# Optimization of setting process of continuous sheet rolling

**Volodymyr Egorov**

*DSc in engineering*
*National Metallurgical Academy of Ukraine*
*Dnipro, Ukraine*

**Olexandr Egorov**

*Ph.D. in Engineering Science*
*National Metallurgical Academy of Ukraine*
*Dnipro, Ukraine*

**Oleg Potap**

*Ph.D. in Engineering Science*
*National Metallurgical Academy of Ukraine*
*Dnipro, Ukraine*

**Olexandr Kryachko**

*Ph.D. in Engineering Science,*
*General Manager of the Research and Manufacturing Enterprise Dneprchermetavtomatika,*
*Dnipro, Ukraine*

**Volodymyr Kuvaev**

*D.Sc. in engineering,*
*National Mining University,*
*Dnipro, Ukraine*

**Mikhail Kuzmenko**

*Assistant Lecturer,*
*National Metallurgical Academy of Ukraine,*
*Dnipro, Ukraine*

Abstract
The analyzes of manufacturing technology and composition of the equipment influence on the main components of energy consumption was carried out in the article and proposals for reducing energy consumption for the production of sheet products while maintaining high performance and quality of sheet metal were developed.
Keywords: ROLLING, ENERGY CRITERION, DEFORMATION CENTER, ROLLING STAND, ROLLING FORCE

A significant part of energy resources of the Ukrainian metallurgy is consumed by rolling mills, and sheet-rolling shops are the most energy intensive. The sheets and strips from 1-1.2 to 12-16 mm thick and from 1850 to 2150 mm width are rolled at these mills. Before a significant rise in the cost of energy, improvement of equipment and technologies, the appearance of new rolling patterns, the automation of rolling mills has pursued mainly two tasks - higher productivity of rolling mills and improving of the product quality.

The main objective of this paper is to analyze the influence of manufacturing technology and configuration of the equipment on the main components of energy consumption and the development of proposals to reduce the energy consumption for the production of sheet products, while maintaining high performance and quality of sheet metal.

The energy in the production of sheet products is consumed for heating the workpiece, its reducing with stand rolls in order to give the necessary form to the finished sheet, and for the work of such production units as shears, conveyors, roll tables and more.

The largest share of electricity accounts for the main rolls drive of rolling stands and the value of the consumption of this energy depends on the set rolling modes.

The rolling stand rolls are a working tool, by which the energy of the rolling engine is transmitted to the deformation center and spent there on the strip shape change. Part of the rolling engine power is used to overcome resistance in the mechanical transmission of the rotation from engine to rolls. They are gearbox, gearing stand and spindles. The other part is consumed for the deformation of the metal in the deformation zone and for elastic deformation of the stand elements when capture of strip with rolls. A certain share of the energy is spent on elastic deformation of the strip section between adjacent stands during rolling with tension. There is a permanent self-regulation of equal energy expenditure and its income from the rolls when rolling. This is achieved due to the sensitivity of the critical (neutral) angle to the slightest disproportion between energies of expenditure and income.

From the above it follows that the rolling process can occur only when there is a backup supply of frictional forces in the deformation zone within the possible change in the neutral angle. Assuming that there is always a supply, it is possible to analyze the energy condition of the rolling process relying only on consideration of energy consumption to change the strip shape. The energy of the elastic strip tension between the stands is transmitted through the strip from one stand to another and is distinct item of expense regardless of the energy required for rolling products plastic deformation. Simplified graphical representation of the deformation process is shown in Fig. 1.1.

We proceed from the formula of Tselikov A. I. expressing the work of deformation (deformation energy), and then convert it to the symbols shown in Fig. 1.1.

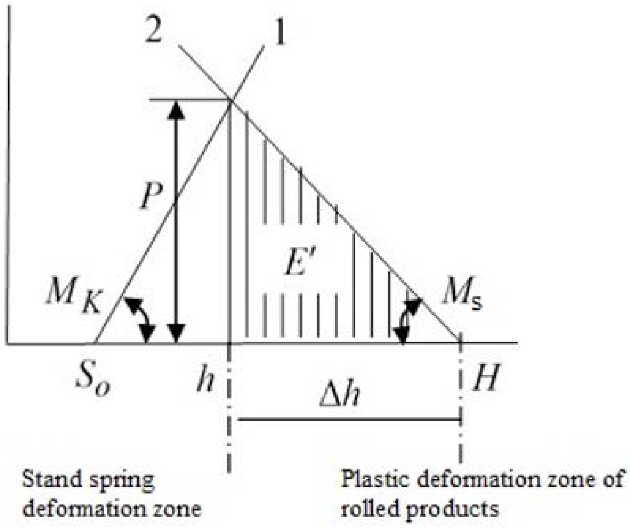


**Figure 1.1.** Dependence *P* of the rolling force from reduction Δ*h* in the stand

This formula has the following form:

$$E = p_{av}V\frac{\Delta h}{h}, \qquad (1.1)$$

where $P_{av}$ – average specific pressure is assumed as constant along the deformation zone, *V* – the volume of the strip, which appeared out of the stand after reduction Δ*h* with thickness *h*.

