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# The roll pressure dependence of the roll forming mill on the basic profile parameters

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**Abstract.** In the article results of the roll pressure dependence of the roll forming mill on the basic profile parameters are given. The pressure roll forming mill has different values with different conditions of curved profile production. It depends on the thickness of the original billet, the bend's radius and also it depends on other parameters: the width of the bendable elements, rolls' diameters, the hem's angles, the settings of the mill, the material properties, etc. It is difficult to solve such a complicated problem - taking into account the influence all factors with using the general theory of plasticity. The issue is complicated due to the influence of these factors, most of which are statistical in nature, different in magnitude and direction. It determines the pressure on the rolls as a stochastic variable.

## 1. Introduction

Stochastic value, in the pressure on the rolls' case, can be fully described if the law of its distribution is known, in other words, the relationship that establishes between the possible values of the variable and the corresponding probabilities. The law of distribution can be established on the basis of the statistical material analysis. The source [1–10] shows that the pressure on the rolls follows a log-normal distribution law. This makes it possible to investigate the dependence of the pressure on the rolls on the profiling parameters by the mathematical processing of experimental data methods, in particular, correlation and regression analysis, mathematical experiment planning. For this purpose, more than 500 pressure values were analyzed with profiling angles and channels from strip $t_0$= 1 ÷ 5 mm thick from carbon and low-alloy steels along single routes with bending angles ↦=0-15˚; ↦=0-30˚; α=0-45˚; α=0-60˚; α=0-75˚; α=0-90˚ with relative bending radius $r/t_0$=0.5÷8, the bend flange's width *B*=50÷350 мм, at different mill settings $s/t_0$ (where *r* – the bending radius, mm; *s* – the gap between the rolls, mm).

## 2. Materials and Methods

To establish the dependence of the pressure on the mill rolls, based on the statistical (not functional) nature of the pressure dependence on the profiling parameters, it is advisable to use methods that correspond to the nature of the studying process. Therefore, the correlation-regression analysis is the most effective method. The data needed to plot an empirical regression line of the dependence $P=f(r/t_0)$ is given in Table 1.

In Table 1, the relative midpoints of the intervals are calculated by the equation $y'=\frac{(y_{cp}-c)}{i}$, the pressure P values by intervals according to the formula $y_x = c + [\Sigma(m_x y')\cdot i]/\Sigma m_x$, the c= 27 kN; $y_x$=P; $x=r/t_0$; $i$=6 кN; $\Sigma m_x$ - the amount included in the interval.

**Table 1.** Correlation table of P dependence on $r/t_0$.

| № | $x = r/t_0$ / $y = P$, кN | $y'$ | $\frac{0 \div 2}{1}$ | $\frac{2 \div 4}{3}$ | $\frac{4 \div 6}{5}$ | $\frac{6 \div 8}{7}$ | $\frac{8 \div 10}{9}$ | $\frac{10 \div 12}{11}$ | $\sum m_y$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 0 ÷ 6 | -4 | 54 | 45 | 23 | 7 | 14 | 3 | 146 |
| 2 | 6 ÷ 12 | -3 | 129 | 31 | 25 | 2 | - | - | 181 |
| 3 | 12 ÷ 18 | -2 | 86 | 5 | 13 | 2 | 1 | - | 107 |
| 4 | 18÷ 24 | -1 | 48 | 1 | - | - | - | - | 49 |
| 5 | 24 ÷ 30 | 0 | 16 | 2 | 1 | - | - | - | 19 |
| 6 | 30 ÷ 36 | 1 | 12 | - | - | - | - | - | 12 |
| 7 | 36÷ 42 | 2 | 7 | - | - | - | - | - | 7 |
| 8 | 42 ÷ 48 | 3 | 2 | - | - | - | - | - | 2 |
| 9 | 48 ÷54 | 4 | 2 | - | - | - | - | - | 2 |
| 10 | 54 ÷ 60 | 5 | 1 | - | - | - | - | - | 1 |
| | $\Sigma m_x$ | | 351 | 84 | 62 | 11 | 15 | 3 | 526 |
| | $\sum(m_x y')$ | | -760 | -284 | -193 | -38 | -58 | -13 | |
| | $y' = \Sigma(my')/\Sigma y'$ | | -2.16 | -3.38 | -3.11 | -3.45 | -3.87 | -4.0 | |
| | $y_x$ | | 14.1 | 6.72 | 8.34 | 6.3 | 3.78 | 3.0 | |

