{1(1)} = A_2 \cdot D_2 \cdot v_{1(2)} = \ldots = A_n \cdot D_n \cdot v_{1(n)} = C \tag{4}$$

where D is the rolls' working diameter inside the pass and n is the revolution rate of the rolls.

The calculation is necessary for every new dimension of tube manufactured. After every calculation, the working diameter of the rolls is deduced with relation to the first or the final pass and the rolling constant is determined.[7,9] The number of revolutions for the other rolls is then calculated according to equation (5):

$$N = \frac{C}{A \cdot D} \tag{5}$$

On the basis of the constant C the working diameters of all the rolls are calculated using equation (6):

$$D = \frac{C}{A \cdot N} \tag{6}$$

The rolls' diameter is a variable only in the projects of a new rolling mill. For mills in operation, the rolls' diameter depends on the diameter of the rolls for standardised types of mill stands.

The explained calculation is very much simplified and it could be applied only for checking in cases when the mill constant is determined with a detailed calculation in which the compression stresses generated by the simultaneous reduction of tube diameter and of tube wall with tensile stresses are considered.

For a detailed calculation it is necessary to first determine the elements of the deformation zone. The reduction of the area is determined for the transverse tube section in every pass opening caliber (reduction of diameter), and the rate of the rolls' revolution (the reduction of the tube wall with elongation). The relation of both reductions depends on the coefficient of the plastic extension, which also represents the relation of the compression and tensile stresses.

3 ELEMENTS OF THE DEFORMATION ZONE

For the calculation of the reduction and the rate in the deformation zone the elements of this zone need to be determined according to **Figure 3**. The zone is defined by the angle of contact α, the neutral angle γ, the gripping length between the surface of the rolls and the tube as well as the tube diameter and the wall thickness.

With the stretch reducing of the tubes, the deformation zone consists of two parts. In the first part with the compression stresses the tube diameter is decreased, and in the second part with the tensile stresses the wall thickness is decreased. Both parts are connected at the neutral angle γ. The total length of the deformation zone l_d from the gripping point to the exit of the tube represents the line of contact between the rolls and the processed tube. The neutral angle γ is calculated with the equation:

$$\gamma = \frac{\alpha}{2} \cdot \left(1 - \frac{\alpha}{2\beta}\right) \tag{7}$$

The angle of contact α is calculated from:

$$\alpha = \arccos\left(1 - \frac{\Delta d}{R}\right) \tag{8}$$

and

$$R = \frac{D_w - 2b}{2} \tag{9}$$

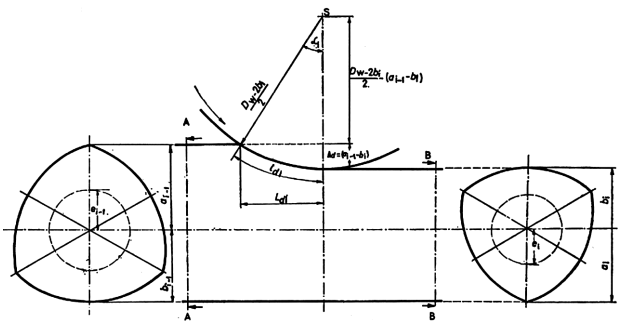

Figure 3: Elements of the deformation zone (10)
Slika 3: Elementi zone deformacije

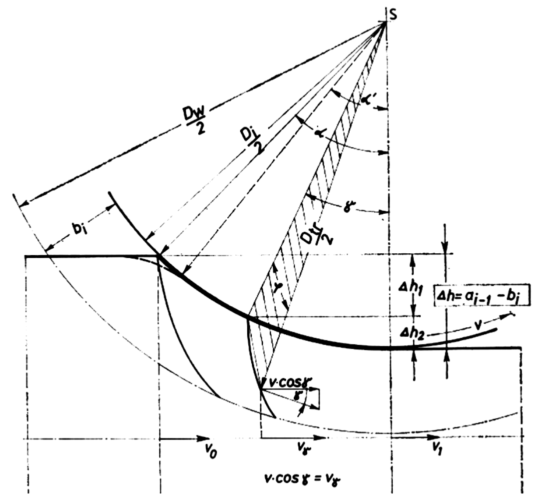

Figure 4: Tube and roll rates and point of the neutral angle in the deformation zone
Slika 4: Hitrost cevi in valjev na točki nevtralnega kota deformacijske zone