We transform this formula to the following form:

$$E = p_{av}Lb_{av}h\frac{\Delta h}{h} = \frac{P}{\sqrt{\Delta hRb_{av}}}\vartheta Tb_{av}\Delta h = M_s\Delta h\frac{T}{\tau_d}\Delta h = M_s\Delta h^2\frac{T}{\tau_d}, \qquad (1.2)$$

where *L* – length of the rolled strip behind the stand; $b_{av}$ – average width of the strip; P – rolling force; $\sqrt{\Delta hRb_{av}}$ – contact area; $\vartheta$ – rolling speed; T – time of rolling the strip with length L; $\tau_d$ – time of moving through the deformation center of the elementary strip area is the same as during the rolling out of the same volume of metal, which is directly in the deformation center; $M_s$ – rigidity of the strip in Fig. 1.1 is a constant.

Of course, energy for rolling is determined by the sum of energies in each stand while rolling the strips in the several stands. In turn, rolling energy in each stand depends on the strip reduction value. After determining a minimum of this dependence we obtain the required values of reductions in the stands when rolling with an energy minimum.

We define the concept of "Stand setting before rolling" for further calculations. In [1] about the problem states that the setting task is to find and use of such settings parameters of the rolling process and equipment, which commissioned in the stand before rolling will provide the high quality of its course against the backdrop of controlled and uncontrolled technological disturbances that may vary in certain range. The settings include the following: roll gaps, rolling speed in the stand, forces of forced roll gaps, etc.

It is obvious that the energy *E* characterizes the total energy that is spent for rolling with two working rolls. Therefore, common laws between the parameters remain, if we analyze the energy consumption *E'* only on the one roll. Then:

$$E' = \frac{1}{2}M_s\Delta h^2\frac{T}{\tau_d} = \frac{1}{2}M_s(H-h)^2\frac{T}{\tau_d}, \qquad (1.3)$$

Let us discuss the obtained results. The factor $M_c(H-h)^2$ can be regarded as the specific plastic energy that corresponds to the strip volume in the roll gap, i.e. the energy per unit volume of the rolled products. The value of this energy is equivalent to the shaded area of a triangle (Fig. 1.1). The total energy spent on plastic deformation of the strip with length $L_1$ is as many times more than in specific, how much $T$ longer than $\tau_d$, if making a decomposition of the total energy on the minimum resolutions.

With taking into account formula (1.3) we analyze the energy consumption during rolling the strip in several stands, for example, in three. We write down the amount of energy:

$$E'_{1-3} = E'_1 + E'_2 + E'_3 = \frac{1}{2}\left\{\begin{matrix}\frac{T}{\tau_{d,1}}\left[M_{s,1}(H-h_1)^2\right] + \frac{T}{\tau_{d,2}}\left[M_{s,2}(h_1-h_2)^2\right] + \\ +\frac{T}{\tau_{d,3}}\left[M_{s,3}(h_2-h_3)^2\right]\end{matrix}\right\} = \tag{1.4}$$
$$= \frac{1}{2}\left\{m_1\left[M_{s,1}(H-h_1)^2\right] + m_2\left[M_{s,2}(h_1-h_2)^2\right] + m_3\left[M_{s,3}(h_2-h_3)^2\right]\right\},$$

where $m_i = \frac{T}{\tau_{d,i}}$ – number of minimum resolutions in $i$-th stand when rolling the strip of finite length during the machine time of rolling, which in continuous rolling is the same for all stands. We investigate the expression on the extremum. Let us write that $m_1 < m_2 < m_3$, as the number of minimum resolutions increases for each successive stand. If we pass to the partial derivatives $\frac{dE'_{1\div k}}{dh_i}$, that it is necessary for finding the energy extremum, the presence in corresponding equations of $m_i$ coefficients that are unknown beforehand "litter" the result. Thus it is necessary to apply the artificial method for removing the effects of $m_i$. Let us consider one of them. Assume that in this arbitrary example $m_1 = 100$, $m_2 = 200$, $m_3 = 300$. These figures mean that during time $T$ through the first stand will pass 100 minimum resolutions, through the second – 200, and through the third – 300. Let us find the first condition under which $\frac{dE'_{1\div 3}}{dh_i} = 0$ in the case when all three stands rolling out the same number of minimum resolutions equals 100. Then we find condition $\frac{dE'_{2\div 3}}{dh_i} = 0$, when only in the second and third stands 100 minimum resolutions are rolling out. If the conditions of extremum in the first and second cases are the same, then it will show that the study of the expression (1.4) on the extremum can be carried out without taking into account the values of $m_i$ coefficients.

