# Detection of optimal parameters of steel sheet billet forming process while bending on PBT 25 three-roller machine

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Technique for detection of optimal parameters during tube billet forming process was designed. These parameters are mentioned: bending roller displacement ($\Delta h$) and distance between centers of back-up rolls ($L$). The objective was to detect such values of these parameters which ensure minimum value of bending moment while tube billet forming with specified inner radius using PBT 25 machine. Using of the developed technique is shown by the example of detecting $\Delta h$ (bending roller displacement) and $L$ (distance between centers of bearing rollers) by the criterion of minimum bending moment while forming of steel sheet into tube billet with 191.42 mm inner diameter. Technological and design restrictions, which were applied during detection of desirable parameters, including maximum displacement at preset values of diameters of bending and back-up rolls, are presented. Taking into account these restrictions, $L$ was varied within the range 195–250 mm and then $\Delta h$ were calculated at the preset inner radius of the tube billet. Range of possible combinations of $\Delta h$ and $L$, which provide obtaining of preset tube billet radius, was calculated considering maximal allowable bending roller displacement. Optimal values for the range of allowable values of $\Delta h$ and $L$ in concordance with the criterion of minimum bending moment were detected. Indirect estimation of the optimal values of $\Delta h$ and $L$ calculation results was done by checking the hydraulic pressure of PBT 25 bending machine. Regression equation was obtained on the basis of complete factorial experiment as a result of this indirect estimation. This regression equation links hydraulic pressure with $\Delta h$ and $L$ forming process parameters.
***Key words***: three-roller bending machine, optimal parameters of forming process, billet radius, bending roller, back-up rolls, bending roller displacement, distance between back-up rolls, bending moment.
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## Introduction

Development of resource-saving technologies in metal processing is connected with determination of the optimal technological parameters [1–3], including those based on the criterion of minimal power characteristics. Such power parameters are usually evaluated on the base of calculation of rolling force and torque in rolling [4] and on the base of calculation of force and bending moment in the processes of bending and metal forming [5, 6]. The principle of minimal plastic deformation capacity is widely used in continuum mechanics [7]. This principle allows to determine, for example, tool parameters, conditions of defects forming during plastic deformation and technological parameters, providing minimal power consumption, in the process of bending for the preset curvature radius of a billet. The experiments with three-roll forming for the curvature radius of formed sheet billet [8, 9] showed that the main influence is provided by displacement $\Delta h$ of bending roller and distance $L$ between the centers of back-up rolls. The empiric relationships between deformation area parameters and internal radius $R$ of a tube billet (from one side) and displacement $\Delta h$ of bending roller and distance $L$ between the centers of back-up rolls (from other side) were obtained in researches [8, 9] on the base of complete factorial experiment during sheet billet forming in the bending unit PBT 25 [10]. The regression equation for determination of the internal radius $R$ of a tube billet for $\Delta h$ and $L$ was obtained in the work [9]:

$$\mathrm{R} = -820{,}58 + 31{,}3\cdot\Delta h + 5{,}66\cdot L - 0{,}194\cdot\Delta h\cdot L \qquad (1)$$

The aim of this research is determination of combination of the following parameters: displacement $\Delta h$ of bending roller and distance $L$ between the centers of back-up rolls in the process of sheet billet bending for the preset internal radius $R$, which provide minimal bending moment.

## Technique for determination of the optimal forming technological parameters

The radius equal to 191.42 mm was chosen as preset internal radius $R$ of a tube billet; it can be obtained e.g. for $\Delta h = 16$ mm and $L = 200$ mm, according to the experimental data and calculation [9]. Let's examine, which other $\Delta h$ and $L$ combinations are available for forming a tube billet with the same internal radius 191.42 mm. The restriction connected with maximal displacement of a forming roller should be taken into account. This condition is used for the following diameters of the forming roller and back-up roll of the PBT 25 unit: $D_{bend}$ = 275 mm, $D_{bckp}$ = 195 mm. The scheme of their location is shown in the **Fig. 1**.

