

Calculation of stresses and strain with the analytical method of pipes in high frequency longitudinal welded pipes

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Abstract-In general, the different phenomena in the production, the different technological processes, are characterized by one or more factors and indicators. These factors, with their specific nature and with the special way of influencing the phenomena or the different technological processes, give the latter a complex character in practice. During the formation and calibration of the pipes, the thickness and radius of bending of the pipes is very important. It is expected that the smaller the bending radius, the greater the stresses and deformations as a result of the large degree of deformation. To calculate the stresses and deformations, pipes of different thicknesses and diameters were obtained: $\varnothing 139,7 \times 4$ mm, $\varnothing 139,7 \times 7,72$ mm, $\varnothing 219,1 \times 5$ mm, $\varnothing 219,1 \times 8$ mm, $\varnothing 244,5 \times 8,94$ mm, $\varnothing 323,9 \times 7,10$ mm and $\varnothing 323,9 \times 10$ mm.

Keywords: bending radius, residual stresses, strain, longitudinal welded pipes, cold plastic formation.

1. Introduction

In the technology of production of welded pipes, the determining role in the achievement of the quality and the geometrical quantities is played by the cold plastic processing, ie the residual stresses and deformations during the formation and calibration of the pipes, according to this work, according to the technology of production in general, the influence of the degree of cold plastic deformation on the mechanical properties of the sheet after formation in the pipe as well as the study of stresses and strains in the cross section of steel pipes of a certain quality are analyzed. Basic purpose of the plastic formation is achieving cylindrical shape of the steel sheet that has width equal to the pipe circumference. With longitudinal welding, forming of circumference is completed. Pipe shaping is continuous process. During material forming, material itself experiences elastic and plastic deformations that cause change in the mechanical properties like strengthening. Therefore, the material stress - strain distribution in the pipe cross section is changing significantly from the initial relaxed state. The calculations were made on steel pipes quality J55 API 5CT, H40 and S235JRG2 manufactured with HF-ERW technology.

2. Preliminary processing (preparation of materials)

The process of cold plastic deformation also makes welded pipes. However, it is significant that in the production process there is a "capture" of residual stresses that increase the resistance to further plastic deformations [1].

The production of welded pipes takes place by a twisting process that takes place in the plastic area of deformation. There are two ways to twist depending on the "magnitude of the stress" and the "size of the reduced diameter of the curve", as follows: $\rho_r = \rho_n / s$

- rolling in an elastic plastic area $5 < \rho_r < 200$ and
- pure plastic area $\rho_r < 5$

Accordingly, the production of seam tubes takes place with (+) coiling in the elastic-plastic area [2].

3.1. Limiting values of the winding radius

One of the most important factors influencing the quality of the products is the rolling- radius bending radius (r), which must be within certain limits. The limit values of the rolling radius define the area in which the rolling operation can be performed. That's it:

- Minimum rolling radius r_{\min}
- The maximum rolling radius r_{\max}

As the winding radius decreases, the single deformations, ie the stresses of the fibers in the material, increase. So if it is:

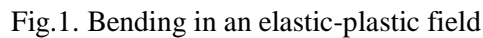
The minimum radius (r_{\min}) of the stresses from the deformation of the outer fibers in the material of the treated piece, which are tensile, so that the tensile strength of the material is not reached, and

The maximum radius (r_{\max}) is determined by the conditions that at a given radius, the stresses in the outer fibers of the material of the processed piece must have a value above the tensile strength since it is a condition for the occurrence of plastic deformations, or an initial condition for rolling of the material [3]. The deformation of a fiber distant by the amount (z) from the neutral axis is:

$$\varepsilon = \frac{z}{\rho_n} = \frac{\rho - \rho_n}{\rho_n}$$

The greatest tensile deformation will occur in the outer fibers for:

$$\rho_n = r + \frac{s}{2}$$


$$\varepsilon_m = \frac{1}{2\frac{r_m}{s} + 1}$$
$$r_{\min} = \frac{s}{2} \left(\frac{1}{\epsilon_m} - 1 \right)$$
$$\epsilon = \frac{s}{2r} \text{ or } r = \frac{s}{2 \cdot \epsilon} = \frac{s \cdot E}{2 \cdot \sigma}$$
$$r_{\max} = \frac{s \cdot E}{2 \cdot \sigma_v}$$
$$\mathbf{r}_{\min} < \mathbf{r} < \mathbf{r}_{\max}$$

