Algorithm and Design Methodology for Energy-Efficient Sheet Products Production Technology

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Abstract. The work presents a calculation method for technology parameters of the continuous cold rolling process of wide steel strips, based on the determination of such reductions by stands and interstand tension, at which the technological process will be ensured with maximum productivity and minimum energy consumption. A method for calculating the rolling parameters is proposed, which will provide the minimum level of energy consumption by the main drives' motors of the rolling stands at the maximum productivity of the continuous mill by eliminating vibrations in the working stands. The created methodology can be used as a base for the software of continuous mills.

1. Introduction

Nowadays a sufficient number of methods for calculating the parameters of continuous cold rolling are known and applied [1-6]. The most widely used methods are based on indicators of the strength of the rolls, the permissible load on the drive elements of the working stands and the possibility of unifying the reduction and tension modes in some mill stands when rolling different profile and grades of the assortment, and some other methods. Experience in calculating rolling modes has shown that it is also advisable to use a calculation methodology that will enable the production of steel strips with the lowest energy consumption and the highest productivity.

Different sources already mention [7-9] the application of the methodology for designing technological parameters of the cold rolling process to ensure the minimum energy consumption and optimal performance by adjusting modes to exclude vibrations in the working stands. Positive experience has been accumulated in the search for optimal modes using well-known models of power parameters. However, in most studies, optimization methods known from the theory of experimental design were used to search for the optimal values of technology factors, which can lead to miscalculations and not full use of economical and increased productivity benefits. Obviously, to find the optimal values of the continuous rolling technology factors, the most rational approach is to compile a matrix containing combinations of all possible values of the technology parameters for a particular mill – local reductions in stands, interstand specific strip tensions and the corresponding total power of the main drive motors, determined using the most reliable methodology. From the matrix compiled this way, the most optimal option is selected according to the criteria “total energy consumption for the process” and “the absence of vibrations in the stands at maximum rolling speeds”.
2. Problem statement and research methodology
The objective of this work was to develop a method for designing cold rolling technology that provides the calculation of the least energy-consuming modes of strip rolling at maximum productivity of a continuous mill.

To conduct the study, we acted as follows. Determined the mechanical characteristics of the strip material - steel grade 08ИС - from the reference data. We selected a profile product range of rolled products - three conventional thickness groups: a thin strip, with a thickness of not more than 0.5 mm, a strip of medium thickness - not more than 0.8 mm, a thick strip, with a thickness of more than 0.8 mm.

Next, we compiled a table of technological parameters for each profile group of the range. The table included the reduction and the specific tension of the strip, found by looking through all possible combinations of these parameters, taking into account the technological limitations of the stands. An example of such a table is given below.

| № | $h_0$, mm | $h_1$, mm | $h_2$, mm | $h_3$, mm | $h_4$, mm | $h_5$, mm | $\sigma_1$, MPa | $\sigma_2$, MPa | $\sigma_3$, MPa | $\sigma_4$, MPa | $N_{dr}$, MW |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 0.00 | 0.00 | 0.00 | 54.81 | 11.18 |
| 2 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 40.30 | 46.31 | 49.69 | 64.81 | 9.97 |
| 3 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 40.30 | 46.31 | 49.69 | 54.81 | 10.08 |
| 4 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 40.30 | 46.31 | 59.69 | 64.81 | 9.74 |
| 5 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 40.30 | 46.31 | 59.69 | 54.81 | 9.82 |
| 6 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 50.30 | 46.31 | 49.69 | 64.81 | 9.95 |
| 7 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 50.30 | 46.31 | 49.69 | 54.81 | 10.05 |
| 8 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 50.30 | 46.31 | 59.69 | 64.81 | 9.72 |
| 9 | 1.50 | 1.13 | 0.84 | 0.65 | 0.31 | 0.30 | 50.30 | 46.31 | 59.69 | 54.81 | 9.97 |
| 10 | 1.50 | 1.13 | 0.84 | 0.61 | 0.31 | 0.30 | 40.30 | 46.31 | 50.37 | 64.81 | 10.03 |
| 11 | 1.50 | 1.13 | 0.84 | 0.61 | 0.31 | 0.30 | 40.30 | 46.31 | 50.37 | 54.81 | 10.14 |
| 12 | 1.50 | 1.13 | 0.84 | 0.61 | 0.31 | 0.30 | 50.30 | 46.31 | 50.37 | 64.81 | 10.01 |
| 13 | 1.50 | 1.13 | 0.84 | 0.57 | 0.31 | 0.30 | 50.30 | 46.31 | 50.37 | 54.81 | 10.16 |
| 14 | 1.50 | 1.13 | 0.84 | 0.57 | 0.31 | 0.30 | 40.30 | 46.31 | 51.03 | 64.81 | 10.07 |
| 15 | 1.50 | 1.13 | 0.84 | 0.57 | 0.31 | 0.30 | 40.30 | 46.31 | 51.03 | 54.81 | 10.18 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 176 | 1.50 | 0.90 | 0.83 | 0.76 | 0.31 | 0.30 | 45.20 | 55.30 | 61.66 | 64.81 | 9.24 |
| 1962 | 1.50 | 0.82 | 0.76 | 0.69 | 0.31 | 0.30 | 46.60 | 57.20 | 61.17 | 0 | 10.02 |

Note: $h_0$ – the thickness of semi-rolled product, $h_1$...$h_5$ – the thickness of the strip at the exit of 1-5 stands accordingly, $\sigma_1$...$\sigma_4$ – specific tension at the exit from stands 1 to 4 accordingly.