With the parameters Δd, D_w and b showed in **Figure 3**.[10]

The friction angle β depends on the temperature T_i, the rolls type m_l, the rolling rate m_2 and the type of the steel processes m_3, and it is calculated from equation (12):

$$\beta = \arctan \mu \tag{10}$$

$$\mu = m_1 \cdot m_2 \cdot m_3 \cdot (1.05 - 0.005 \cdot T_i) \tag{11}$$

Figure 4 shows that the neutral angle γ determines the point where the tube rate in the rolling direction is equal to the horizontal component of the circumferential roll velocity on the transport radius ($v_\gamma = v \cos \gamma$), the point where the tube rate at the exit of the deformation zone (v_1) becomes greater than the circumferential roll velocity on the transport line.[6,10]

According to this analysis $v_1 > v_\gamma > v_0$ and with the dependence of the observation point, in the deformation zone the relative positive and negative motion occurs with respect to the roll circumferential velocity.

4 ROLLING RATE

To achieve the reduction of the tube diameter and wall thickness it is necessary to establish the proper relation of the rates in all the phases of the stretch reducing. The proper relation of the rates ensures the continuous processing of the changes of the diameter and the wall tube section area. As for other continuous rolling processes, the law of constant volume must be respected. For different points of the deformation zone, this law is given by the relations (12) and (13):

a) At the exit of the deformation zone

$$A_1 \cdot v_{1(1)} = A_2 \cdot v_{1(2)} = \ldots = A_n \cdot v_{1(n)} \tag{12}$$

The law of constant volume requires that in the first pass the initial rate is smaller than the pass exit rate. The pass exit rate is increased with the decrease of the section of the tube wall until the rolling is ended.

At the neutral point of the deformation zone

$$A_{\gamma(1)} \cdot v_{\gamma(1)} = A_{\gamma(2)} \cdot v_{\gamma(2)} = \ldots = A_{\gamma(n)} \cdot v_{\gamma(n)} \quad (13)$$

The distribution of the rates and their relative place in the deformation zone for the tube rolling in a three-rolls oval pass is shown in **Figure 4**. The tube rate is equal to the horizontal component of the circumferential roll velocity and the tube rate at the exit of the deformation zone is greater than the circumferential roll velocity on the transport radius. For an angle lower than γ, a relatively positive tube motion occurs (the zone of overtaking), while, for the angle lower than γ a relatively negative motion of the tube occurs (the tube straggling zone), **Figure 5**.

The overtaking, i.e., the difference in the roll circumferential velocity and the tube exit rate, is given in equations (14), (15) and (16).

$$s_i = \frac{v_{1(i)} - v_{\mathrm{tr}(i)}}{v_{\mathrm{tr}(i)}} \quad (14)$$

$$s_i = \frac{\dfrac{A_{\gamma(i)}}{\mathrm{A}_{(i)}} v_{\mathrm{tr}(i)} \cos\gamma_{(i)} - v_{\mathrm{tr}(i)}}{v_{\mathrm{tr}(i)}} \quad (15)$$

$$s_i/\% = \left(\frac{A_{\gamma(i)}}{\mathrm{A}_{(i)}} \cos\gamma_{(i)} - 1 \right) \quad (16)$$

The tube exit rate from the pass deformation zone according to equations (7) and (8) and with respect to the neutral angle (**Figure 4**) is calculated according to equations (17), (18) and (19).

$$v_i = \frac{A_{\gamma(i)} v_{\gamma(i)}}{\mathrm{A}_{(i)}} \quad (17)$$

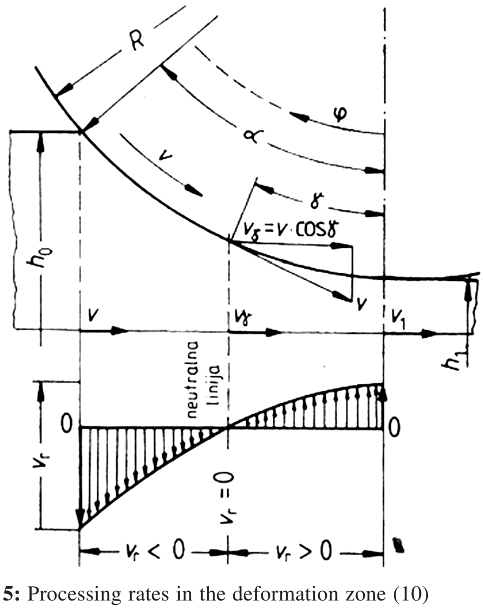

Figure 5: Processing rates in the deformation zone (10)
Slika 5: Hitrosti preoblikovanja v coni deformacije (10)