If condition (6) is not met, then two boundary conditions can be observed which:

For ($r < r_{\min} = c \cdot s$) cracks appear and the outer fibers of the coiled piece break and break, and

For ($r > r_{\max} = \frac{s \cdot E}{2\sigma_v}$) there are no permanent plastic deformations in the rolled piece, which means that after removing from the tool the piece will be straightened again.

3.2. Springback in sheet metal forming – pipe forming

Each plastic deformation is followed by an elastic deformation. As a consequence of this phenomenon, the dimensions of the plastic deformed piece change after unloading.

The permanent deformation (ε_t) can be represented as the difference between the plastic (ε_{pl}) and the elastic deformation (ε_{el}):

$$\varepsilon_t = \varepsilon_{pl} - \varepsilon_{el}$$

While the rolled piece is under load (in a tool), as a consequence of the plastic deformation (ε_{pl}) the following characteristic dimensions are obtained.

- Coil-bending radius r_1 ,
- profile angle α_1 ,
- bending angle $\varphi_1 = 180 - \alpha_1$

When the piece is removed from the tool, it is unloaded and with it a partially elastic straightening, due to the elastic deformation (ε_{el}). The permanently deformed piece (ε_t) has the following dimensions:

- bending radius $r_2 = r_1 + \Delta r$
- bending angle $\alpha_2 = \alpha_1 + \Delta \alpha$
- bending angle $\varphi_2 = 180 - \alpha_2$

The bending radius increased by (Δr ($r_2 > r_1$)), the profile angle also increased by ($\Delta \alpha$ ($\alpha_2 > \alpha_1$)), while the bending angle decreased ($\varphi_2 < \varphi_1$). If the dimensions i are required by the constructive drawing of the bent piece, then the printer is made with a radius, and at an angle, which are determined by the pattern:

$$r_i = r_1 = r_2 - \Delta r$$

$$\alpha_i = \alpha_1 = \alpha_2 - \Delta \alpha$$

The size of the elastic springback depends on the ratio (r / s). For this reason, the problem of elastic straightening with the winding over large radius, ie with the winding in the elastic-plastic field, is first considered.

Under the action of the external bending moment, the support will bend under the corresponding radius of the neutral line. After unloading, the support is straightened elastically, its curvature becomes smaller, and the radius of curvature increases to the value $\rho_2 > \rho_1$.

The stress moment of the elastically deformed layer (height- $2z_0$) acts against the external moment and tends to straighten the girder. After unloading, the plastically deformed layer (height- $2z_0$) deforms elastically, under the action of the bending moment of the elastically deformed layer. This means that those fibers that have shortened will now elongate.

Further theoretical and experimental investigations indicate that the magnitude of the springback decreases with decreasing r/s ratio, ie increasing the curvature of the bent piece.

The elastic springback factor is calculated according to the formula:

$$K = \frac{r_1 + \frac{s}{2}}{r_2 + \frac{s}{2}} = \frac{\varphi_2}{\varphi_1}$$

Factor K depends on the type of material and the ratio r/s . The diagram in Fig. 1, according to the

examination of G. Sachs, allows finding this factor for various materials in the interval $1 \leq \frac{r_2}{s} \leq 100$.

