UDC 621.7

Mathematical Simulation of Kinematic and Energy-Power Parameters for the Continuous Rolling Process of Seamless Pipes

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Simulation of the kinematic and energy-power parameters for the continuous plug rolling of pipes is described. Mathematical relations and algorithm based on joint basis of the energy equations and static ones (energy-static method) for calculating power rate and speed mode at a given level of inter-stand tension are shown.

Keywords: SPEED MODE; ENERGY-POWER PARAMETERS; INTERSTAND TENSION; CONTINUOUS ROLLING MILL

Introduction

The main processes of continuous rolling of seamless pipes are plugging operation in the lines of continuous mill and plugless tube reducing in sinking-sizing or stretch reducing mills. These processes are the most productive and, therefore, recently their use is increasing in the manufacture of pipe assortment. First of all these are pipes for the exploration and settlement of wells.

Originally, during plugging in the continuous mills a long floating plug was used. However, the pipe length and the outer diameter were limited, what reduced the efficiency of the continuous rolling. Therefore, in recent years the processes of continuous rolling with retained mandrel are used, thus increasing the outer diameter of the pipe to 426 mm with the same length, or increase pipe length with a smaller diameter.

During continuous rolling of pipes on a floating plug as a rule stands with two-high grooves are used. However, in the mills with retained mandrel stands with three-high grooves have been bought into use in recent years. These, above all, are PQF mills of the SMS Meer production and FQM mills of Danieli production. Stand with three-high grooves in stretch reducing mills were first used much earlier.

Since the processes of rolling in multiroll grooves and with retained mandrel appeared relatively recently, issues of their mathematical modeling are relevant. The objective of this research is to create a mathematical model of continuous rolling mill, namely, development of the algorithm for calculating energy-power parameters of continuous processes of pipe rolling.

Results and Discussion

The experience of studying the processes of continuous rolling [1] showed that an effective way of mathematical description is the energy method. If this energy equation is supplemented by the equations of equilibrium, the modeling capabilities become even more versatile.

The basis of a mathematical model of continuous rolling mill is the algorithm formulated as a result of the ideas presented in paper [2]. Its essence is as follows.

1. The given initial data are the geometrical parameters and properties of the shell, geometrical parameters of the produced pipe, geometric dimensions of the rolls and the mandrel, the mandrel velocity, values of the friction coefficient at the contact with the rollers and the mandrel, longitudinal stresses in the pipe in the interstand intervals.

2. At a given level of longitudinal stresses power balance equations are solved in the deformation zone of each mill stand and the angular coordinate of the contact point lying in the top of the groove is determined, where the speed of the roller and pipe are equal (neutral angle γ). In general, the power balance equation for a single stand has the form:

$$N_f + N_s + N_{fr} + N_{fm} - N_r \pm N_m + N_0 - N_1 = 0, (1)$$

where N_f - power of form changing under deformation; N_s - shear power on the surface of the entrance to the deformation zone; N_{fr} - slipping friction power at the contact surface of the pipe with rollers; N_{fm} - slipping friction power at the contact surface of the pipe with the mandrel; N_r - power supplied by rollers in the deformation zone; N_m - power supplied (taken away) by the mandrel in the deformation zone; N_0 - back tension power; N_1 - front tension power.

3. The speed of the rollers rotation v^* is set by one of the stands (preferably the first or last), which determines overall speed level of the rolling process.

4. Using the known speed of the rollers rotation in one of the stands and the known value of the neutral angle on top of the groove we determine the speed of the pipe entering into the stand (if this is the first stand of the mill) or the outlet speed of the pipe from the stand (if it is the last stand of the mill).

5. With the known speed of the pipe at any of the sections of the continuous mill and the known lengthening coefficients λ according to the stands we determine pipe speed in all areas of the continuous mill.

6. From the known speed of entering or outlet of the pipe in the deformation zone and the known value of the neutral angle on the top of the groove we determine rotational speed of the rollers in the considered stand.

For illustration purposes, a flow chart is shown in **Figure 1**. The algorithm **in Figure 1** corresponds to the case when the rotational speed of the rollers of the first stand is set.