$$v_{\gamma(i)} = v_{\mathrm{tr}(i)} \cos\gamma_{(i)} \quad (18)$$

$$v_{1(i)} = \frac{A_{\gamma(i)}}{\mathrm{A}_{(i)}} v_{\mathrm{tr}(i)} \cos\gamma_{(i)} \quad (19)$$

The tube exit rate is deduced from the mill constant C in equation (4) according to equation (20).

$$v_{1(i)} = \frac{C}{\mathrm{A}_{(i)}} \quad (20)$$

The number of revolutions of the rolls is calculated on the basis of the transport radius and the circumferential velocity in this radius from equation (21).

$$N_i = \frac{v_{\mathrm{tr}(i)}}{D_{\mathrm{tr}(i)}\pi} 60 \quad (21)$$

The number of revolutions of the rolls for every pass in the stretch-reducing mill N_{i}, depends on the initial rate, thus the number of revolutions of the first pass n_1; it depends on the number of revolutions for every caliber and it is calculated using equations (22) and (23).

$$n_i = n_1 N_i \quad (22)$$

With a multiplication of the number of stands with the number of revolutions of the first pass the number of revolution is obtained for every pass.

$$N_i = \frac{A_{\gamma(1)} D_{\mathrm{tr}(1)} \cos\gamma_{(1)}}{A_{\gamma(i)} D_{\mathrm{tr}(i)} \cos\gamma_{(i)}} \quad (23)$$

The number of revolutions of the first pass depends on the tube entering rate, i.e., the rate of tube welding.

5 DETERMINATION OF THE SECTION AREA OF THE TUBE DURING THE STRETCH-REDUCING PROCESS

By continuous rolling of the tubes on the stretch-reducing mill the mutual relation of the rates is defined as the change of the area of the tube section in the deformation zone.[11,12] The base equation for the calculation of the section area is:

$$A_i = \pi \cdot s_i (d_{\mathrm{sri}} - s_i) \quad (24)$$

As the tubes are rolled with three rolls oval calibers, the calculation of the section area is complex, especially if the point in the deformation zone is also considered. With standard processing, the reduction diameter is equal for all the passes with the exception of the first and the two last passes. The average relative reduction diameter without elongation is in the range of 3 % to 5 %, and in the range 7 % to 12 % if the elongation s is also considered. With practical technology, the diameter reduction is given by the dimension of the caliber of pass size[6,7] (**Figure 6**).

The basic caliber dimensions are the width a and the height b (**Figure 6**). With relation to the previous, in the following stand the caliber is changed for an angle of 120° and the width ($a_{i\text{-}1}$) becomes the height with the size

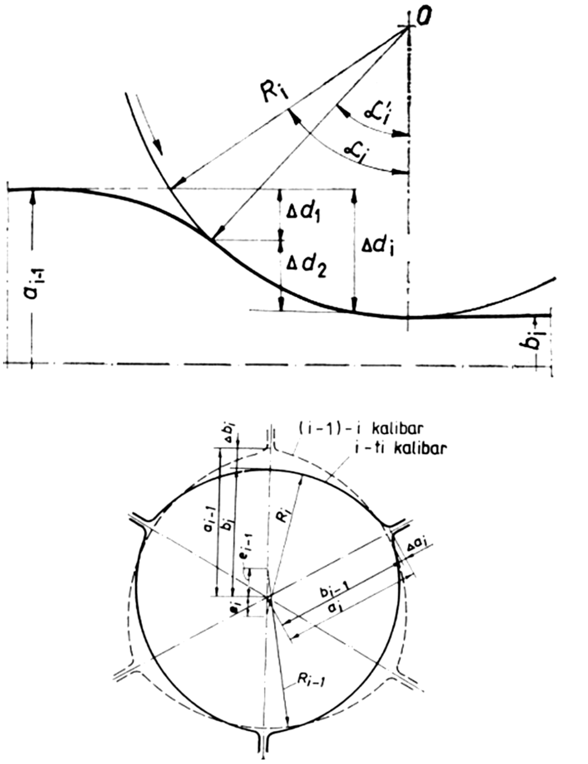

Figure 6: a) reduction of tube diameter, b) dimensions of the three rolls caliber
Slika 6: a) redukcija premera cevi, b) dimenzije kalibra s tremi valji

decreased by the reduction in this pass (Δb_i) (**Figure 6**). Simple equations for the calculations of the change of diameter Δd_i and wall thickness s_i are the relations (25) and (26).