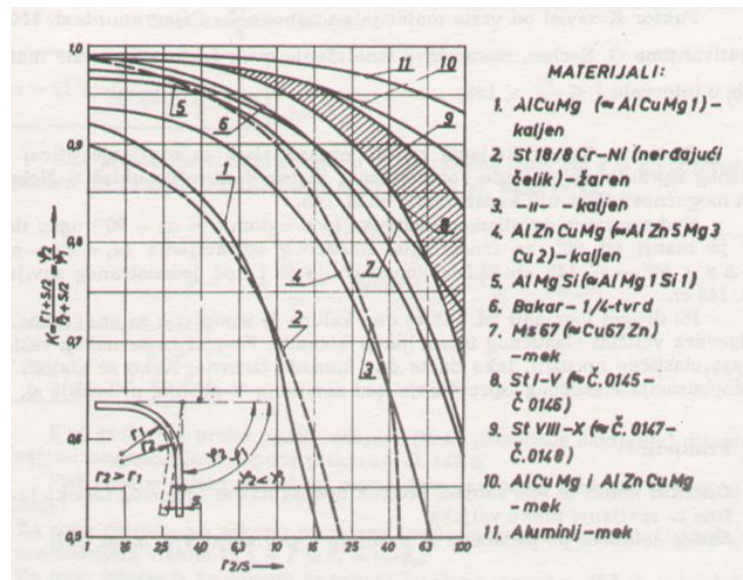


Fig.2. The coefficient of springback K is found by the ratio (G. Sachs)[3]

4. Analytical method for calculation of residual stresses and strains based on the elastic opening (springback) after the formation of the pipes

When forming tubes with twisting, in that case the material is in the elastic-plastic field, this case falls into the problem of linear stress state and the condition should be fulfilled:

Tab.1. Mechanical properties and geometric dimensions of the metal strip

Steel quality	Width of the tape [mm]	Tape thickness [mm]	Clamping limit [daN/mm ²]	Tear strength [daN/mm ²]	Modulus of elasticity [daN/mm ²]	Pipe profile [mm]
S235JRG2	697,12	8	$\sigma_v^{\min} = 23.5$; $\sigma_v^{\max} = 47$	$\sigma_m^{\min} = 34$	E=20000	Ø219,1
S235JRG2	697,12	5	$\sigma_v^{\min} = 23.5$; $\sigma_v^{\max} = 47$	$\sigma_m^{\min} = 34$	E=20000	Ø219,1
S235JRG2	445,98	4	$\sigma_v^{\min} = 23.5$; $\sigma_v^{\max} = 47$	$\sigma_m^{\min} = 34$	E=20000	Ø139,7
S235JRG2	1057,06	7.10	$\sigma_v^{\min} = 23.5$; $\sigma_v^{\max} = 47$	$\sigma_m^{\min} = 34$	E=20000	Ø323,9
S235JRG2	1057,06	10	$\sigma_v^{\min} = 23.5$; $\sigma_v^{\max} = 47$	$\sigma_m^{\min} = 34$	E=20000	Ø323,9

4.1 Forming stan - Cage Roller

- Horizontal duo flats with open calibers: 2(F_1 , F_2)
- Horizontal duo flats with closed calibers: 3(F_3 , F_4 , F_5)

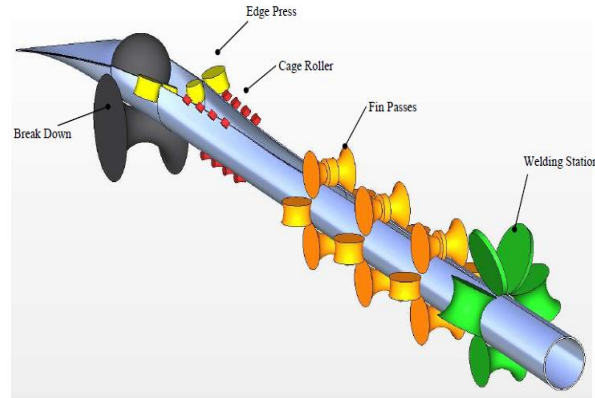


Fig.3. Schematic representation of the formation of the tape in the pipe (Forming Stand) - on HF-ERW line [4]

4.1.1 Calculation of stresses and deformations for pipe diameter Ø219,1×8 mm

1. Break Down (F_1, F_2)

$$\rho_n = \sqrt{R \cdot r} = \sqrt{661 \cdot 653} = 656.98 \text{ mm} ; \quad \rho_n = r + \frac{s}{2} = 653 + 4 = 657 \text{ mm}$$

