Method of load calculation of electrical drives of rolling mills during heavy plate manufacturing

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Abstract. During manufacturing of heavy strips and plates from difficult-to-form steel grades on sheet and wide-strip rolling mills there is a problem of exact calculation of power parameters of rolling. It is pointed out that known methods do not provide required precise information at high deformation zones in a stand. An improved calculation method for rolling pressure and load torque of electrical drive engine is suggested further. This method considers peculiar strain of product in high deformation zones and its accelerated motion in reverse mode. Improved analytical dependences for rolling pressure and load torque of electrical drive are reviewed. Control flow chart and main screen of developed software for calculation of wide-strip rolling parameters are presented. Comparative analysis of calculation data and experimental results of engine equivalent currents during tube steels rolling is made. As a result improved precision of calculation method is justified.

1. Introduction
Service experiment for plate mill 5000 and mastering rolling of hollow billet on continuous wide-strip mill 2000 predetermine the need of theoretical analysis of power parameters of heavy plate rolling [1,2]. Speed and load charts of electrical drives of a rolling mill are interdependent constraining factors applied to technological process. This is why their analysis is required for development of new and improvement of available technological software.

Process of rolling of a heavy plate on continuous hot mills and on reversible sheet mills is different. Rolling on continuous hot mill is characterized by variable speed. Front of the piece is collected in sequence by each stand and a baller on low threading speed. Then all stands, a rolling table and a baller speed up simultaneously to maximal operating speed. Lowing down of stands is individual after a trailing end leaves a certain stand.

Drafting on reversing mill 5000 is performed by one horizontal four-high stand and a two-roll edger stand [3]. Universal stand operates in reverse mode – slabbing is performed within several passes. Before and after a stand there are turn-around machines with side guides to ensure 90-degree turn of sheet slabs [4]. Acceleration and speed reduction of electrical drive are carried out with plates in rolls. Acceleration takes place immediately after the plate is collected by a roll; speed reduction torque is determined by preselected speed of plate release on an outgoing table.
Analysis of loading modes of rolling mill electrical drives is a time consuming task associated with numerous mathematical calculations. Specialized software significantly facilitates calculations. To implement computerized analysis of operation modes of engines of stand main electrical drives we need to develop new methods and software.

2. Set up of the problem
In practice, to calculate power parameters of rolling one traditionally applies methods developed based on the works of academy fellow A.I. Tselikov. In most cases, the results for hot rolling of plates are reasonable for engineering calculation. The author of the publication [5] examined methods of numerical definition of rolling pressure. To solve the differential equation

\[
\frac{d\sigma_y}{dx} - \frac{P_x}{\sigma_y} - \frac{t_x}{y} = 0
\]

(1)

unit roll pressure \(P_x\) -stress \(\sigma_y\) dependence was analyzed. Main vertical intensity formula was used

\[
\sigma_1 = \left( \frac{P_x}{\cos \phi} \cdot \cos \phi \cdot t_x \cdot \frac{dx}{\cos \phi} \cdot \sin \phi \right) \cdot \frac{1}{dx}
\]

(2)

The second term, due to its small amount in comparison with the first member, was not considered by the author. In this case problem solution (1) provides the following formula for rolling pressure \(P\) calculation

\[
P = \frac{b_0 + b_1}{2} \cdot \frac{l}{\Delta h} \cdot \frac{k \cdot h_0}{\delta} \cdot \left( \frac{h_0}{h_1} \right)^{\delta} + \left( \frac{h_0}{h_1} \right)^{\delta} - 2 \cdot \frac{\delta^3 \Omega}{\eta^2}
\]

(3)

In equations (1) – (3) the following keys are introduced: \(x, y\) – coordinates of reference section of deformation zone on roll face; \(\phi\) – angle between the tangent to roll bow at calculation point and level; \(t_x\) – specific friction force between rolling metal and roll face; \(h_{0}, h_{1}\) and \(b_{0}, b_{1}\) – thickness and width of a sheet slab before and after rolling; \(\Delta h\) – draught; \(l\) – length of deformation belt; \(h_\gamma\) – plate height in neutral plane; \(\delta\) – factor depending on roll parameters.

For lower deformation zones, which occur during light plate rolling, the given equations provide reasonably precise calculations of power parameters. However, during heavy plate rolling it is unacceptable to dismiss the second term of equation (2). Given that rolled sheet slab is 350 mm thick and working roll diameter is 1210 mm, angle \(\phi\) is 20°, thus, the second term of equation is relevant.

As a result we face the need to develop an improved calculation method of rolling pressure and rolling torque considering the effect of thickness factor. Moreover, plates move unevenly on reversing mill because they leave rolls with acceleration. That is why we must take into account inertial force \(U\) of metal (figure 1) [5]. When developing a new method it is important to consider that the ratio between level of deformation zone and radius of working rolls significantly influence static rolling torque.