$$\Delta d_i = a_{i-1} - b_1 \tag{25}$$

$$s_i = s_{i-1} - \frac{s_{i-1} - s_i}{d_{i-1} - d_i}(d_{i-1} - d_\gamma) \tag{26}$$

The average outside tube diameter d_{sri} is determined by the dependence of the dimensions of the three-rolls oval caliber according to **Figure 6** by applying equation (27):

$$d_{sri} = \frac{2.865 \cdot b_i^2 - 0.365 \cdot a_i^2 - 0.5 \cdot b_i \cdot a_i}{2b_i - a_i} \tag{27}$$

According to[2,6,8] it is possible to determine the tube dimensions accurately. The tube section outside the deformation zone is calculated using equations (28) and (29).

$$A_i = 3\left[R_i^2 \rho_1 - (R_1 - s_1)^2 \rho_{(2)i}\right] - \\ -\frac{3e_i}{2}\sqrt{3}\left[R_1 \cos v_{(1)i} - (R_i - s_i)\cos v_{(2)i}\right] \tag{28}$$

$$d_{sri} = \frac{A_i}{s_i \pi} + s_i \tag{29}$$

At the neutral angle of the deformation zone, the outside tube diameter is:

$$d_{sri} = 2\sqrt{\frac{A_{i(\gamma)}}{\pi}} \tag{30}$$

The area of the section of the tube wall in the neutral position of the deformation zone is:

$$A_{1(\gamma)} = s_{i(\gamma)} \pi (d_{i(\gamma)} - s_{i(\gamma)}) \tag{31}$$

The area of the tube at the exit from the deformation zone is:

$$A_{i(k)} = 3\left(R_i^2 \arcsin\frac{a_i\sqrt{3}}{2R_i} - \frac{a_i e_i \sqrt{3}}{2}\right) \tag{32}$$

6 TUBE-WALL-STRETCHING REDUCTION

For proper stretch reducing of the tubes it is of basic importance to know the maximum allowed changes of the tube-wall thickness and diameter. The tube reduction from the initial to the end size is defined by the maximum deformation and stressing of the material at the processing temperature for every phase of the processing.[2,9,11]

The wall reduction is defined by the coefficient of plastic elongation. The maximum value of this coefficient determines the limit value of the reduction of the wall thickness. On the other hand, the maximum wall reduction thickness also depends on the maximum drawing force and on the material deformation resistance at the processing temperature. For this reason, it is necessary to determine, for every phase of stretch reducing, the maximum value of the coefficient of plastic extension to prevent the tube tearing. Theoretically, the maximum value of the coefficient of plastic extension is 1, while the practical value is in the range 0.1 to 1. The coefficient is calculated for the design of the passes for every step of the processing and the related changes to the tube diameter and the wall thickness. The calculation is performed by assuming that the deformation is uniform over the whole tube section and that the elongation is equal for all the passes.[2,6,8]

With the analysis of the coefficient of plastic elongation, it is necessary to consider the following:

a) the coefficient for the total elongation (average per pass) z_u makes it possible to determine the total elongation of the tube. From the physical point of view, z_u exists only for ideal cases, when the coefficient of plastic extension is equal for all the passes and it is equal to z_u. This cannot be achieved during practical processing, as, in the first and in the last stands of the processing line the possibility of drawing with the rolls is limited and $z_i < z_u$. For this reason, the elongation is greater in the middle caliber than z_u.
b) In theory, the initial and the end extension coefficients exist; however, the values of both are not clearly defined and as the average elongation coefficient the arithmetical value of both coefficients is calculated:

$$z_{i_{sr}} = \frac{z_{i-1} + z_i}{2} \tag{33}$$

This value is then used to calculate the decrease of wall thickness. Theoretically, the value of the coefficient of extension could be between 0.0 and 1.0.