Reduced radius of bending:

$$\rho_r = \frac{\rho_n}{s} = \frac{657}{8} = 82.125 \text{ [mm]}$$

$$5 \leq \rho_r \leq 200 ; 5 \leq 82.125 \leq 200$$

$$\varepsilon_{1,2} = 2 \cdot \left(\frac{\rho - \rho_n}{\rho_n} \right) = 2 \cdot \left(\frac{661 - 657}{657} \right) = 0.0121764 \text{ [}\mu\varepsilon\text{]}$$

2. Degree of deformation in the rolling mill for formation – Fin Passes (F_3, F_4, F_5)

$$\varepsilon_{3,4,5} = 6 \cdot \left(\frac{\rho' - \rho'_n}{\rho'_n} \right) = 6 \cdot \left(\frac{113.53 - 109.53}{109.53} \right) = 0.219579 \text{ [}\mu\varepsilon\text{]}$$

3. The total deformation is:

$$\varepsilon_u = \varepsilon_{1,2} + \varepsilon_{3,4,5} = 0.0121764 + 0.219579 = 0.2317554 \text{ [}\mu\varepsilon\text{]}$$

$$\varepsilon_{1,2}^{\max} = \frac{\varepsilon_{1,2}}{\varepsilon_u} = \frac{0.0121764}{0.2317554} \cdot 100 = 5.25398 \text{ [%]}$$

$$\varepsilon_{3,4,5}^{\max} = \frac{\varepsilon_{3,4,5}}{\varepsilon_u} = \frac{0.219579}{0.2317554} \cdot 100 = 94.74601 \text{ [%]}$$

$$\varepsilon_u = \varepsilon_{1,2} + \varepsilon_{3,4,5} = 5.25398\% + 94.74601\% = 99.9999 \cong 100[\%]$$

4. Maximum and minimum bending radius

$$\text{Condition: } \frac{D}{s} < \frac{E}{\sigma_v} + 1; \quad \frac{219.1}{8} < \frac{20000}{23.5} + 1 \Rightarrow 27.38 < 852$$

If the above condition would not be fulfilled, then after the exit of the sheet metal from the roller comes its complete elastic springback, due to the fact that in that case the deformations are in the elastic field[5]

$$r_{\min} < r < r_{\max}; \quad 16 < 653 < 3404.25$$

$$r_{\min} = c \cdot s = 2 \cdot 8 = 16[\text{mm}]; \quad r_{\max} = \frac{s \cdot E}{2 \cdot \sigma_v} = \frac{8 \cdot 20000}{2 \cdot 23.5} = 3404.25 [\text{mm}]; \quad r = 653[\text{mm}]$$

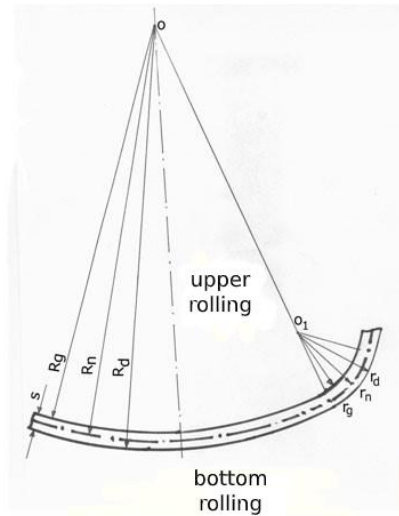


Fig.4. Schematic representation of the formation of the bending pipe in the cage for the formation of the pipe

5. Before elastic opening

The inner angle of the profile before the elastic opening:

$$\alpha_1 = \frac{b}{r} = \frac{697.12}{653} = 1.0675 [\text{rad}] \cdot 57.296^\circ = 61.16348^\circ; \quad \text{rad} = 57.296^\circ$$

The outer angle of the profile before the elastic opening

$$\varphi_1 = \pi - \alpha_1 = 3.141 - 1.0675 = 2.0735 [\text{rad}] = 118.803^\circ$$

The coefficient of elastic opening (springback) K is found by the ratio $r_2/s = 687.578 / 8 = 86$ and from the diagram. For steel quality S235JRG2 is K = 0.95

