Development and Industrial Testing of Advanced Rolling Conditions at 4-Stand Mill 2100 of PAO Severstal

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Abstract. The paper presents the results of development of improved cold rolling process conditions at the 4-stand mill 2100, which allows to increase the efficiency of the process by enhancing the quality of rolled products and minimizing the occurrence of the surface defects of work rolls. Based on industrial tests, the developed advanced rolling conditions are accepted for use in production.

The increase of efficiency of the sheet rolling process by improving the quality attributes of rolled metal, increase the tool-life and reduce energy requirements is a very important aspect of competitiveness of metal produced in Russia. These improvements require technological advancement based on overall assessment of the existing production parameters, including mathematical modelling.

One of the quality indicators of cold-rolled steel that determines the condition of good application of metal and organic coating onto a strip is reduced contamination of the surface. Cold-rolled metal produced at the 4-stand mill 2100 of PAO Severstal after the reconstruction done in the end of 2016 had significant surface contamination. Contamination per a unit of sheet surface area was 25 % higher than for the metal produced at the 5-stand mill. Besides, the main equipment – work rolls of the mill – were accompanied by frequent damage of roll bodies and consequently significant roll consumption. Roll consumption at the 4-stand mill was 30 % higher compared to the 5-stand cold-rolling mill. All of that predetermined the necessity of the assessment of production technology of cold-rolled metal at the 4-stand mill 2100, including finding technology parameters which influence the degree of rolled metal contamination and the factors that determine the emergence of surface layer defects of the work rolls.

The studies of the influence of cold rolling modes on the strip surface cleanliness were based on its dependence on the positioning of neutral planes in deformation zones of the working stands, the hypothesis being the following [1, 2]: the enlargement of backward slip zone in a deformation zone helps cleaning the strip surface, because the circumferential stress in this zone along the rolling direction helps to remove the contamination from a deformation zone.

Rolling modes of more than 280 strips were taken for the study, fixed by an automatic measurement and a data control system, with the link to the quantity of grease and mechanical impurities and the reflectivity of light. For the specified modes with the application of a mathematical model, the geometric and power characteristics of deformation zones of the working stands were determined, including indicator $X_i$, which characterizes the position of the neutral plane $NN$ in $i$-th stand (Figure 1):
\[ X_i = \frac{x_{ba}}{x_{pl}} , \]

where \( x_{ba} \) is the length of backward slip zone of a plastic area; \( x_{pl} \) is the full length of a plastic area.

The analysis of the indicators of the mechanical and grease impurities of the cold-rolled strips surface, the parameters of speed modes, reduction and tension modes, rolling forces and torques allowed us to determine that the most meaningful factors which influence contamination are: frequent percentage reduction in stand 1 (\( \varepsilon_1 \), %) and the indicators that characterize the positions of neutral planes in stand 1 (\( X_1 \)) and in stand 3 (\( X_3 \)). To increase the surface cleanliness of the cold-rolled strip it is necessary to decrease the reduction percentage \( \varepsilon_1 \) and indicator \( X_1 \) and increase the indicator \( X_3 \) at the same time.

In the papers dedicated to the matters of roll strength improvement [3-5], the results of the studies of technological modes’ influence on roll damage and on the emergency failures of rolls are narrowed down to the recommendations on minimizing the rolling conditions, that is the reduction of rolling force in the stands, exclusion of surface and internal defects of hot-rolled metal with meeting the requirements for limit deviation of thickness from the nominal value. Furthermore, the improvement of rolling modes with the assessment of work rolls operation parameters and the important direction is the increase of rolling process efficiency.

The analysis of technological rolling modes at the 4-stand mill 2100 of the strips of steels of different hardness categories showed that:

1) Interstand specific tensions \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) in the respective interstand spaces No. 1, No. 2 and No. 3 are basically the same, and in several cases the tension in the second interstand space \( \sigma_2 \) is lower than in the first one \( \sigma_1 \) (Figure 2). According to [2] specific tensions in every following interstand space should increase in connection to work hardening.