For $z_{teor} < 0.5$ the wall thickness is increased and the diameter reduction of 3 % to 5 % is achieved. The increase of thickness of the tube wall is necessary to obtain in the following pass a homogenous decrease of tube diameter and to maintain, in a safe range, the material stressing.

For $z_{teor} = 0.5$ the wall thickness is unchanged and practice shows that it remains unchanged also for $z = 0.55$

For $z_{teor., max} = 1.0$ in parallel, the tube diameter in and the wall thickness are decreased. It cannot be achieved in practice because it leads to tearing of the rolled tube. The maximum practically used extension coefficient is of $z = 0.7$ to 0.8.

Theoretically, the coefficient is the ratio of axial stress and the deformation resistance of the material, such that:

$$z = \frac{\sigma_i}{k_f} \tag{34}$$

The analytical dependence of the stress and deformation is given by the equations:

$$\frac{\sigma_r - \sigma_{sr}}{\varepsilon_r} = \frac{\sigma_1 - \sigma_{sr}}{\varepsilon_1} = \frac{\sigma_t - \sigma_{sr}}{\varepsilon_t} \tag{35}$$

$$(\sigma_r - \sigma_{sr}):(\sigma_1 - \sigma_{sr}):(\sigma_t - \sigma_{sr}) = \varepsilon_r : \varepsilon_1 : \varepsilon_t \tag{36}$$

The average stress also depends on the type of the processed material. In equation (37) the dependence upon the deformation resistance k_f is:

$$\sigma_{sr} = \frac{1}{3} \cdot (2 \cdot \sigma_1 - k_f) = \frac{1}{3} \cdot (\sigma_r + \sigma_1 + \sigma_t) \tag{37}$$

On the other hand, the stress depends also on the relation of the wall thickness and the tube diameter:

$$\sigma_{sr} = \sigma \cdot \left(\frac{s}{d}\right)_{sr} \tag{38}$$

$$k_f = \sigma_1 - \sigma_t \tag{39}$$

$$\frac{\sigma_{r_{sr}}}{\sigma_{t_{sr}}} = \left(\frac{s}{d}\right)_{sr} = \upsilon_{sr} \tag{40}$$

The solution of equations (35) and (36) given in equation (41) is obtained by applying the equations (34), (37), (38), (39) and (41):

$$\frac{2 \cdot z \cdot (\upsilon - 1) + (1 - 2 \cdot \upsilon)}{\varepsilon_r} = \frac{z \cdot (\upsilon - 1) + (1 + \upsilon)}{\varepsilon_1} = \frac{z \cdot (\upsilon - 1) + (2 - \upsilon)}{\varepsilon_t} \tag{41}$$

Equation (41) is the basis for equation (42), which is used for the calculation of the plastic extension by stretch reducing the tubes:

$$z = \frac{\varepsilon_1 \cdot (2 - \upsilon) + \varepsilon_t (1 + \upsilon)}{(\varepsilon_1 - \varepsilon_t) \cdot (1 - \upsilon)} \tag{42}$$

The coefficient "υ" obtained from (40) cannot be used in practice, and it is corrected by considering the uniform tube deformation "T" deduced from equation (43).

$$T = \frac{\upsilon_{sr}}{1 - \upsilon_{sr}} \tag{43}$$

Applying the corrected value "T", the relation for the average coefficient of plastic extension is calculated from equation (44).

$$z_{sr} = \frac{\varepsilon_1 \cdot (2 - T) + \varepsilon_t (1 + T)}{(\varepsilon_1 - \varepsilon_t) \cdot (1 - T)} \tag{44}$$

The values for the coefficient z_{isr} obtained from equation (42) are appropriate to those obtained from equation (44). However, the calculation is simpler by applying equation (42), and this equation is recommended for use in practice. The values of "z_{isr}" calculated from the equations (42) and (44) differ only in the second decimal[2].

The coefficient "T" calculated from equation (43) is reliable for the relation $(s/d)_{sr}$ in the range from 0.27 to 0.275. If the relation differs from this range and it is not constant during the processing, the correction of the coefficient "T" becomes necessary. For this reason, an additional coefficient "k" is used that considers the effect of the diameter reduction on the thickness reduction. For the three rolls the caliber the coefficient "k" is calculated from equation (45).

$$k_i = \frac{1}{1 + 0.70\delta_i^2} \tag{45}$$

Finally, for the coefficient "T" the following equation is obtained:

$$T = \left[\frac{0.868 \cdot \upsilon_{sr} + 0.264 \cdot \upsilon_{sr}^2}{1 - \upsilon_{sr}}\right]^{\frac{1}{1 + 0.70\delta_i^2}} \tag{46}$$

From equations (46) and (44) the average value of the coefficient of extension is calculated and used for the determination of the tube-wall reduction in the i-pass.