Based on the expression (1.4), under condition that $m_1 = m_2 = m_3 = \text{const}$ we can write:

$$\frac{dE'_{1-3}}{dh_1} = M_{s1}H + M_{s1}h_1 + M_{s2}h_1 - M_{s2}h_2 = 0,$$
$$\frac{dE'_{1-3}}{dh_2} = -M_{s2}h_1 + M_{s2}h_2 + M_{s3}h_2 - M_{s3}h_3 = 0, \tag{1.5}$$
$$\frac{dE'_{1-3}}{dh_3} = -M_{s3}h_3 = 0.$$

Having considered the first two equations of this system and solving them for the unknown values of the initial $h_1$ and $h_2$ we obtain:

$$h_1 = \frac{M_{S1}M_{S2}H + M_{S1}M_{S3}H + M_{S2}M_{S3}h_3}{M_{S1}M_{S2} + M_{S1}M_{S3} + M_{S2}M_{S3}}, \tag{1.6}$$

$$h_2 = \frac{M_{S1}M_{S2}H + M_{S1}M_{S3}h_3 + M_{S2}M_{S3}h_3}{M_{S1}M_{S2} + M_{S1}M_{S3} + M_{S2}M_{S3}}. \tag{1.7}$$

In order to analyze the rolling conditions in the last two stands ($m_2 = m_3 = \text{const}$) it is necessary to consider together only the last two equations of the system (1.5):

$$h'_2 = \frac{M_{S2}h_1 + M_{S3}h_3}{M_{S2} + M_{S3}}.$$

Now, if in the expression for $h'_2$ substitute the value $h_1$ from (1.6), we find that $h_2 = h'_2$, where $h_2$ is defined by the formula (1.7). It follows that the search of conditions for an extremum of functions like (1.3) can be carried out without taking into account the values $m_i$, that greatly simplifies the calculations. From a physical point of view it means that the conditions of energy extremum can be found by analyzing the energy consumption on changing the form of metal portions amount per unit located within each of the deformation centers of stands irrespective to the strip of one or another length on the mill.

From the mathematical analysis it is known that the function test of several variables on maximum or minimum results in the need to perform complicated mathematical expressions. In this case we can confine ourselves to test for an extremum function of only two variables. It is necessary to check whether the roots of equations (1.6), (1.7) of the system (1.5) are the extremum coordinates of function $E'_{1-3} = f(h_1, h_2)$, when $m_i = 1$. It is known from the theory that if $D > 0$ when $df''_{xy} > 0$, the function $f(x, y)$ has a minimum, and for $D$ with respect to our conditions the following expression is recommended:

$$D = \left(\frac{d^2 E_{1-3}}{dh_1^2}\right)\left(\frac{d^2 E_{1-3}}{dh_2^2}\right) - \left(\frac{d^2 E_{1-3}}{dh_1 dh_2}\right)^2 > 0.$$

Having prepared the necessary components:

$$\frac{d^2 E_{1-3}}{dh_1^2} = (M_{s1} + M_{s2}) > 0; \; \frac{d^2 E_{1-3}}{dh_1 dh_2} = -M_{s2}; \; \frac{d^2 E_{1-3}}{dh_2^2} = (M_{s2} + M_{s3}),$$

We write down:

$$D = (M_{s1} + M_{s2})(M_{s2} + M_{s3}) - (-M_{s2})^2 = M_{s1}M_{s2} + M_{s1}M_{s3} + M_{s2}M_{s3} > 0.$$

From this result follows that the energy consumption becomes minimal, if prestand mill is set so that the output strip thicknesses in the first and second stands are determined by formulas (1.6) and (1.7). In other words, the notation (1.4) acquires the value of the criterion, i.e. $E'_{1-k} \rightarrow \min$.

Table 1.1 summarizes the formulas in which the values of the optimal initial strips thicknesses are expressed as the ratio "numerator/denominator".