![Figure 1. Direction of forces acting on rolls during accelerated movement of rolled metal](image_url)
3. Main part
What makes the new method distinctive are the more precise equations used for calculation of rolling pressure and static torque during heavy plate rolling. Torque equation is written as

\[ M_r = 2 \cdot P \cdot \psi \cdot \sqrt{R_c \cdot (h_0 - h_1) - \frac{(h_0 - h)^2}{4}} \]  

(4)

where \( \psi \) is a position coefficient of thrust force acting on rolls; \( R_c \) is working roll radius.

Rolling pressure is calculated based on dependences

\[ P = \sqrt{P_{x}^2 + P_{y}^2}; \quad P_x = \frac{1}{2} G \cdot \frac{l_1 - l_2}{\lambda} + \frac{G}{g} \cdot j \cdot l_2; \quad P_y = \frac{b_0 + b_1}{2} P_x; \]

\[ P_{\phi} = \frac{8 \cdot R_{r}^2}{(h + 2 \cdot R_{r}) \sqrt{h + 4 \cdot R_{r}}}; \quad \arctg \left( \frac{h + 4 \cdot R_{r}}{\sqrt{h + 4 \cdot R_{r}}} \right) - \arctg \left( \frac{\phi}{2} \right) \]

\[ \tau = \frac{2 \cdot R_{r} \cdot \ln \left( \frac{\phi}{2} + 1 \right)}{h + 2 \cdot R_{r}} + k \cdot \ln \left( \frac{h}{2} + R_{r} \cdot (1 - \cos \phi) \right) + k \cdot \left[ 1 - \ln \frac{h}{2} \right] \]

(5)

where \( G \) – weight of the plate; \( L_j \) – length of the plate at delivery; \( x \) – rolling out as a result of plate travel; \( l_2 \) – length of plate delivered from the rolls at a given torque; \( j \) – plate acceleration at delivery; \( g \) – free fall acceleration. The remaining parameters are noted above.

The author of the publication [6] has deducted a ratio for calculation of position coefficient of thrust force acting on rolls

\[ \psi = \frac{a_{M}}{l} = \frac{1 + 2 \cdot p_0 / p_1}{1 + p_0 / p_1} \]  

(6)

Analysis of equation (6) leads to conclusion that at \( l/h = 1 \) and \( p_0 / p_1 \to \infty \) highest value \( \psi = a_{M} / l \) is 0.67. At \( l/h \to 0 \) value of \( \psi \) comes close to 0.5, and at \( l/h \to \infty \) – to 0.33. Analytical angle value \( \beta \) for different distribution laws for surface stress was calculated by well-known Russian scientists metallurgists A.A. Korolev [7], N.S. Spiridonov [8], N.M. Kirilin [9] and others. The calculations were made for those cases when frictional forces were in proportion to unit roll pressure. Similar research was conducted to identify the conditions for frictional force consistency as described in the publication [10]. When calculating the arm, the author [9] assumed that unit rolling pressure is distributed according to equations by Tselikov [11]. As a result of his research he concluded that with increase of drafting, the relation between angle \( \beta \) to entering angle \( \alpha \) (arm coefficient \( \psi \)) decreases from 0.5, at light draft, to 0.4...0.45 at approximately 0.6 draft.

The results of researches by E.S. Rokotyan [12] and G. Valkvist [13], conducted in working environment on blooming and sheet mills are of our main interest. Analysis of their research results shows that value of angles \( \beta \) and \( \alpha \) ratio during hot rolling ranges from 0.30...0.35 to 0.55...0.57. At that, low values correspond with lighter plates (2.5-5 mm) and upper values correspond with heavier plates (10-20 mm). These values rise when rolling temperature increases and draft decreases. For one thickness value variances \( \psi \) are relatively insignificant and do not exceed 15...20%. However, all these researches do not precisely explain how the angle \( \beta \) will change during heavy plate rolling.

To find how the angle of application point of rolling pressure resultant force changes during heavy plate rolling we conducted a series of experiments on rolling mill 5000. Steel grades K52, K56, 09G2S, 15HNSD, 10G2FBU, 15ps, X70, PC D40 were used. Change in angle of application point of rolling pressure resultant force in relation to entering angle is presented on figure 2. The analysis shows that angle \( \beta \) for each steel grade relates in the same way to angle \( \alpha \), so it is possible to conclude that it does not depend on properties of steel, but rather on level of deformation zone.
General tendency of change of angle $\beta$ on figure 2 is reflected by power characteristic. Dependability approximant $R^2$ demonstrates how many points from presented selection are contained on the curve (the higher $R^2$, the better representation of dynamic pattern of approximant parameter). In the given case dependability is 98%, approximate connection $\beta = f(\alpha)$ is written as:

$$\beta = 0.391 \cdot \alpha^{1.1459} \quad (7)$$

A theoretical model for calculation of power parameters of rolling was developed based on equations (4)-(6). Theoretical model is actualized as software components in graphic environment of simulation study Simulink in MATLAB Packet.