In equation (44) the logarithmic values for the axial, tangential and radial deformations are included, which are calculated from equations (47), (48) and (49).

a) ε_{li} – lg of axial deformation from equation (47).

$$\varepsilon_{li} = \left[\frac{s_{(i-1)} \cdot d_{(i-1)} - s_{(i-1)}}{s_i \cdot (d_{(i)} - s_{(i)})}\right] \tag{47}$$

b) ε_{ti} – lg of tangential deformation from equation (38).

$$\varepsilon_{ti} = \ln \frac{d_i - s_i}{d_{(i-1)} - s_{(i-1)}} \tag{48}$$

c) ε_{ri} – lg of radial deformation from equation (49).

$$\varepsilon_{ri} = l \frac{s_i}{s_{(i-1)}} \tag{49}$$

The diameter reduction "δ_i" per pass in equations (45 and 46) is calculated from equations (50):

$$\delta_i = \frac{d_{(i-1)} - d_i}{d_{(i-1)}} \tag{50}$$

From equation (43) the coefficient "T" is deduced for the case when:

a) v_{sr} ⇒ for thin tube wall as (51)

$$T \approx v_{sr} \tag{51}$$

b) v_{sr} ⇒ for the full section of the rolled tube according to (52)

$$T \approx 2 \cdot v_{sr} \tag{52}$$

The parameters affecting the maximum value of the coefficient of plastic extension are[2,7]:

- the material plasticity at the processing temperature considering the strain hardening in the deformation zone and the softening between the rolling passes that depends on a given tube rate on the distance between the rolling stands,
- the diameter reduction,
- the total previous deformation,
- the rolling rate,
- the uniformity of the temperature over the tube length.

7 VERIFICATION OF THE CALCULATION

The calculation was verified on an industrial stretch-reducing mill with 18 three-rolls passes. The possibility to change the number of revolutions (minimum and maximum for every pass) of the mill are shown in **Figure 7**.

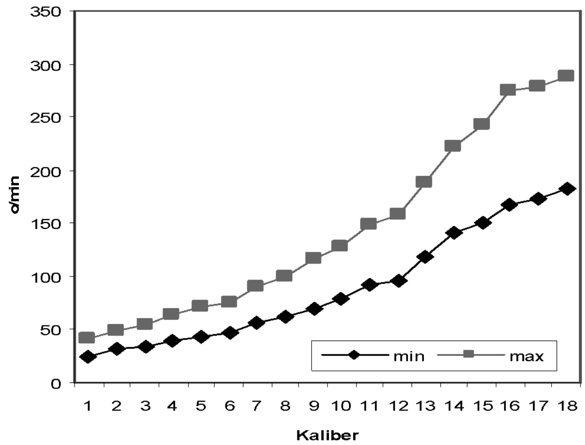

Figure 7: Maximum and minimum number of revolutions at the industrial stretch-reducing mill

Slika 7: Največje in najmanjše število vrtljajev na industrijski valjarni za raztezno reduciranje