Thus, the outlined above algorithm allows determining the speed mode of continuous rolling mill, which provides a given mode of tensions. Similarly, the problem of determination the speed mode of the reducing mill is solved. The main difference in this case is that the power supplied to the deformation zone from the mandrel and slipping friction power at the contact surface of the pipe with a mandrel are equal to zero.

For automation the calculation by the presented algorithm a software product in the algorithmic language C++ was developed. As an example, **Figure 2** shows the results of calculation speed modes of the 8-stand continuous mill for three different modes of interstand tensions (influence of the level of tension on the lengthening coefficient. of the pipe is not yet included).

With the help of the developed software product the inverse problem - determining the level of interstand tensions occurring at a given speed mode - can be solved.

In order to assess the validity of the developed mathematical model were calculated high-speed modes of continuous rolling mill TMK-IPSCO, established in Ambridge (USA). The comparison results are shown in **Figure 3**.

In order to determine power parameters on the contact surfaces of the pipe metal and technological tools the power balance conditions applied to the entire deformation zone can be used.

Since during the pipe plugging shape of longitudinal section of the deformation zone is asymmetric in the vertical direction, it is necessary to consider the equilibrium equations of the projections of forces on the longitudinal axis (x-axis) and the equilibrium equations of the projections of forces on the vertical axis (y-axis). The system of equations of equilibrium in this case takes the form

$$\begin{cases} T_0 - n\left[\left(F_{r0} - F_{r1}\right)\cos\dfrac{\alpha_0}{2} - P_x\right] - T_1 + F_{fm} = 0; \\ \left(F_{r1} - F_{r0}\right)\sin\dfrac{\alpha_0}{2} - P_x ctg\dfrac{\alpha_0}{2} + P_{fm} = 0, \end{cases} \quad (2)$$

where T_0 - back tension force; n - number of rolls forming a groove; F_{r0} - frictional force in the area of backward creep the contact surface of the pipe and the roller; F_{r1} - frictional force in the area of forward creep the contact surface of the strip and the roller; α_0 - entering angle; P_x - longitudinal component of the force vector of rolling; T_1 - front tension force; F_{fm} - frictional force at the contact surface of the pipe with the mandrel; P_{fm} - normal force affecting the mandrel by a single roller.

In modern continuous pipe rolling mills high-performance lubricant compositions are used for lubricating mandrels and the inner surface of the shells is covered with deoxidizing mixtures.

Because of this across the contact pipes and mandrels friction mode is realized close to the liquid one. If we assume that the conditions of friction across the contact of the pipe and the mandrel are described by Newton's law [4], than from the first equation of equilibrium equations system of deformation zone (2) it follows

$$P_x = \left\{ \frac{\pi}{nS_c} \left[S_1\sigma_1\left(d_1 - s_1\right) - S_0\sigma_0\left(d_0 - s_0\right) \right] + f\sigma_{sc} \frac{S_{c0} - S_{c1}}{S_c} ctg\frac{\alpha_0}{2} - \mu \frac{\Delta v_m}{t\sin\frac{\alpha_0}{2}} \frac{S_{cm}}{S_c} \right\}, \quad (3)$$