**Table 1.1**. Summary formulas

| Thickness | Number of mill stands | Numerator of values $h_i$ |
|---|---|---|
| 1 | 2 | 3 |
| $h_1$ | 2 | $M_{s1}H + M_{s2}h_2$ |
| | 3 | $(M_{s1}M_{s2} + M_{s1}M_{s3})H + M_{s2}M_{s3}h_3$ |
| | 4 | $(M_{s1}M_{s2}M_{s3} + M_{s1}M_{s2}M_{s4} + M_{s1}M_{s3}M_{s4})H + +M_{s2}M_{s3}M_{s4}h_4$ |
| | 5 | $(M_{s1}M_{s2}M_{s3}M_{s4} + M_{s1}M_{s2}M_{s3}M_{s5} + M_{s1}M_{s2}M_{s4}M_{s5} + +M_{s1}M_{s3}M_{s4}M_{s5})H + M_{s2}M_{s3}M_{s4}M_{s5}h_5$ |
| $h_2$ | 2 | $h_2$ |
| | 3 | $M_{s1}M_{s2}H + (M_{s1} + M_{s2})M_{s3}h_3$ |
| | 4 | $(M_{s1}M_{s2}M_{s3} + M_{s1}M_{s2}M_{s4})H + (M_{s1}M_{s3}M_{s4} + +M_{s2}M_{s3}M_{s4})h_4$ |
| | 5 | $(M_{s1}M_{s2}M_{s3}M_{s4} + M_{s1}M_{s2}M_{s3}M_{s5} + M_{s1}M_{s2}M_{s4}M_{s5}) \cdot \cdot H + (M_{s1} + M_{s2})M_{s3}M_{s4}M_{s5}h_5$ |
| $h_3$ | 2 | |
| | 3 | $h_3$ |
| | 4 | $M_{s1}M_{s2}M_{s3}H + (M_{s1}M_{s2} + M_{s1}M_{s3} + M_{s2}M_{s3})M_{s4}h_4$ |
| | 5 | $(M_{s1}M_{s2}M_{s3}M_{s4} + M_{s1}M_{s2}M_{s3}M_{s5})H + (M_{s1}M_{s2} + +M_{s1}M_{s3} + M_{s2}M_{s3})M_{s4}M_{s5}h_5$ |
| $h_4$ | 2 | |
| | 3 | |
| | 4 | $h_4$ |

| | | |
|---|---|---|
| | 5 | $M_{s1}M_{s2}M_{s3}M_{s4}H+(M_{s1}M_{s2}M_{s3}+M_{s1}M_{s2}M_{s4}+$ $+M_{s1}M_{s3}M_{s4}+M_{s2}M_{s3}M_{s4})M_{s5}h_5$ |
| Denominator of values $h_i$ | | |
| | 2 | $M_{s1}+M_{s2}$ |
| | 3 | $M_{s1}M_{s2}+M_{s1}M_{s3}+M_{s2}M_{s3}$ |
| | 4 | $M_{s1}M_{s2}M_{s3}+M_{s1}M_{s2}M_{s4}+M_{s1}M_{s3}M_{s4}+M_{s2}M_{s3}M_{s4}$ |
| | 5 | $M_{s1}M_{s2}M_{s3}M_{s4}+M_{s1}M_{s2}M_{s3}M_{s5}+M_{s1}M_{s2}M_{s4}M_{s5}+$ $+M_{s1}M_{s3}M_{s4}M_{s5}+M_{s2}M_{s3}M_{s4}M_{s5}$ |

From table 1.1 follows that, for example, the thickness of the strips in three stand mill at semifinished rolled products thickness $H$ should be following:

$$h_2=\frac{M_{s1}M_{s2}H+(M_{s1}+M_{s2})M_{s3}h_3}{M_{s1}M_{s2}+M_{s1}M_{s3}+M_{s2}M_{s3}},$$

and the thickness of the strip at the last stand is equal to the given thickness $h_3$.

Analysis of the table provides another method for finding the initial thicknesses by reduction of the strip. It is enough to find thickness of the strip after the first stand, and then use the formulas:

$$\Delta h_i=\frac{M_{s1}}{M_{si}}\Delta h_1,\ \Delta h_2=\frac{M_{s1}}{M_{s2}}\Delta h_1 \text{ etc,}$$

where $\Delta h_1=H-h_1$.

From these formulas, for example, from equation

$$\Delta h_4=\frac{M_{s3}}{M_{s4}}\Delta h_3=\frac{M_{s1}}{M_{s4}}\Delta h_1$$

follows that the rolling force in the stands is $P_1=P_2=\cdots P_i$. This is an important practical conclusion, which shows that while respecting the energy criterion the rolling forces at all stands should be equal to each other.

This conclusion allows creating algorithms for the automated calculation of the setting rolling strips mode with minimal power consumption.

**Conclusion**

The analysis of technology and composition influence of the equipment on the main components of energy expenditure was carried out. The analysis of the question of sheet mill setting before rolling was performed and specific energy criterion for strips rolling was determined. It was established that the while respecting of the energy criterion, the rolling force at all stands should be equal to each other.

**References**

1. Tselikov A. I. *Teoriya rascheta usiliy v prokatnyih stanah* [The calculation theory of forces in rolling mills], Moscow, Metallurgy, 1963, 494 p.