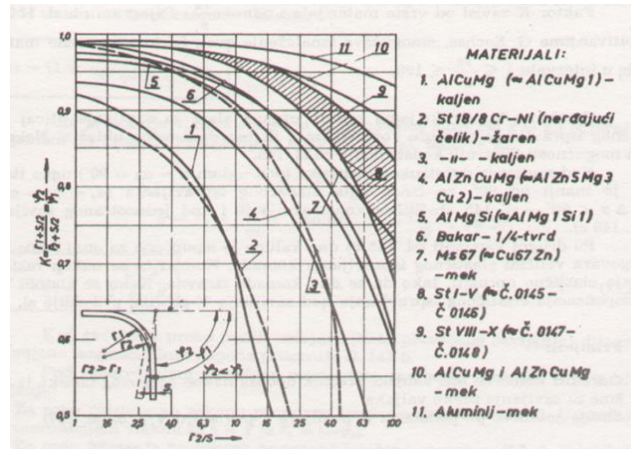


Fig.5. The coefficient of elastic opening (springback) K is found by the ratio r_2/s (G. Sachs)

6. After elastic opening

The outer angle of the profile after the elastic opening:

$$\varphi_2 = \varphi_1 \cdot K = 2.0735 \cdot 0.95 = 1.969825[\text{rad}] \cdot 57.306 = 112.863^\circ$$

$$\text{condition: } \varphi_2 < \varphi_1; \quad 112.863 < 118.803$$

$$\Delta\varphi = \varphi_1 - \varphi_2 = 118.803 - 112.863 = 5.94[^\circ]$$

$$\text{opening: } x = \frac{219.1 \cdot 5.94^\circ}{360^\circ} = 3.60[\text{mm}]$$

The inner angle of the profile after the elastic opening:

$$\alpha_2 = \pi - \varphi_2 = 180 - 112.863 = 67.137^\circ$$

$$\Delta\alpha = \alpha_2 - \alpha_1 = 67.137 - 61.16348 = 5.97352^\circ; \quad \frac{5.97352}{67.137} \cdot 100\% = 8.8975\%;$$

$$\Delta\alpha = 5.97352^\circ$$

$$\alpha_t = \alpha_2 - \Delta\alpha = 67.137 - 5.97352 = 61.163^\circ; \quad \frac{61.163}{67.137} \cdot 100\% = 91.10\%$$

$$\alpha_t = 61.163^\circ; \quad \alpha_t + \Delta\alpha = 8.8975\% + 91.10\% \cong 100\%$$

According to the elastic opening: $\Delta\varphi \cong \Delta\alpha$; $5.946^\circ \cong 5.973^\circ$

$$7. \text{ Total deformation: } \varepsilon_u = 0.2317554$$

$$8. \text{ Plastic deformation is: } \alpha_t = 61.163^\circ \Rightarrow 91.10[\%]$$

$$\varepsilon_{pl} = \varepsilon_u \cdot \alpha_t = 0.2317554 \cdot 91.10\% = 21.112 = \frac{21.112\%}{100\%} = 0.21112$$

9. Elastic deformation is: $\Delta_\alpha = 5.97352^\circ \Rightarrow 8.8975[\%]$

$$\varepsilon_{el} = \varepsilon_u \cdot \Delta_\alpha = 0.2317554 \cdot 8.8975[\%] = 2.0620436 = \frac{2.0620436[\%]}{100[\%]} = 0.0206204$$

$$\varepsilon_{uk} = \varepsilon_{el} + \varepsilon_{pl} = 0.0206204 + 0.21112 = 0.2317404$$

10. Permanent deformation:

$$\varepsilon_t = \varepsilon_{pl} - \varepsilon_{el} = 0.21112 - 0.0206204 = 0.1904996$$

11. Radius of the profile after the elastic opening:

$$K = \frac{r_1 + \frac{s}{2}}{r_2 + \frac{s}{2}} \Rightarrow r_2 = \frac{r_1 + \frac{s}{2}}{K} - \frac{s}{2} = \frac{653 + \frac{8}{2}}{0.95} - \frac{8}{2} = 687.578 \text{ [mm]}$$

$$\Delta r = r_2 - r_1 = 687.578 - 653 = 34.578 \text{ [mm]}$$

12. Tool tendon:

$$t = 2r \sin \frac{\alpha_1}{2} = 2 \cdot 653 \cdot \sin \frac{61.163}{2} = 653[\text{mm}]$$