*Note. In all tables, y'-relative midpoint; my-sum of pressure values in the interval*

Figure 1 shows the experimental regression line. From the analysis of the experimental regression line, it follows that with a relative bending radius increasing to $r/t_0 \approx 5 \div 6$, the pressure decreases, and then the P decreasing slows down. A function of this type is well described by an equation of the logarithmic type.

$$y = 13.186 - 5.605\ln(x) \quad (1)$$

(reliability coefficient of approximation $R^2 = 0.8715$), along which the calculated regression line was plot Figure 1.

The closeness the dependence indicator of y on x with nonlinear regression is the correlation ratio

$$\eta = S(y_x)/S(y) \quad (2)$$

where $S$ – the standard deviation value of the corresponding dispersion estimate. Where $S^2(y_x) = \frac{1}{n}(\Sigma m_x y_x^2) - y_x^2$ – dispersion estimate $y_x$ is relative to total average dispersion estimate $y$, but $S^2(y_x) = \frac{1}{n}\Sigma m_y (y - y_x)^2$ – dispersion estimate $y$ is relative to total average dispersion estimate $y_x$.

The correlation ratio is a general the closure connection indicator, not taking into account the communication form. Therefore, in the non-linear correlation case , a regression coefficient is introduced.

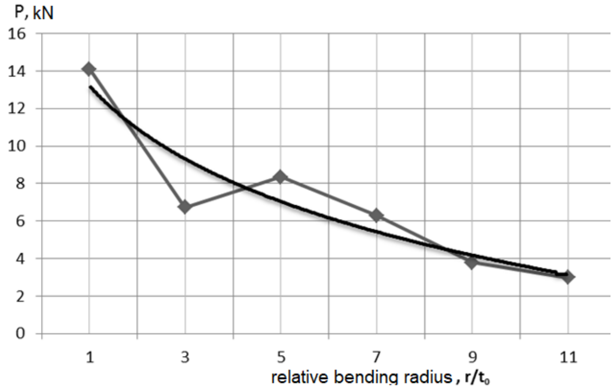


**Figure 1.** Experimental and calculated regression lines of pressure dependence on relative bending radius.

$$\eta' = \frac{s(y_p)}{s(y)} \qquad (3)$$

where $S^2(y_p) = \frac{1}{n}(\Sigma m_x y_p^2) - y^2$ – the estimate of the calculated variances $y_{p'}$ obtained from equation (1) with relative to total average $y$.

The correlation ratio η=0.39 indicates the influence of the relative bending radius on the magnitude of the force on the mill rolls.

Similarly to table 1, for the dependence of pressure P on the width of the flange to be bent a correlation table was created.

The values of pressure plotted on the graph Figure 2 from the correlation and the empirical regression line which is plotted from them shows the dependence of P on the width of the shelf being folded can be approximated by a quadratic function — a second order parabola $y=14.34-4.5376x+1.01167x^2$, accuracy coefficient of approximation for which the calculated regression line is constructed.