**Program flow and interface**

We developed program flow and specialized software for computerized analysis of power parameters of sheets and heavy plates rolling. Flow chart of main software is shown on figure 3. Software is written in Object Pascal in visual object oriented programming environment for creation of applications for Windows Borland Delphi 7.0. This environment was chosen due to its simple terms for creation of applications and a rather rich library of generic components. Variety of basic primary objects have allowed for coding a program using standard libraries, and, thanks to flexibility of each component’s settings it was possible to create the program in a unified style.

A compiled program has one file with the specified name. Figure 4 represents a window of the program made for calculation of rolling patterns of heavy strips in roughing and finishing mill groups of the mill 2000. There is also a version of the same program used for same calculations for the mill 5000.

The user window is divided into four sections. The top section contains general view of roughing and finishing mill groups. The section underneath the top one contains chart bars illustrating load on engines (percentage of nominal values). Bars are colored, depending on the load; green color of bars indicates load between 0% and 80%, yellow color – 80-90%, and red color – load exceeding 90%. The third section contains input data for calculation, including roll radius, gearbox ratios, nominal current and engine speed values, as well as rolling speed and acceleration. Finally, fourth section is intended for input of values of thickness, width and rolling temperature for each interstand space.

Operations with the program begin with data input (constants). They may be put in manually or imported from a preformed file. After having put in data, user initiates calculation. Input and output data may be shown on the display or printed out. Calculation logs as well as input and output data are exported in .xls file.

4. **Theoretical and experimental study**

To check efficacy of calculation method for operating modes as implemented in the software we applied it to calculate electromagnetic torque of 4-12 stand electrical drives of rolling mill 2000.
Figure 3. Control flow chart.
Figure 4. View of user window. **Legend (left to right, top to bottom):** roughing mill group, finishing mill group, stands, percentage of load of stands’ engines, mill parameters, roll radius (in mm), gearbox ratio, nominal engine current (in A), nominal engine speed (in rpm), rolling speed (in m/sec), rolling acceleration (in m/sec²), roughing mill group, rolling thickness (in mm), rolling width (in mm), rolling temperature, yield point of metal (in N/mm²), finishing mill group.

The calculation was made for hollow billet rolling, steel grades 22GU, 09G2D, 09G2S, 09GSF, 13G1S-U. Steel grades and rolling modes correspond with experimental studies given in [14]. Results of efficacy estimation show that experimental and estimated data vary within the range from -7.8% to +6.6%. So the precision of calculations based on suggested method is satisfactory.

This method was applied to calculate equivalent current of direct current motors of electrical drives in rolling mill 2000 and electromagnetic torque of synchronous motor of stand rolls in rolling mill 5000. Results of calculations and experimental studies of operating modes of the given electrical drives are provided in table 1 and 2 respectively. For rolling mill 2000 operating modes are shown for hollow billet rolling using the given grades of steel, for rolling mill 5000 operating modes are for sheet slabs of the following steel grades: 10HSND, K56, K60, K65 и St3sp. Comparison of the results of theoretical and experimental study leads to conclusion that calculations are satisfactory: calculation error does not exceed 9-10%.
include calculation results of the last stands).

7.5%...+7.1% range, while for traditional method it is with

power parameters during heavy sheet slab rolling provides more accurate results than traditional

method. So, for the given range the error against experimental data for suggested method is within

-7.5%...+7.1% range, while for traditional method it is within -15%...+14.6% range (analysis does not

include calculation results of the last stands).

Table 1. Results of calculations and experimental studies of equivalent current of electrical drives in rolling mill 2000 during tube steel rolling.

| Source of data | Equivalent current of engines by stands, A |
|----------------|------------------------------------------|
|                | №4 | №5 | №6 | №7 | №8 | №9 | №10 | №11 | №12 |
| experiment     | 10624 | 9643 | 8564 | 7547 | 6421 | 8572 | 6058 | 6049 | 5552 |
| calculation    | 10321 | 8974 | 8573 | 7904 | 6989 | 8162 | 6511 | 6060 | 5023 |
| experiment     | 11110 | 11231 | 12591 | 7808 | 6019 | 6750 | 5376 | 5691 | 7095 |
| calculation    | 11056 | 11929 | 13434 | 8450 | 5588 | 6116 | 5768 | 5607 | 7015 |
| experiment     | 17418 | 15777 | 16464 | 7864 | 7865 | 9695 | 7623 | 8009 | 7801 |
| calculation    | 17604 | 16770 | 16922 | 7547 | 7387 | 10458 | 7816 | 8342 | 8031 |
| experiment     | 16676 | 14420 | 15617 | 13028 | 11066 | 13744 | 11015 | 10570 | 8610 |
| calculation    | 15096 | 13135 | 17144 | 12042 | 10488 | 12383 | 11838 | 9619 | 8987 |
| experiment     | 18356 | 16806 | 14947 | 11736 | 9685 | 12351 | 10490 | 11409 | 5736 |
| calculation    | 17071 | 17634 | 15987 | 12519 | 9700 | 12084 | 10748 | 11352 | 5383 |