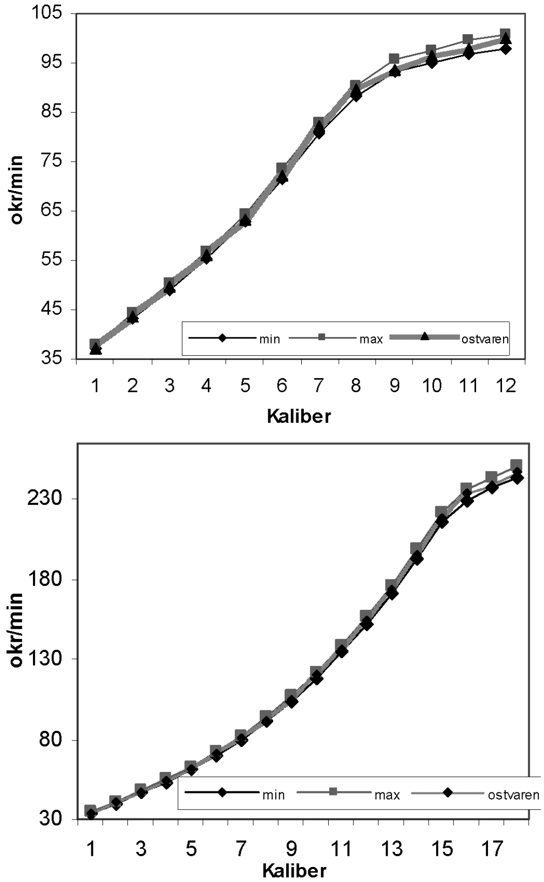

Figure 8: Number of revolutions calculated for the tubes: a) ϕ 21.3 mm × 2.65 mm and b) ϕ 48.3 mm × 3.25 mm

Slika 8: Število vrtljev, izračunanih za cevi: a) ϕ 21,3 mm × 2,65 mm in b) ϕ 48,3 mm × 3,25 mm

On the mill, the welded tubes of ϕ117.3 mm × 3.8 mm are rolled to tubes of size from ϕ 17.1 mm × 2.0 mm to ϕ 114.3 mm × 4.5 mm. The pass designing was verified for the tubes ϕ 21.3 mm × 2.65 mm and ϕ 48.3 mm × 3.25 mm. The rolling of tubes ϕ 21.3 mm × 2.65 mm is carried out in 18 passes and of the tubes ϕ 48.3 mm × 3.25 mm in 12 passes. For both tube dimensions and for each pass the minimum and maximum number of revolution was calculated, which is shown in **Figure 8**. It is clear from this figure that the calculated values were achieved and the design verified. All the produced tubes have the required mechanical and technological properties and the required dimensional accuracy, thus confirming that the pass design is also reliable for industrial production.

8 CONCLUSION

In this article the process of the design of passes is given for the hot-stretch reducing of tubes. The calculations are based on data from references and our own industrial data. The mutual dependence of the processing parameters is also considered, and the calculation of the tube rate and the reduction for every processing step is explained. Since the reduction of the tube-wall thickness is achieved with stretching, the processing rate and the reduction of the wall thickness are mutually dependent and determine the extent of the internal stresses in the processed material. The corresponding parameters are related through the coefficient of plastic extension, which was also calculated.

The processing parameters are calculated and verified for two tube dimensions in current industrial production. The agreement between the calculated and the obtained dimensions of the tubes confirms the accuracy and the reliability of the designed passes. The rolled tubes have the properties required by the standards and confirm that the relation between the reduction of the wall and the tube diameter as well as the processing rate and the extent of stresses were considered with sufficient accuracy.

i – number of passes of the stretch-reducing mill
d_0 – external tube diameter
d_n – external tube diameter in the i – pass
Δd – reduction of tube diameter
s – tube-wall thickness
s_i – tube-wall thickness in the i – pass
C – rolling constant
V_1 – tube exit rate from the rolls
A – pass surface
D – working diameter of rolls (bottom of passes)
D_w – ideal rolls diameter
D_{tr} – transport diameter of rolls
a – pass width
b – pass height
n – number of revolutions of the rolls
A – area of tube section
α – angle of contact
γ – neutral angle in the deformation zone
φ – angle change in the deformation zone
β – angle of friction
μ – friction coefficient
v – circumferential velocity of rolls
v_0 – tube rate in the deformation zone
v_γ – tube rate in the deformation zone at the neutral angle γ
v_t – tube rate at the exit of deformation zone
m_1 – coefficient dependent on rolls quality
m_2 – coefficient dependent on rolling rate
m_3 – coefficient dependent on steel microstructure
z – coefficient of plastic extension
z_i – coefficient of plastic extension in the i- pass
z_{ku} – total coefficient of plastic extension
z_{sr} – average coefficient of plastic extension
k_f – deformation resistance of the rolled material
σ_l – axial stress
σ_r – radial stress
σ_t –tangential stress
σ_{sr} – total average stress
ε_l – lg of axial deformation
ε_t – lg of tangential deformation
ε_r – lg of radial deformation
υ – coefficient of the relation of reduction of tube wall and diameter
T – coefficient of correction of the coefficient z
k – coefficient of correction of the coefficient z with respect to the diameter reduction

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