$$R^2=0.9761 \qquad (4)$$

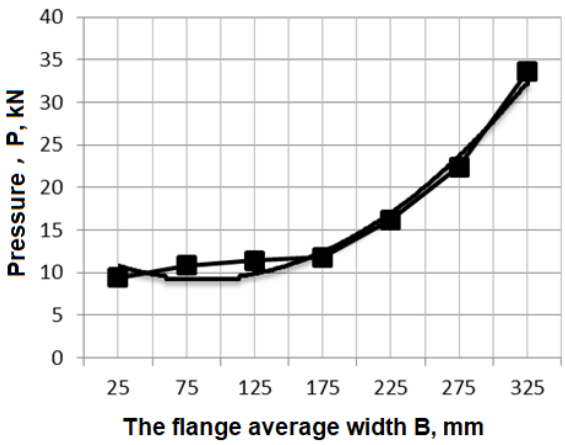


**Figure 2.** Experimental and calculated regression lines of the pressure dependence on the width of the flange.

The coefficients in equation (4) are calculated by the least squares method and the calculated regression line Figure 2 with the regression coefficient is $\eta'$=0.81; the correlation relation is $\eta_B$=0.36.

The pressure dependence on the angle $\alpha^o$ of the bend is represented by a correlation table similar to Table 1 and in Figure 3.

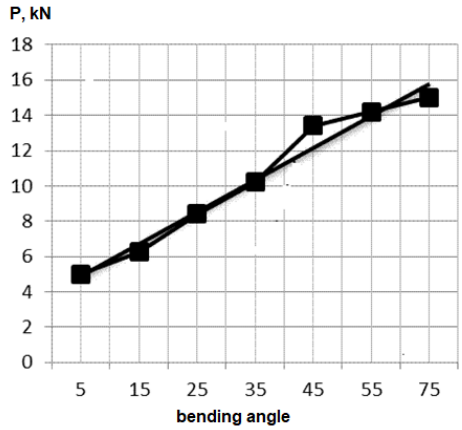


**Figure 3.** Experimental and calculated regression lines of pressure dependence on bending angle, α°.

The estimated regression line is plotted on the equation

$$y = 3.0743 + 1.8186x \tag{5}$$

Correlation coefficient $r_\alpha$=0.91, approximation reliability coefficient $R^2$=0.9739.

The efforts in the mill stands with a gap between the rolls *s* of equal strip $t_0(s=t_0)$ thickness are not significant. As the initial parameters for the strength calculations, they cannot be taken, because the degree of possible roll forming mill overloading is very high. The reason for such overloads is the change in the gap between the rolls. This is due to the fact that sometimes accidentally, most often deliberately, with non-compliance with the geometry of the profile, they change the compression of the rolls, while the gap is practically not controlled, and the efforts of overloads can exceed the efforts of the normal process several times.

The dependence of pressure on the gap between the rolls is represented by the correlation Table 2 and in Figure 4.

The estimated regression line is based on the equation

$$y = 32.328 -12.76\ln(x),\ x = \frac{s}{\tau_0} \tag{6}$$

The correlation ratio $\eta_{s/t}$=0.55 indicates a fairly significant dependence of the force on the rolls on the mill setting, and the regression coefficient $\eta' = 0.88$ indicates a good approximation of the dependence of P on $s/t_0$, the equation described by equation (6), (reliability coefficient of approximation $R_2$ = 0.9583).

**Table 2.** Correlation table dependencies *P* from *s/t₀*.

| № | $x=s/t_0$ / $y=P$ [кН] | $y'$ | **0.7** | **0.8** | **0.9** | **1.0** | **1.1** | **1.2** | **1.3** | $\sum m_y$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 0 ÷ 6 | -4 | - | - | 6 | 134 | - | 2 | 4 | 146 |
| 2 | 6 ÷ 12 | -3 | - | - | 11 | 145 | 11 | 8 | 6 | 181 |
| 3 | 12 ÷ 18 | -2 | - | 3 | 6 | 94 | 3 | 1 | - | 107 |
| 4 | 18÷ 24 | -1 | - | 8 | 8 | 31 | 1 | 1 | - | 49 |
| 5 | 24 ÷ 30 | 0 | 6 | 4 | - | 6 | 1 | 1 | 1 | 19 |
| 6 | 30 ÷ 36 | 1 | 5 | 1 | 1 | 3 | 3 | - | - | 12 |
| 7 | 36÷ 42 | 2 | 1 | 1 | - | 5 | - | - | - | **7** |
| 8 | 42 ÷ 48 | 3 | - | 1 | 1 | - | - | - | - | 2 |
| 9 | 48 ÷54 | 4 | - | 1 | 1 | - | - | - | - | 2 |
| 10 | 54 ÷ 60 | 5 | 1 | - | - | - | - | - | - | 1 |
| | $\sum m_x$ | | 13 | 19 | 36 | 418 | 16 | 13 | 11 | 526 |
| | $\sum(m_x y')$ | | 12 | -4 | -67 | -1177 | -40 | -35 | -34 | |
| | $\hat{y}'=\sum(m_x y')/\sum m_x$ | | 0.92 | -0.21 | -1.86 | -2.80 | -2.50 | -2.7 | -3.09 | |
| | $\hat{y}_x$ | | 32.52 | 25.74 | 15.84 | 10.20 | 12.0 | 10.8 | 8.46 | |