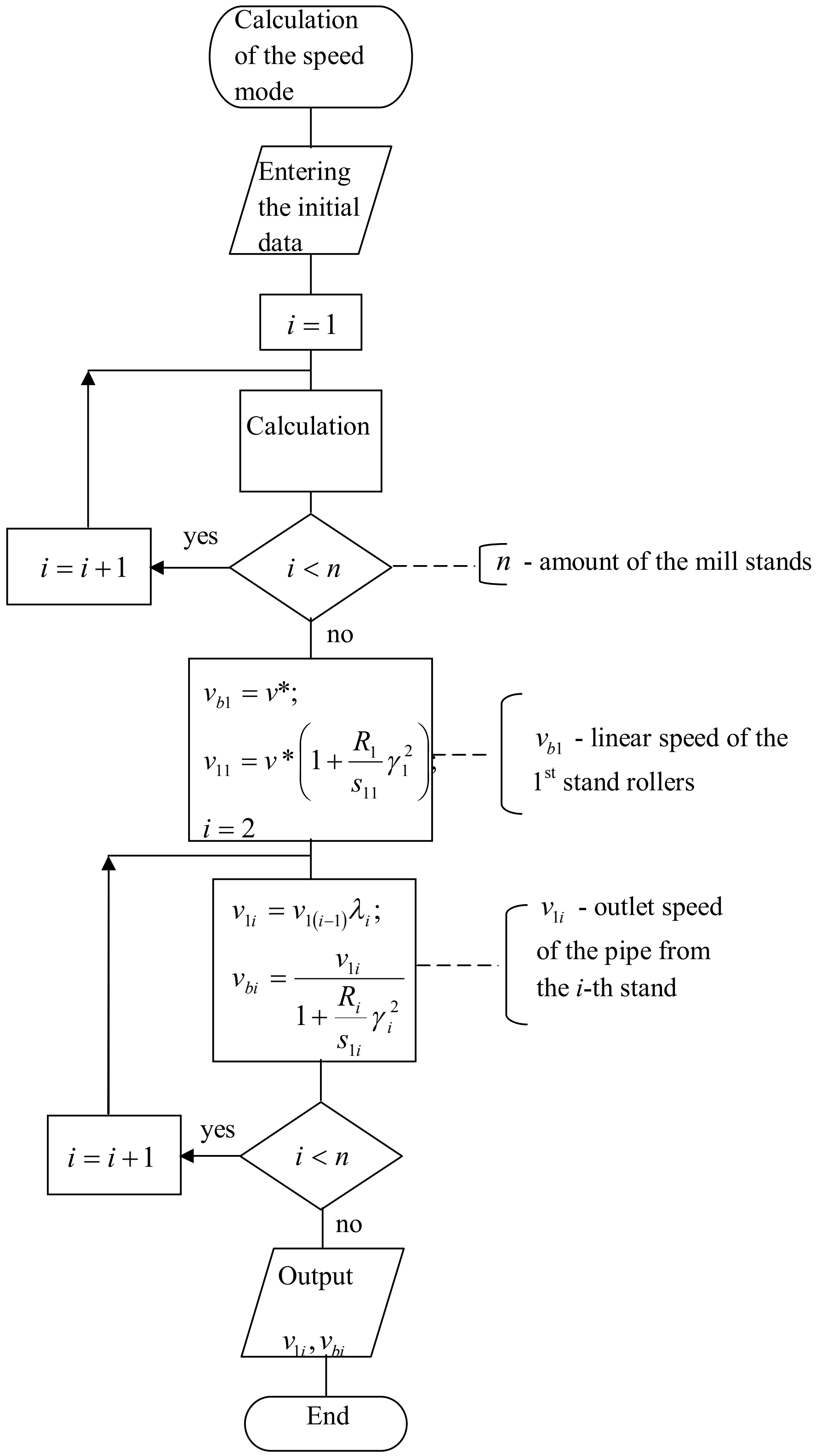

Figure 1. The flow chart of the algorithm for calculating speed mode of the continuous mill