$$p = (8-10) \text{ daN/mm}^2 = 9 \text{ daN/mm}^2 \text{ specific resistance}$$

13. Contact surface between tool and tape:

$$A = t \cdot 2 \cdot f = 653 \cdot 2 \cdot 0.8 = 1044.8[\text{mm}^2]$$

14. Deformation force:

$$F = p \cdot A = 9 \cdot 1044.8 = 9403.2[\text{daN}]$$

15. Moment of bending in the elastic-plastic field:

$$M = \sigma_v \cdot \frac{b \cdot s^2}{4} = 23.5 \cdot \frac{697.12 \cdot 8^2}{4} = 262117.12[\text{daNmm}]$$

16. Cross-sectional area:

$$A = \frac{1}{100} \cdot \frac{(D^2 - d^2)}{4} \cdot \pi = \frac{1}{100} \cdot \frac{(219.1^2 - 211.1^2)}{4} \cdot 3.141 \cdot 2 = 54[\text{cm}^2]$$

17. Moment of inertia:

$$J_x = J_y = \frac{1}{10000} \cdot \frac{(D^4 - d^4)}{64} \cdot \pi = \frac{1}{10000} \cdot \frac{2304461783 - 1985879685}{64} \cdot 3.141 \cdot 2 = 3126[\text{cm}^4]$$

18. Axial resistance moment:

$$W_x = W_y = \frac{1}{1000} \cdot \frac{(D^4 - d^4)}{32D} \cdot \pi = 0.001 \cdot \frac{318582097.5}{7011.2} \cdot 3.141 \cdot 2 = 285.44[\text{cm}^3]$$

19. Inertia half-radius

$$i_x = i_y = \sqrt{\frac{J_x = J_y}{A}} = \sqrt{\frac{3126}{54}} = 7.60[\text{cm}]$$

20. Polar moment of inertia:

$$J_0 = 2J_{xy} = 2 \cdot 3126 = 6252[\text{cm}^4]$$

21. Polar resistance moment (torsional constant):

$$W_0 = 2W_{xy} = 2 \cdot 285.44 = 570.88[\text{cm}^3]$$

22. Plasticity module:

$$S = \frac{(D^3 - d^3)}{6000} = \frac{10517853.87 - 9407293.63}{6000} = 185.1[\text{cm}^3]$$

23. Elastic and plastic stresses:

$$\sigma_{el} = S \cdot \varepsilon_{el} = 185.1 \cdot 0.0206204 = 3.8168[\text{daN/mm}^2] = 38.168 [\text{MPa}]$$

$$\sigma_{pl} = S \cdot \varepsilon_{pl} = 185.1 \cdot 0.21112 = 39.078[\text{daN/mm}^2] = 390.783 [\text{MPa}]$$

24. The opening: $x = 3.60 [\text{mm}]$

$$25. \text{Residual stresses: } \sigma = E \cdot t \left[\frac{1}{D_0} - \frac{1}{\left(\frac{x}{\pi} + D_0 \right)} \right] = 2 \cdot 10^5 \cdot 8 \left[\frac{1}{219.1} - \frac{1}{\left(\frac{3.60}{3.141} + 219.1 \right)} \right] = 38 [\text{MPa}]$$

26. Residual deformation: $\varepsilon = \frac{\sigma}{E} = \frac{38}{2 \cdot 10^5} = 0.00019 \cdot 10^6 = 190 [\mu\varepsilon]$

Tab.2. Analytical-theoretical results on residual stresses and deformations calculated on the basis of the elastic opening (springback) of the pipes