2) Rolling process in stand 1 is always done with front upthrust, which is showed by the graph of changes in second volume of metal, rolled in stands No. 1 and No. 2 (Figure 3, the curve is in the 1st quadrant of the coordinate plane), which leads to the significant increase of rolling force [6], and to frequent slipping of the rolls. To exclude these negative occurrences, it is needed to decrease the particular percentage reduction in the 1st stand.

3) High percentage of damages of work roll bodies of stand No. 1 is connected to frequent damage at strip gripping, because the gripping condition is not fulfilled (\( \tan \alpha < \mu \), where \( \alpha \) is the gripping angle; \( \mu \) is the friction coefficient). For the stand No. 1: \( \tan \alpha = 0.058 > \mu = 0.038 \), which confirms the necessity to decrease the particular reduction in the stand.

The modelling of the technological modes of cold rolled metal production at the 4-stand mill 2100 with the application of the integrated model of cold rolling process [7, 8], which reflects the dynamic

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**Figure 1.** Deformation zone diagram: \( h_{i-1}, h_i \) is the strip thickness at the entry and exit from the \( i \)-th stand; \( h_n \) is the strip thickness in a neutral plane; \( x_{fo} \) is the plastic area forward slip zone length; \( l_{ci} \) is the deformation zone length of \( i \)-th stand; \( x \) is the rolling axis; \( y \) is the axis which connects the centres of the rolls.
interconnection of the rotating system of the driveline, stand system and deformation zone, allowed us to phrase the main terms of the mill rolling concept which is the following:

1) **Deformation mode** should be assigned with maximum percentage reduction in the stand No. 2, determined from the condition of uniform loading of the first two stands by the rolling force \( P_1 \approx P_2 \). In the stand No. 4 in order to get cold rolled strips with specified surface quality values and measurement precision the reduction should be in the range of 5-7 %.

2) **Tensions mode**, depending on the purpose of rolling may be set according to two alternative schemes:
   - scheme 1: \( \sigma_1 < \sigma_2 < \sigma_3 \) or \( \sigma_1/\sigma_{a1} = \sigma_2/\sigma_{a2} > \sigma_3/\sigma_{a3} \);
   - scheme 2: \( \sigma_1 < \sigma_2 < \sigma_3 \) or \( \sigma_1/\sigma_{a1} = \sigma_2/\sigma_{a2} < \sigma_3/\sigma_{a3} \),

   where \( \sigma_{a1} \), \( \sigma_{a2} \), \( \sigma_{a3} \) are the actual points of strip material yield respectively at the exit from stands No. 1, No. 2 and No. 3. For the purpose of excluding breakages and tightening of cold rolled strips the specific tensions for the established process should not exceed 27 % from the existing value of the strip material yield point.

The introduced reduction and tension modes are significantly different from the ones established at the mill right now, but their implementation will allow:

   - Prevention of slipping in stand No. 1 and damage of the roll bodies by decreasing the percentage reduction in the stand and fulfilling condition \( \sigma_1 < \sigma_2 \). For example, for the traditional steel grades 08пс

![Figure 2. Distribution of specific tensions over the interstand spaces, MPa.](image1)

![Figure 3. Changes in the difference of second volumes of metal in stands No. 1 and No. 2, m^3/s.](image2)
(08ps) and 08IO (08Yu) $\sigma_2$ exceeds $\sigma_1$ for approximately 20 MPa, earlier this condition was not fulfilled (Figure 2).

- Increased cleanliness of the strip surface by decreasing the percentage reduction in stand No. 1 and assigning tensions according to scheme 1, and for stand No. 3 the inequality $\sigma_2 > \sigma_1$ is typical, which leads to the decrease of parameter $X_1$ (offset of the neutral plane to the side of metal entering in the deformation zone of stand No. 1) and to the increase of $X_3$ (offset of neutral plane to the side of metal exiting from the deformation zone of stand No. 3). According to scheme 1 the distribution of interstand tensions for steel grades 08nc (08ps) and 08IO (08Yu) $\sigma_2$ exceeds $\sigma_1$ for approximately 25 MPa. Earlier such scheme was not used in the technological modes.