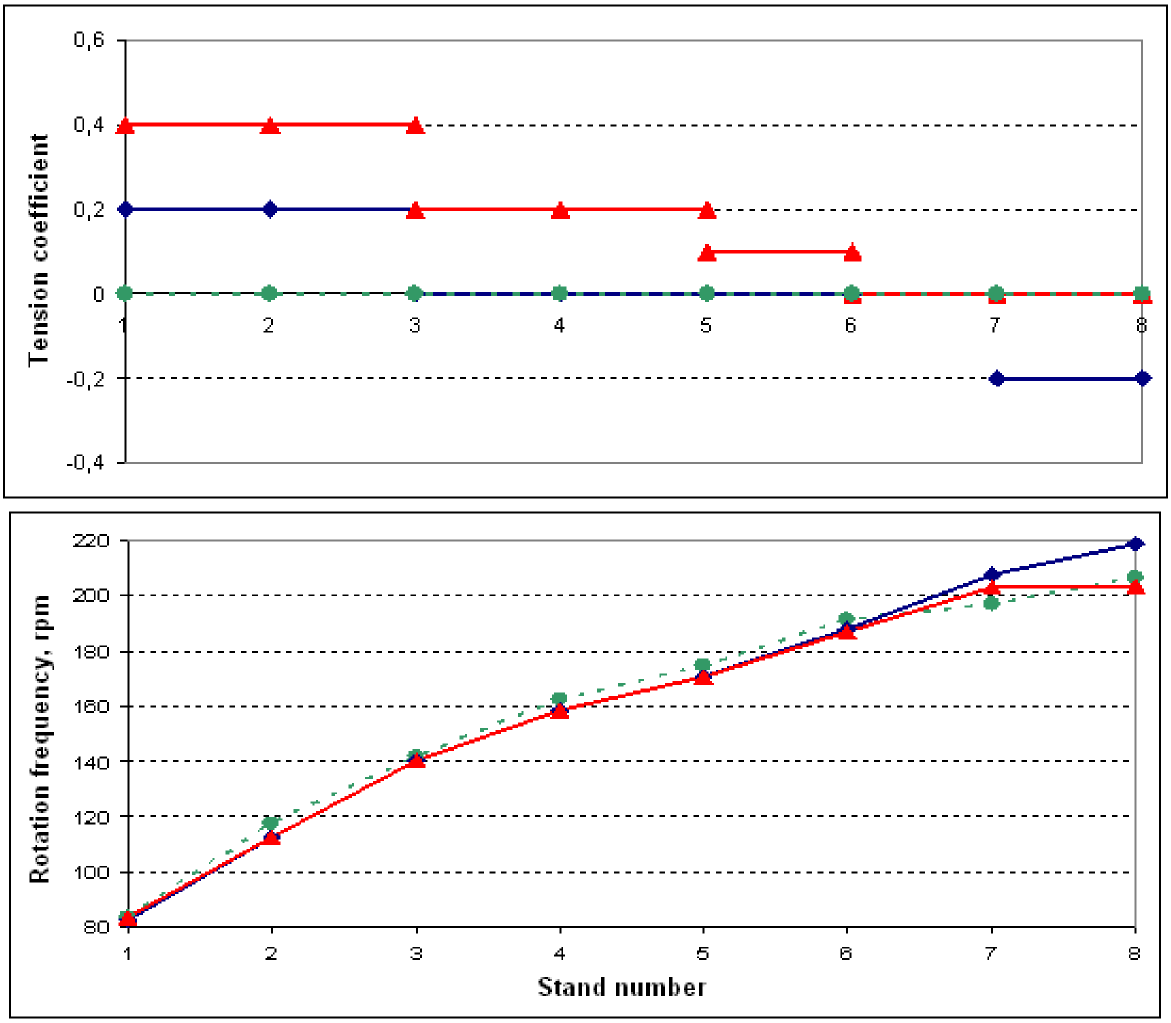

Figure 2. Influence of tension mode on the speed rate of the rolling mill

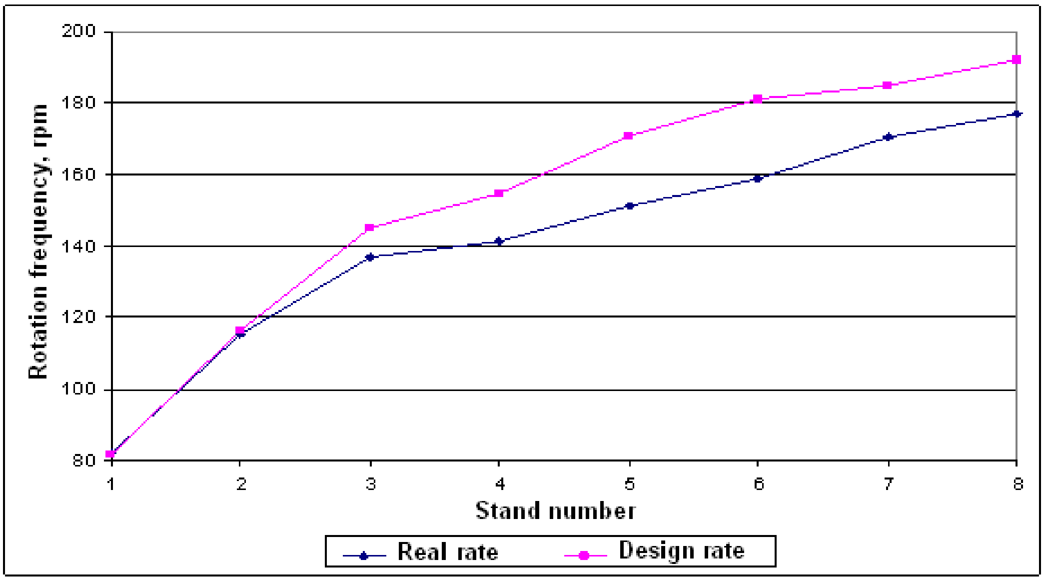

Figure 3. Comparison of the design and real speed rates

where S_c - area of the contact surface of the pipe and the roller; S_1, S_0 - cross sectional area of the pipe, respectively, during its outlet from deformation zone and entering into it; S_{c0} - area of backward creep the contact surface of the pipe and the roller;

S_{c1} - area of forward creep the contact surface of the pipe and the roller; S_{cm} - area of the contact surface of the pipe and the mandrel; d_0 - outside diameter of the pipe at the entering into the deformation zone; s_0 - pipe wall thickness at the entering into the deformation zone; d_1 - outside diameter of the pipe at the outlet from the deformation zone; s_1 - pipe wall thickness at the outlet from the deformation zone; σ_0 - back strain tension; σ_1 - forward strain tension; σ_{sc} - averaged according to the volume of deformation zone by the resistance of the metal to plastic deformation; f - friction coefficient on the contact surface of the pipe with the roller; μ - viscosity coefficient of the lubricant applied to the mandrel; Δv_m - sliding velocity of the pipe on the surface of the mandrel; t - thickness of the lubricant layer between the pipe and the mandrel.

In paper [3] it is shown that for the case of metal rolling in grooves of a simple form knowing the longitudinal component of the force vector of rolling we can determine the average pressure p_r at the contact surface of the pipe and the roller according to the formula

$$p_r = \frac{P_x}{S_c}\sqrt{1+\left[\left(\frac{\partial z_c}{\partial y}\right)^2+1\right]ctg^2\frac{\alpha_0}{2}}, \quad (4)$$

where z_c - function describing the groove form.

With the known value of p_r from the second equation of equilibrium equations system of the deformation zone (2) value of p_m the average pressure on the mandrel can be determined by the formula