Steel quality	J55	H 40	S 235 JRG2, RST 37-2				
Tube profile	$\emptyset 139.7 \times 7.72$ mm	$\emptyset 244.5 \times 8.94$ mm	$\emptyset 139.7 \times 4$ mm	$\emptyset 219.1 \times 5$ mm	$\emptyset 219.1 \times 8$ mm	$\emptyset 323.9 \times 7.1$ Mm	$\emptyset 323.9 \times 10$ mm
$\varepsilon_{1,2}$	0.01867816	0.01224322	0.00953516	0.0075930	0.0121764	0.00731193	0.00514239
$\varepsilon_{3,4,5}$	0.33790487	0.21944035	0.17045454	0.135098	0.219579	0.12963301	0.18420729
ε_u	0.35658303	0.23168357	0.1799897	0.146916	0.2317554	0.13694494	0.18934968
ε_{el}	0.06859318	0.049598818	0.0485216	0.0289877	0.0206204	0.03112073	0.04058331
ε_{pl}	0.28972371	0.182089385	0.13146	0.1137023	0.21112	0.1058242	0.14876636
ε_t	0.22113053	0.132490567	0.0829384	0.0847146	0.1904996	0.07470347	0.10818304
ρ_r	54	82	104.875	131.7	82.125	137	97.31
$5 \leq \rho_r \leq 200$	$5 \leq 54 \leq 200$	$5 \leq 82 \leq 200$	$5 \leq 104.875 \leq 200$	$5 \leq 131.7 \leq 200$	$5 \leq 82.125 \leq 200$	$5 \leq 137 \leq 200$	$5 \leq 97.31 \leq 200$
$\frac{D}{s} < \frac{E}{\sigma_v} + 1$	$18 < 537.5$	$27.34 < 738$	$34.925 < 852$	$43.82 < 852$	$27.3 < 852$	$45.61 < 852$	$32.39 < 852$
$r_{min} < r < r_{max}$	$15.44 < 413.78 < 1689.14$	$17.88 < 733.14 < 2199.4$	$8 < 417.5 < 1702.12$	$10 < 656 < 2127.66$	$16 < 653 < 3404.25$	$14.2 < 970.2 < 3021.2$	$20 < 967.31 < 4574$
K	0.88	0.86	0.81	0.87	0.95	0.85	0.86
$\Delta\varphi [^\circ]$	14	16.66	22.567	15.488	5.94	17.77	16.649
χ [mm]	5.43	11.31	8.75	9.426	3.60	16	14.979
σ_{res} [MPa]	138	107.70	111.93	61.668	38	67.95	89.70
$\varepsilon_{res} [\mu\varepsilon]$	677.45	530.56	559.654	308.34	190	339.758	448.58

5. Conclusions

The following conclusions are reached during the analytical-theoretical calculations:

- One of the main factors influencing the quality of the pipes is the bending radius of twisting which is necessary to move within certain limits: $r_{\min} < r < r_{\max}$
- During the formation of the bending pipe, the material is in the elastic-plastic area, this case falls into the problem of the linear state of stress and the condition must be met: $5 \leq \rho_r \leq 200$
- If the condition $D / s < E / \sigma_v + 1$ is not fulfilled, after the exit of the sheet metal from the rollers, its complete elastic opening (springback) occurs, since in that case the deformations are found to be elastic area.
- Theoretical and experimental researches indicate that the magnitude of the decreases with t elastic opening (springback) he decrease of the ratio (r / s) , ie with the increase of the bending of the coil.
- Based on the proposed conditions and based on the analytical results given in Table 2, the formation and calibration of tubes leads to the conclusion that the conditions are met.
- During the formation and calibration of the pipes, the material or sheet metal is in the elasto-plastic area, it is normally expected that after the formation of the formed pipe from the rolling mill without welding to occur elastic opening (springback) up to a certain percentage, which depends on: the quality of the sheet material, the radius of rolling, the thickness of the sheet and the speed of formation with rolling during the technological process.
- In the technological process of production of tubes with length, there are two phases of deformation with rolling: Break Down forming cages and Fin Passes forming cages. In the theoretical-analytical calculation based on the results in Table 2, the degree of deformation is higher in the forming station Fin Passes and as a consequence the radius of coil in forming and calibrating tubes is smaller compared to the forming station Break Down.
- Comparing the obtained values for the degree of deformation for the profiles of tubes as in the above table, it is noted that with the pipes with smaller diameter the values of the degree of deformation increase as a result that the radius of bending is smaller in relation to the tubes are generally transverse. As a consequence of this, the calculated values of the residual stresses and strains increased with the profiles with smaller diameter in relation to the profiles with larger diameter, and the material of the sheet metal also strengthened.

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