For all the mode options created this way, the rolling forces and motor powers of the main drives were determined. To calculate the power parameters, a method was used that incorporates an elastic-plastic model of the deformation zone. The reliability of this mode is confirmed by publications [9].

Based on the study results of the obtained modes' parameters, we established the range of changes in the required motor powers of the main drives of the working stands for conducting the process on a rolling mill of a particular type. For a 1700 5-stand mill, when rolling a strip of 08ИС steel, 0.3 mm
thick and 1020 mm wide from a 1.5 mm semi-finished rolled product, this range was from 9.24 MW to 11.18 MW at a rolling speed of 12 m/s, i.e. the change in the parameter being optimized amounted to 17.3% of the minimum possible required power when changing the values of the technology factors.

Of all the combinations of parameters for each grade's group and profile assortment, one was selected that provided the minimum energy consumption for the process, taking into account limitations on the allowable rolling forces and motors power of the main drives. Such an optimal set of parameters is presented in Table 1 in a row number 176. When we were looking for an optimal set of parameters, the total amount of processed data for each brand and profile assortment was about 2000 units. The optimal rolling mode was tested by the criterion of vibration resistance at maximum rolling speeds of up to 20 m/s.

The algorithm, which was used in order to determine the least energy-consuming mode of strip production is shown in Figure 1.

Studies using the algorithm were performed both for the stationary mode and for the mode in which the fluctuation of the strip thickness along its length was taken into account.

3. The results and its discussion

Modeling of power parameters for the modes calculated using the algorithm shown in Figure 1 made it possible to determine the amount of energy consumption at the existing mill and the potential for reducing energy consumption using the methodology proposed in [1].

The results of the assessment of energy consumption for the continuous rolling process at the 5-stand mill 1700 are presented in Figure 2.

The diagrams in Figure 2 allow us to conclude that there is a potential possibility of reducing process energy consumption. The largest number of possible technological modes - is up to 30% - that will ensure the energy consumption in the range of 8.9-9.2 MW at a rolling speed of 12 m/s. At the same time, the diagram shows that it is possible to conduct a process with a total energy consumption of less than 8.5 MW at the same rolling speed. There are less than 5% of such modes in the amount of all possible ones. It is advisable to reduce the energy consumption to conduct the rolling process in accordance with the technology that provides this minimum level of energy consumption. It is established that the process with the specified energy consumption ranges at speeds of 12 m/s is possible without the occurrence of vibrations in the stands of a continuous mill.

The results of modeling the rolling modes produced on a significant amount of data made it possible to establish the influence of technology parameters on the level of energy consumption. Thus, the change in the total required power for conducting the rolling process at the 5-stand mill, depending on the local reductions in the stands and the specific tension is shown in Figure 3.

From the dependencies shown in Figure 3, it can be seen that the highest decrease in the total energy consumption is influenced by the values of the local reductions in the first and second-to-last stands, as well as the values of the interstand tensions. Moreover, the increase of reduction in the first and second-to-last stands and all the specific tensions reduce the level of process energy consumption.

These studies of technology parameters finally made it possible to establish the nature of their influence on the amount of energy consumption:
- a decrease in the total required power for the entire studied profile assortment is ensured by an increase in local reduction in the first stand, and this value has the most significant effect when rolling the thicker strips;
- the increase of specific tensions in all interstand gaps will have an additional impact on the decrease of required power when producing strips of all steel grades regardless of the work roll barrel diameter, the decrease of the total energy consumption with the increase of the specific tension in one of the interstand gaps on 10MPa may reach the value of 120 kW with the rolling speed up to 12 m/sec;
- unloading of the intermediate stands by the value of local reduction with the transition of the remaining reduction to the first and second-to-last stands ensures a reduction in the required total drive power of the working stands in the production of strips with a thickness of less than 0.5 mm;
Figure 1. Algorithm for determination of energy-efficient mode.

Initial data: the minimum allowable interstand tension of the strip and local reductions in all stands, except for the last and second-to-last stands, the step of changing the reductions and tension, the number of mill stands.

Calculation number \( i := 1 \), stand number \( k := 1 \)

Are rolling forces and powers in the stand \( k \) higher than allowed ones?

Calculation of power parameters in the stands, total required drive power of all stands.

Increase of the front tension in the stand \( k \) by the step value.

Is the front tension value higher than allowed in technical specification?