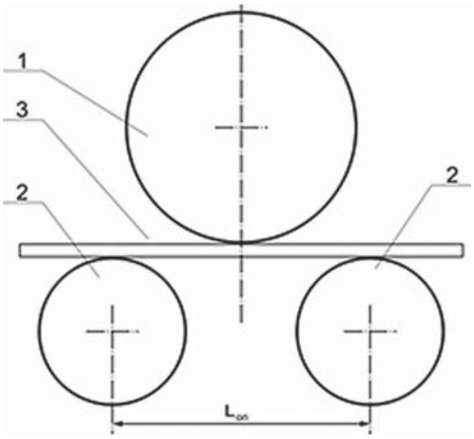


**Fig 1. Scheme of location of the forming roller and back-up rolls in the PBT 25 unit:** *1* – bending roller ($D_{bend}$ = 275 mm); *2* – back-up rolls ($D_{bckp}$ = 195 mm); *3* – sheet billet

The maximal value of bending roller displacement can be determined via the formula:

$$h_{max} = \frac{D_{bend} + D_{bckp}}{2} + S - \sqrt{\left(\frac{D_{bend} + D_{bckp}}{2} + S\right)^2 - \left(\frac{L}{2}\right)^2}, \quad (2)$$

where $D_{bend}$ – bending roller diameter, mm;
$D_{bckp}$ – back-up roll diameter, mm;
$S$ – thickness of sheet billet, mm;
$L$ – distance between the centers of back-up rolls, mm.

Taking into account that the equation (1) was obtained in the process of steel 20 sheet forming with thickness 6 mm and width 40 mm, the $S$ value was preset as 6 mm. When getting the equation (1), the range of distance $L$ variation was 200–260 mm and displacement $\Delta h$ was 16–22 mm [9]. Minimal distance between the centers of back-up rolls was 195 mm, i.e. it corresponds to the diameter of back-up roll, while maximal distance is determined by the technical characteristics of the PBT 25 unit and is equal to 265 mm [10]. As soon as the limit of extrapolation should not exceed 1/3 of retrospective [11], and taking into consideration constructive and technological restrictions, the range of $\Delta h$ displacement variation is within 12 – 39.67 mm, while $L$ varies from 195 to 265 mm. Distance $L$ between the centers of back-up rolls was taken equal to 200, 230 and 260 mm, as in the previous experiments and calculations [8, 9]. For these distances, the maximal allowable $\Delta h$ displacements were 21.72, 29.19 and 38.05 respectively. Based on these values, the field of possible $\Delta h$ and $L$ combinations, which provide obtaining of the preset radius, was calculated (**Table 1**).

$$M = L_b\left[\frac{3}{32}E\frac{S_s^2}{\rho} + \frac{\sigma_T}{\sqrt{3}}\left(1 - \frac{\Pi}{E}\right)\left(S^2 - S_s^2\right) + \frac{\Pi}{9\rho}\left(S^2 - S_s^2\right)\right], \quad (3)$$

The bending moment M of steel strip was determined via the following relationship [12]

where $S_s = \frac{\sigma_T}{E}\rho$, $L_b$ – length of a forming billet, mm;

$S$ – billet thickness, mm; $E$ – Young's modulus; $\sigma_T$ – yield strength, MPa; $\rho$ – radius of bending sheet billet in the examined cross section (curvature radius), mm; $\Pi$ – strengthening modulus.

To provide calculation of a bending moment as a curvature parameter, according to the below-presented scheme (**Fig. 2**) [8], the radius $R_{cir}$, which is proportional to ρ and is connected with $\Delta h$ and $L$, was accepted. This radius is a leg, located on the OC line (where O is a center of a bending roller) and having projection on the axis OO1, equal to $R_{cir} - \Delta h$. At the same time $R_{cir}$ should be larger than a bending roller radius. The possible option of location of $R_{cir}$ and its projection OF are displayed in the Fig. 2.