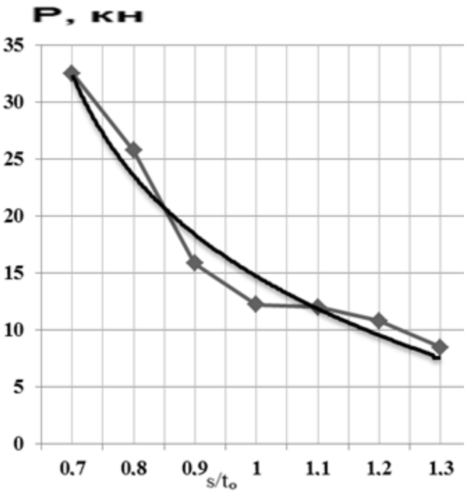


**Figure 4.** Experimental and calculated regression lines of pressure dependence on mill settings.

Based on the pair correlation equations (1,4,5,6) the general dependence of pressure on profiling parameters can be represented by the equation:

$$P=\left(\frac{s}{t_0}\right)b_1\cdot\left(\frac{r}{t_0}\right)b_2\cdot\alpha b_3\cdot Bb_4 \quad (7)$$

After logarithm of both parts we get $y=b_0+b_1x_1+b_2x_2+b_3x_3+b_4x_4$

where y =lnP;$b_0,b_1,b_2,b_3,b_4$–- equation parameters; $x_1,x_2,x_3,x_4$ – logarithms $s/t_0$, $r/t_0$,α, B.

To simplify the calculation of the coefficients in (7) on the basis of experimental data using the least squares method using matrices, the variables are coded using the formulas:

$$X_1 = (\ln x_1 - \ln x_{01})/\ln(\Delta x_{01});$$
$$X_2 = (\ln x_2 - \ln x_{02})/\ln(\Delta x_{02});$$
$$X_3 = (\ln x_3 - \ln x_{03})/\ln(\Delta x_{03});$$
$$X_4 = (\ln x_4 - \ln x_{04})/\ln(\Delta x_{04}). \quad (8)$$

Before creation a planning matrix, the area in which the experiment will be performed must be specified, other words, boundary values for each factor $x_i$ *min* (lower level) and $x_i$ *max* (upper level) described by the process technology. The midpoint $x_{i\ avr}$ between the boundary values is the planning center or the middle (main) level. For the convenience of matrix theory using in the calculation of coefficients in (7) by the least squares method, the levels are coded in such a way that the upper corresponds to: +1, the middle: 0, the lower: -1. Often a $X_i$ is called an encoded variable. The results of coding are shown in Table 3.

**Table 3.** Coding of variable factors.

| Level | $\frac{s}{t_0}$ | $\frac{r}{t_0}$ | α° | B | $X_1$ | $X_2$ | $X_3$ | $X_4$ |
|---|---|---|---|---|---|---|---|---|
| Upper | 1.2 | 3 | 90 | 150 | 1 | 1 | 1 | 1 |
| Average | 1.0 | 2 | 60 | 100 | 0 | 0 | 0 | 0 |
| Lower | 0.8 | 1 | 30 | 50 | -1 | -1 | -1 | -1 |

The planning matrix for two-quarters of the replicas from the complete factorial experiment $N=2^4$ with generating ratios $x_4=x_1x_2x_3$ and $x_4= - x_1x_2x_3$ determining contrasts $x_1x_2x_3x_4 = - 1$ and respectively is presented in the Table 4.