Reducing the specific tension value to the minimal allowed.

Increase of the reduction in the \( k \) stand by the step value.

The choice of the rolling mode option from the list of total \( i \) numbers, when working using the chosen mode the total power will be minimal, an assessment of the mode according to the criterion "vibration resistance".

The End.
Figure 2 – Distribution of total energy consumption when using all possible combinations of technology parameters for rolling a strip of 0.5 mm thick (08ПС steel) with a speed of 12 m/s.

- when the reduction of the strip with thickness more than 0.5 mm takes place at the second-to-last stand, the increase of the energy discharge can be observed, but when rolling thinner strips, the opposite – energy discharge reduces, while the reduction increases by 2%, the change of energy consumption may reach the value of 150 kW with the rolling speed of 12 m/sec.

The least energy-consuming rolling modes were also analyzed by the values of technological parameters, the results of this analysis for a 5-stand mill are presented in Figure 4 for finished strips with a thickness of 0.3 to 0.5 mm.

It was also established that the proposed algorithm and methodology will be most effective when designing the processing modes of the thinnest strips, as can be seen from the diagram in Figure 5.

According to the results of the study, it was determined that the diameter of the roll barrel and the steel grade of the strip will not affect the efficiency of the methodology.

As an example of using the created methodology in [1], presented is the rolling mode for a 5-stand continuous mill with a barrel diameter of the work roll in all stands equal to 600 mm, which ensures a reduction in the required power for the process by 3.5% compared with the current mode used on a 5-stand mill 1700.

It should be noted that due to thickness fluctuations along the length of the semi-finished rolled product, there are also fluctuations in the required drive power in the working stands. Thus, when changing the thickness of the strip in front of the first stand by 5% of the nominal value, the level of power fluctuations can increase up to 3-4% of its average value when the mill is working (for example, 1700 5-stand mill) using the existing technology.
Figure 3 – The influence of the specific tension in the last interstand gap on the total required drives' motors power of the continuous mill stands a) local reductions in the first b) and second-to-last c) stands.
Figure 4 – Ranges of the local reductions a) and specific tensions b) in work stands of the 5-stand mill 1700, providing minimal energy consumption when rolling
Figure 5 - The diagram that shows the influence of the thickness of the finished strip on the decrease of the required power of rolling process.

Figure 6 - The diagram that shows changes in the required power of the main drive motors of the stands (over time) when rolling a strip 0.5 mm thick made of 01ЮТ steel when operating a 5-stand mill 1700 according to existing technology (1) and developed using the newly proposed automated algorithm (2).
The experience of applying the newly proposed algorithm showed that energy-efficient modes provide a reduction in power fluctuations by 1-2%. A fragment of the diagram that shows changes in the momentary required power (over time) for the rolling process is shown in Figure 6.

The decrease in power fluctuations when using energy-efficient modes can be explained by the fact that at each moment of time, when the thickness of the semi-finished rolled product changes, the rolling technology will be most optimal from the point of view of energy consumption.

The results of computer-aided design of modes for a wide range of assortments made it possible to formulate general recommendations on the selection of technology parameters (see Table 2). It is worth noting that when implementing these recommendations, it is necessary to take into account the limitations of the working stands in terms of rolling forces and power, as well as the conditions for ensuring a stable rolling process.

| Table 2. Recommendations for choosing the parameters of the reduction and tension of the steel strip during continuous rolling. |
| Parameter | Value |
| --- | --- |
| Specific interstand tension | The maximum possible of the regulated values is 22% of the yield strength of the strip material. |
| Reduction in the first stand | Reduction, that provides the rolling force or the first stand main drive power loading for 65-75% of the maximal allowed values. |
| Reduction in second-to-last stand | Reduction, that provides the rolling force or the first stand main drive power loading for 65-75% of the maximal allowed values, when producing strips with the thickness less than 0.5 mm. |
| Reduction in the last stand | 4-8% when rolling in the 5-stand continuous mill, 8-12% when rolling in the 4-stand mill |
| Reductions in intermediate stands | Equal distribution of the remaining total reduction between the intermediate stands, according to the condition of equal rolling force distribution in these stands. |

Using algorithm for checking the technological mode for vibration resistance can improve the performance of a continuous mill during the process.

The results of the work can be used in automated control systems for the technological process of continuous mills when determining the modes of reduction and tension of the steel strip.

4. Conclusion
This work presents parameters’ calculation method for the continuous cold rolling technology of wide steel strips. The method is based on the definition of such reductions in every stand and interstand tensions, that will provide the running of the technological process with maximum performance and minimum energy consumption. The type of the steel strip reductions and tensions that affects the amount of energy consumption and operating is determined, as well as the effect of different steel profiles and grades, diameter of the work rolls barrels in the stands. A way for calculation of rolling parameters is suggested, that will provide the minimal level of the power being consumed by the main rolling stands drives’ motors with maximum performance of the continuous mill by means of excluding the vibrations in the work stands. The created method can be used in the continuous mills software.
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