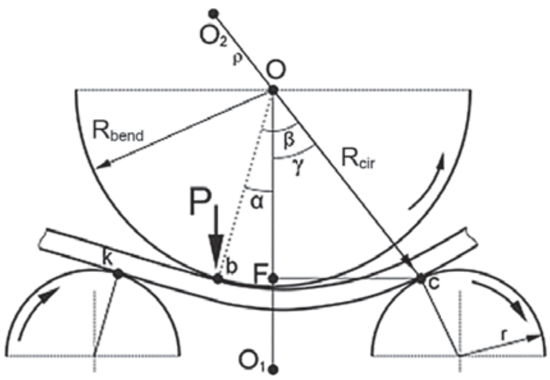


**Fig. 2. The scheme of non-symmetric deformation area during rotation of rolls and roller**

According to this scheme, $R_{cir}$ was determined via the equation (4):

$$R_{cir} = \Delta h / (1 - \cos\gamma) \quad (4)$$

The angle γ is equal to difference of the angles β and α, which are calculated according to the regression equations [8]:

$$\beta = 231.17 - 7.1\Delta h - 0.984L + 0.04\Delta h \cdot L; \quad (5)$$
$$\alpha = 23.5 + 2\Delta h - 0.06L - 0.007\Delta h \cdot L. \quad (6)$$

Table 1. **Combinations of $\Delta h$ and $L$ values for obtaining of tube billet with $R$ = 191.42 mm**

| No. of combination | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $L$, mm | 195 | 197.27 | 200 | 205 | 210 | 215 | 220 | 225 | 230 | 235 | 240 | 245 | 250 |
| $\Delta h$, mm | 14.04 | 15.00 | 16.00 | 17.51 | 18.70 | 19.68 | 20.46 | 21.17 | 21.76 | 22.26 | 22.69 | 23.09 | 23.43 |

| Table 2. **$R_{cir}$ values for $\Delta h$ and $L$ combinations during manufacture of tube billet with R = 191.42 mm** | | | | | | | |
|---|---|---|---|---|---|---|---|
| No. of combination | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| $L$, mm | 200 | 205 | 210 | 215 | 220 | 225 | 230 |
| $\Delta h$, mm | 16.00 | 17.51 | 18.70 | 19.68 | 20.46 | 21.17 | 21.76 |
| $R_{cir}$, mm | 139.91 | 153.68 | 159.43 | 159.23 | 155.13 | 148.26 | 140.12 |

Then the equation for the angle γ looks like

$$\gamma = 207.67 - 9.1\Delta h - 0.924L + 0.047\ \Delta h \cdot L \qquad (7)$$

The radius $R_{cir}$ and the angle γ were calculated based on the values of $\Delta h$ and $L$ (see the Table 1). Taking into account, that $R_{cir}$ should exceed the radius of a bending roller (i.e. > 137.5 mm), the results of $R_{cir}$ calculations for the combinations 1–2 and 10–13 were rejected. The final results of $R_{cir}$ values are presented in the **Table 2**.

Based on the data of the Table 2, the graph of $R_{cir}$ variation depending on – and $L$ was built (**Fig. 3**). It is seen that maximal value of $R_{cir}$ corresponds to the values of $\Delta h$ and $L$ combination No. 5 (see the Table 2).

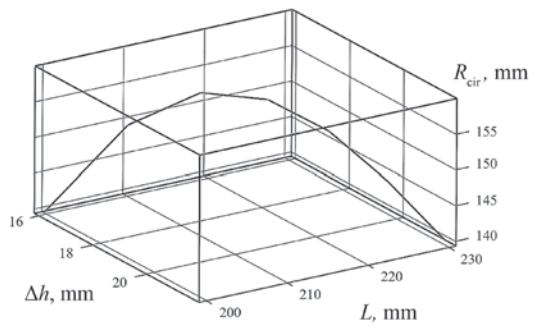


**Fig. 3. The graph of $R_{cir}$ variation depending on $\Delta h$ and $L$**

Calculation of bending moments was carried out for the following strip and strip material parameters: $b = 0.04$ m; $h = 0.006$ m; $\sigma_{0.2} = 310$ MPa; E = 200,000 MPa; П = 10,000 MPa [5]. The results of calculation of bending moments $M$ are presented in the **Table 3**.

Based on the data of the Table 3, the graph of bending moment variation depending on $\Delta h$ and $L$ was built (**Fig. 4**).