**Table 4.** Planning matrix.

| № | $\frac{s}{t_0}$ | $\frac{r}{t_0}$ | α° | B | Code designation | | | | | Output | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | X0 | $X_1$ | $X_2$ | $X_3$ | $X_4$ | *P,кN* | y=lnP |
| 1 | 0.8 | 3 | 30 | 150 | 1 | -1 | 1 | -1 | 1 | 21.5 | 3.0681 |
| 2 | 1 | 2 | 60 | 100 | 1 | 0 | 0 | 0 | 0 | 11.3 | 2.4224 |
| 3 | 1.2 | 1 | 30 | 150 | 1 | 1 | -1 | -1 | 1 | 5.0 | 1.6094 |
| 4 | 1 | 2 | 60 | 100 | 1 | 0 | 0 | 0 | 0 | 11.5 | 2.4424 |
| 5 | 0.8 | 1 | 90 | 150 | 1 | -1 | -1 | 1 | 1 | 52.0 | 3.9513 |
| 6 | 1.2 | 1 | 30 | 50 | 1 | 1 | -1 | -1 | -1 | 3.1 | 1.1314 |
| 7 | 1.2 | 3 | 90 | 150 | 1 | 1 | 1 | 1 | 1 | 4.7 | 1.5476 |
| 8 | 1 | 2 | 60 | 100 | 1 | 0 | 0 | 0 | 0 | 10.1 | 2.3126 |
| 9 | 1 | 2 | 60 | 100 | 1 | 0 | 0 | 0 | 0 | 10.3 | 2.3322 |
| 10 | 0.8 | 3 | 30 | 50 | 1 | -1 | -1 | 1 | -1 | 15.9 | 2.7660 |
| 11 | 0.8 | 1 | 90 | 50 | 1 | -1 | -1 | -1 | -1 | 41.7 | 3.7542 |
| 12 | 1.2 | 3 | 90 | 50 | 1 | 1 | 1 | 1 | -1 | 3.3 | 1.1939 |

The experiments realization order is randomized according to the table of random numbers.

The coefficients $b_0, b_1, b_2, b_3, b_4$ are determined based on the planning matrix and the inverse matrix.

$$(X)^{-1} = \left\| \begin{matrix} 1/12 & 0 & 0 & 0 & 0 \\ 0 & 1/8 & 0 & 0 & 0 \\ 0 & 0 & 1/8 & 0 & 0 \\ 0 & 0 & 0 & 1/8 & 0 \\ 0 & 0 & 0 & 0 & 1/8 \end{matrix} \right\|$$

They are equal to the diagonal terms of the matrix $(X'X)^{-1}$ multiplied by $\Sigma y$, that is

$$b_0 = \frac{1}{12}\Sigma_1^{12} y_i; bi = \frac{1}{8}\Sigma_1^{8} x_i y_i;$$

The selective coefficients for the parameters are determined independently of each other with the lowest possible variances, because the matrix was taken with the mutually orthogonal column vectors. The application of the least squares method provides the minimum estimate of the variance $S^2(y)$. Calculated the coefficients, we obtain an equation reflecting the dependence of the pressure on the rolls on the profiling parameters in coded form

$$y = 2.2776 - 1.0071X_1 - 0.2338X_2 + 0.2340X_3 + 0.1664X_4 \tag{9}$$

The adequacy of equation (9) is verified by analysis of variance estimates. The estimate of the variance that defines the inadequacy of the presentation of the results of the experiment with $f_1$=4 degrees of freedom equal 0.005102, and zero points when $f_2$=3 the degrees of freedom equal 0.004164. The ratio of these two estimates gives the estimated variances of the Fisher criterion $F_p = 1.22$ *At* a probability of 0.95 and four and three degrees of freedom the table value of the Fisher criterion $F_T=9.1$ Comparison $Fp = 1.22 << 9.1 = F_T$ allows to make a conclusion about the obtained mathematical model adequacy of the studied dependence.