$$p_m = p_в\frac{S_c}{S_{cm}}\cos\frac{\alpha_0}{2}+f\sigma_{sc}\left(\frac{S_{c0}-S_{c1}}{S_{cm}}\right)\sin\frac{\alpha_0}{2}. \quad (5)$$

The obtained formulae can also be used to determine the average pressure of metal on the rolls during tube reduction. For this purpose in the formula (3) $\mu = 0$ should be taken and if the change in wall thickness during reduction is not taken into account, $s_1 = s_0$. Given the change in wall thickness then s_1 can be determined by one of the known formulae [5].

Conclusions

Through the complex use of power equations and equations of statics (energy-static method) mathematical dependences were obtained and an algorithm for calculating the energy-power parameters of continuous processes of pipe rolling at a given level of interstand tensions was developed.

The issue of setting the value of interstand tension is a separate problem and depends on the chosen quality criterion of continuous rolling process - providing maximum productivity of the mill, obtaining maximum precision of wall thickness, maximum reduction of energy costs, and other criteria. That is, a science-based tension mode selection in the continuous rolling mill fundamentally involves solving an optimization problem.

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* Published in Russian

Received October 3, 2011

Математическое моделирование кинематических и энерго-силовых параметров процессов непрерывной прокатки бесшовных труб

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В статье изложены методики моделирования кинематических и энергосиловых параметров процесса непрерывной прокатки труб на оправке. Приведены математические зависимости и алгоритм расчета, позволяющие на основе энергетических уравнений и уравнений статики (энерго-статический метод) провести расчет энергосиловых параметров непрерывных процессов прокатки труб при заданном уровне межклетевых натяжений.