Table 2. Results of calculations and experimental studies of rolling torque in rolling mill 5000.

| Steel grade | Sheet slab size, mm | Draft, % | Rolling torque, kN |
|-------------|---------------------|----------|-------------------|
| thickness   | width               | length   | experiment        | calculation |
| 10HSND      | 300                 | 3040     | 2400              | 6.08        | 2984 | 3284 |
| K56         | 300                 | 3120     | 2050              | 11.28       | 4195 | 4700 |
| K60         | 300                 | 2600     | 2400              | 9.89        | 4124 | 4522 |
| K65         | 300                 | 2600     | 2400              | 11.89       | 5761 | 6242 |
| St3sp       | 300                 | 2900     | 2700              | 9.67        | 3084 | 3318 |

Results of experimental rolling of sheet slab, 300 mm, different steel grades, on rolling mill 2000 and results of theoretical calculations based on traditional method and software-implemented method are given in table 3.

Table 3. Results of calculations and experimental studies of sheet slab 300 mm rolling.

| Steel grade, sheet slab size | Equivalent current of engines by stands, A/(% to experiment) |
|-----------------------------|-------------------------------------------------------------|
| experiment                  | №7 | №8 | №9 | №10 | №11 | №12 | №13 |
| steel grade 20, 8000×1750×300| 12.5 | 12.6 | 12.8 | 12.2 | 12.0 | 8.9 | - |
| traditional method          | 13.4 | 12.1 | 12.0 | 11.9 | 10.5 | 4.8 | - |
| suggested method             | 12.9 | 12.8 | 13.0 | 12.7 | 12.8 | 8.6 | - |
| method                       | +7.2% | -4.0% | -6.3% | -2.5% | -15.0% | -54% | - |
| experiment                  | 9.9  | 8.4  | 10.2 | 8.7  | 8.9  | 5.6 | 5.4 |
| traditional method          | 10.7 | 9.0  | 11.0 | 8.9  | 10.2 | 6.1 | 4.1 |
| suggested method             | 10.3 | 9.0  | 10.6 | 9.1  | 9.0  | 5.9 | 5.0 |
| method                       | +8.0% | +7.1% | +7.8% | +2.2% | +14.6% | +8.9% | -25% |
| 08 ps, 8000×1330×300         | 10.3 | 9.0  | 10.6 | 9.1  | 9.0  | 5.9 | 5.0 |
| suggested method             | 10.3 | 9.0  | 10.6 | 9.1  | 9.0  | 5.9 | 5.0 |
| method                       | +4.0% | +7.1% | +3.9% | +4.5% | +1.1% | +5.3% | -7.5% |

Comparative analysis of the given data leads to conclusion that suggested method of calculation of power parameters during heavy sheet slab rolling provides more accurate results than traditional method. So, for the given range the error against experimental data for suggested method is within -7.5%...+7.1% range, while for traditional method it is within -15%...+14.6% range (analysis does not include calculation results of the last stands).
5. Conclusion

Experimental studies of operating modes of heavy plate mill 5000 electrical drives and wide-strip rolling mill 2000 have shown that direct application of simplified method by A.I. Tselikov is unacceptable when calculating power parameters of rolling of heavy plates from difficult-to-form steels. Calculating error for first passes on rolling mill 5000 is as high as 38%. It predetermined the need to develop a new more precise method.

Analytical dependences for rolling pressure during rolling of sheet slabs thicker than 250 mm are given. When developing a new method, particularity of rolling mill accelerated movement was considered. Angle of application point of rolling pressure resultant force in rolling mill 5000 stand was determined experimentally. It was found that this angle is defined by deformation zone configuration and does not depend on steel grade.

Program flow and software for computerized analysis of power parameters of rolling and operating modes of electrical drives in heavy plate and wide-strip rolling mill was developed. It was confirmed that the software provides calculations for rolling pressure and torque with error not higher than 7.5% for all passes.

Experiment has proved efficacy of calculated data, which lets us recommend the suggest method and software for extended application.

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