After decoding and potentiation equation (9) is given to the form:

$$P = \frac{0.59 \cdot \alpha^{0.42} \cdot B^{0.30}}{(s/t_0)^5 \cdot (s/t_0)^{0.43}}, kN \tag{10}$$

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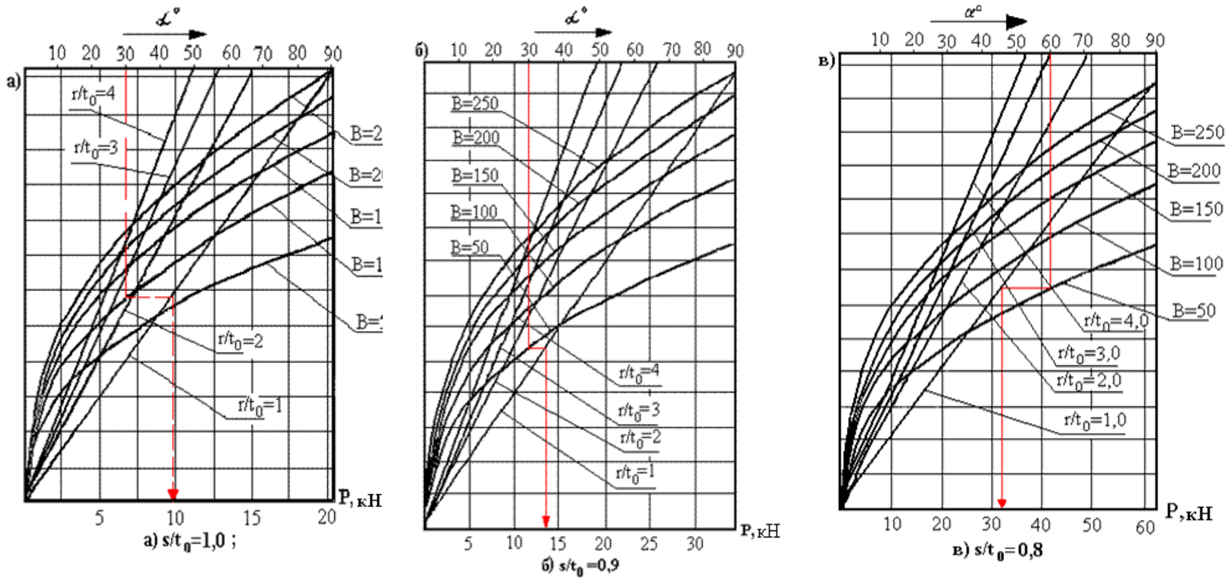


**Figure 5.** Nomograms for determining the pressure on the rolls on the parameters of the profiling and setting of the mill.

## 3. Conclusion

In this way, using mathematical methods of experimental data, an adequate pressure dependence equation for the specified parameters was obtained. Also confidence intervals were calculated and nomograms were constructed, according to which, depending on the geometric dimensions of the profile, the profiling route and the mill settings, it is possible to determine the forces occurring in the working rolls of the roll forming mill.

When developing the process of profiling and calculating the calibration of the rolls, you can use the graphs of the pair dependence of pressure on the profiling parameters (Figure 1-–3), drawing attention to the mill setting (gap between the rollers). In case of non-compliance with the geometry of the profile is often prescribed preload rolls. At the same time, the gap is practically not controlled, and the force of overloads can exceed the efforts of the normal process several times.

When calculating the pressure from the presented nomograms for design calculations based on the different stiffness of the individual mill sites and the safety factor conditions, the safety factor should be taken 2–3.

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