- Decreased rolling forces in the stands, and damage to the roll bodies and reduced total energy requirements by implementing reduction mode and tensions scheme 2 with gradual increase of specific tensions from the first interstand space to the last one. For example, for steels 08nc (08ps) and 08IO (08Yu) the difference $(\sigma_2 - \sigma_1) = (\sigma_1 - \sigma_2) \approx 20$ MPa, in basic mode technology difference $(\sigma_3 - \sigma_2)$ did not exceed 10 MPa (Figure 2).

Based on the described concept of cold rolling process strip production modes were developed for the most high-demand section sizes and steel grades. As an example Tables 1 and 2 show technological and energy and power parameters of basic and advanced strip rolling modes for steel 08nc (08ps) of 1254 mm width and 0.45 mm thickness made out of material of 1.9 mm thickness at the speed of 15 m/s.

**Table 1.** The parameters of actual strip rolling mode dimensions 1.9→0.45×1254 mm, steel grade 08nc (08ps).

| Stand No. | $h_i$, mm | $\varepsilon_i$, % | $\sigma_i$, MPa | $P_i$, MN | $N_{engi}$, kW | $X_i$ |
|-----------|-----------|-------------------|-----------------|-----------|----------------|-------|
| 1         | 1.158     | 40.7              | 158             | 11.56     | 2015           | 0.8007|
| 2         | 0.687     | 40.7              | 158             | 9.54      | 2082           | 0.9464|
| 3         | 0.459     | 33.2              | 168             | 9.83      | 2106           | 0.8393|
| 4         | 0.45      | 1.96              | 40.3            | 6.27      | 128            | 0.8791|

**Table 2.** The parameters of the advanced strip rolling mode dimensions 1.9→0.45×1254 mm, steel grade 08nc (08ps).

| Stand No. | $h_i$, mm | $\varepsilon_i$, % | $\sigma_1$, MPa | $\sigma_2$, MPa | $P_1$, MN | $P_2$, MN | $N_{eng1}$, kW | $N_{eng2}$, kW | $X_1$ | $X_2$ |
|-----------|-----------|-------------------|-----------------|-----------------|-----------|-----------|----------------|----------------|-------|-------|
| 1         | 1.159     | 39                | 160             | 150             | 10.2      | 10.3      | 1867           | 1882           | 0.7634| 0.7775|
| 2         | 0.672     | 42                | 180             | 170             | 9.5       | 9.8       | 2164           | 2221           | 0.9348| 0.9303|
| 3         | 0.474     | 29.5              | 155             | 190             | 8.2       | 8.0       | 1713           | 1643           | 0.8631| 0.8133|
| 4         | 0.45      | 5                 | 52.5            | 52.5            | 9.3       | 9.0       | 398            | 336            | 0.8112| 0.8369|

Note. Indices 1, 2 – the value of the parameter with the existing interstand tensions distribution scheme; $N_{engi}$ – engine capacity of the $i$-th working stand.

It is seen in the tables that for the advanced modes, in comparison to the basic ones, force in stand No. 1 is decreased by 11 % and the total capacity of engines, as a minimum, is decreased by 3 %. The distribution of tensions according to scheme 2 leads to additional energy efficiency which is 1 % while rolling strips less than 1.2 mm thick, and 4 % for strips with the thickness of more than 1.2 mm. The decrease of the attribute which characterizes the position of the neutral plane in stand No. 1 and its increase in stand No. 3, provided by the distribution of interstand tensions in accordance with scheme 1 helps to improve the cleanliness of the strip surface.
Conclusions and results
To check the efficiency of the developed modes, testing was done at the 4-stand mill 2100, consisting of two stages. During the first stage the simulation of coil rolling using the existing mill software; it showed the possibility to implement the proposed concept. During the second stage industrial testing was done at 34 heats, meant either for annealing or for galvanizing.

Rolling with the advanced modes provided the decrease in the total amount of mechanical impurities at the strip surface from 215 mg/m² to 150 mg/m², that is 30%; the increase of the average rolling speed for 35 % (for the strips of up to 1.0 mm thickness the speed was 17 m/s, for over 1.0 mm it was 15 m/s). During the testing there were no damages or delamination of the surface of the roll bodies.

Based on the results of the industrial testing the developed rolling modes, which provide the increase of strip surface cleanliness and minimize the reasons of roll surface layer defects appearance, were implemented into production.

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