When looking for optimal parameters, various optimization methods and algorithms are used, e.g. iteration method, Gauss-Seidel method etc. [13–15]. Use of the concrete method and algorithm depend on selection of a goal function parameters and on technique of choosing of calculated points [15]. The passive algorithm, characterized by simultaneous selection of all points (see Table 3) until beginning of calculation, as well as the scanning method with varied pitch for search of optimal parameters $\Delta h$ and $L$, were used during looking for the minimal value of bending moment. This method includes calculation of a goal function for all argument values (see Table 3), at first with large pitch and then with small pitch (within the range with minimal value of a goal function) [15].

It can be seen from the table and graph that minimal value of bending moment $M$ is located within the range space $\Delta h = 18.7$ mm; $L = 210$ mm (combination No. 5) and $\Delta h = 19.68$ mm; $L = 215$ mm (combination No. 6). To conduct

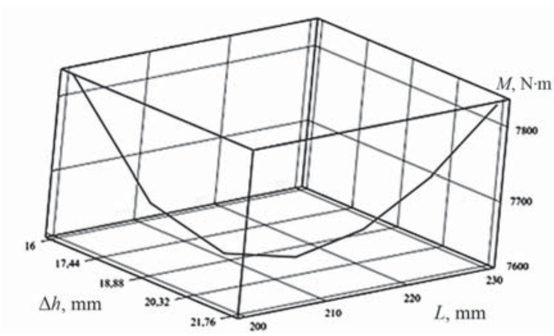


**Fig. 4. The graph of bending moment M variation depending on $\Delta h$ and $L$**

more exact determination of the values $\Delta h$ and $L$, which provide the minimal value of $M$ for the preset tube billet radius $R = 191.42$ mm, we decreased pitch by $L$ from 5 to 1 mm and calculated the corresponding values $\Delta h$ for $L$ within the range from 210 to 215 mm. Then the values of $R_{cir}$ and $M$ were again determined for obtained combinations of $\Delta h$ and $L$. The results are presented in the **Table 4**.

It was established on the base of the results that tube billet with internal radius $R = 191.42$ mm can be obtained at minimal bending moment for $\Delta h = 19.12$ mm; $L = 212$ mm (combination No. 3 in the Table 4).

| Table 3. **Values of bending moments for different $\Delta h$ and $L$ combinations** | | | | |
|---|---|---|---|---|
| No. of combination | $\Delta h$, mm | $L$, mm | $R_{cir}$, mm | $M$, N·m |
| 3 | 16 | 200 | 139.91 | 7829.7 |
| 4 | 17.51 | 205 | 153.68 | 7674.7 |
| 5 | 18.7 | 210 | 159.43 | 7617.7 |
| 6 | 19.68 | 215 | 159.23 | 7619.6 |
| 7 | 20.46 | 220 | 155.13 | 7659.9 |
| 8 | 21.17 | 225 | 148.26 | 7732.3 |
| 9 | 21.76 | 230 | 140.12 | 7827.2 |

Table 4. **The values of bending moments during forming of a tube billet from $R$ = 191.42 mm for different $\Delta h$ and $L$ combinations within the range of $L$ variation 210–215 mm**

| $\Delta h$, mm | $L$, mm | No. of combination | $R_{cir}$, mm | $M$, N·m |
|---|---|---|---|---|
| 18.7 | 210 | 1 | 159.43 | 7617.7 |
| 18.92 | 211 | 2 | 159.80 | 7614.2 |
| 19.12 | 212 | 3 | 159.95 | 7612.8 |
| 19.32 | 213 | 4 | 159.88 | 7613.4 |
| 19.5 | 214 | 5 | 159.65 | 7615.6 |
| 19.68 | 215 | 6 | 159.23 | 7619.6 |

## Evaluation of pressure calculation results in hydraulic system of PBT 25 machine

Three-roller bending machine PBT 25 is not equipped with sensors for measuring power engineering parameters. The only measuring device which can control loads is a manometer of hydraulic system of bending roller transfer. Thereby indirect assessment of the found values $\Delta h$ = 19.12 mm and $L$ = 212 mm was conducted by pressure in hydraulic system. Previously the pressure values were used for assessment of loads in the process of forming of tube billets during complex of experimental investigations at the abovementioned machine [8, 9]. To obtain relationship between pressure $p$ (from one side) and bending roller transition $\Delta h$ and distance $L$ between the centers of back-up rolls (from other side), the full factorial experiment FFE-2 was carried out [13]. Each of the factors $\Delta h$ and $L$ were varied in two levels. Zero levels of factors correspond 19 mm for upper roll transition $\Delta h$ and 230 mm for distance $L$ between the centers of back-up rolls, the varying intervals were 3 mm and 30 mm respectively. The billets from steel 20, with 6.0 mm thickness and 40 mm width, were used for forming. The planning matrix was prepared (**Table 5**) and the following experiments were conducted: 4 experiments according to the experimental plan and 2 parallel experiments for each of the recommended techniques [13]. The values Yu1 and Yu2 correspond to the results of pressure measurements in the first and second parallel experiments, while the value $Yu_{av}$ is an average pressure value which was calculated via those two experiments.

As a result of statistical processing of experimental data, the mathematical model in the form of regression equation was obtained. As soon as the calculated Fisher criterion is equal to 0.0021, what is less than the table value 7.71 [13], the model is recognized as an adequate one. The equation looks like:

$$p = -50.46 + 4.527 \cdot \Delta h + 0.183 \cdot L - 0.015 \cdot \Delta h \cdot L. \qquad (8)$$

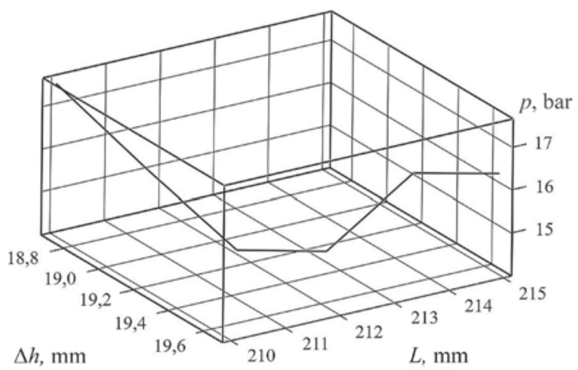


**Fig. 5. The graph of pressure $p$ variation depending on $\Delta h$ and $L$**

The pressure p was calculated on the base of the mentioned combinations, using the values of $\Delta h$ and $L$; the corresponding graph was built (**Fig. 5**).

It can be seen from this graph that the minimal pressure value in hydraulic system of the bending machine corresponds to $\Delta h$ = 19.12 mm and $L$ = 212 mm, correspond in its turn to the combination No. 3 in the Table 4. Correlation coefficient between the values of bending moment $M$ for the values of $\Delta h$ and $L$ from the Table 4, and the pressure p values for the same $\Delta h$ and $L$, made 0.8. It corresponds to high correlation relationship and confirms applicability of indirect assessment of the found optimal values of $\Delta h$ = 19.12 mm and $L$ = 212 mm for pressure in hydraulic system.

Table 5. **Planning matrix and results of pressure measurements**

| No. | $X_0$ | $X_1$ | $X_2$ | $X_1X_2$ | Pressure p, bar | | |
|---|---|---|---|---|---|---|---|
| | | $\Delta h$ | $L$ | | Yu1 | Yu2 | $Yu_{av}$ |
| 1 | 1 | 1 | 1 | 1 | 9 | 9 | 9 |
| 2 | 1 | –1 | 1 | –1 | 6 | 5.5 | 5.75 |
| 3 | 1 | 1 | –1 | –1 | 18 | 18.5 | 18.25 |
| 4 | 1 | –1 | –1 | 1 | 9 | 10 | 9.5 |

### Conclusion

The technique for determination of technological parameters of tube billet forming was developed. This technique includes transfer $\Delta h$ of a bending roller and distance $L$ between the centers of back-up rolls, providing minimal bending moment during tube billet forming with preset internal radius $R$ in three-roller bending machine. As an example, the values of $\Delta h$ and $L$ parameters, which provide optimal bending moment during forming of tube billet with internal radius 191.42 mm, were determined. These values were equal to 19.12 mm and 212 mm respectively. Indirect assessment of calculation results for the optimal values of $\Delta h$ and $L$ for minimal pressure in hydraulic system of a bending machine was carried out for the found optimal technological parameters. This technique can be used for development of power-saving conditions of forming of tube billets in the bending machine PBT 25.

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