DOI: 10.17580/cisisr.2020.01.07

DETERMINATION OF RATIONAL FRICTION TEMPERATURE IN LENGTHWISE ROLLING

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Key words:
rolling, rolls, strip, seizing area, contact temperature, deformation, rolling intensity.

ABSTRACT

The paper presents the study of the process of lengthwise rolling. This process is characterized by elastic-plastic deformation, slipping friction, seizing friction, rest friction arising in the contact area between rolls and strip. The rolling process during the contact between rolls and strip is described, as well as rolling forces causing elastic deformation of metal products. The work of elastic-plastic deformation and friction is the cause of contact heat forming during lengthwise metal rolling. The contact temperature can vary depending on its value from room level (at low energy values and small deformation rates) to high temperature (at high energy values and large deformation rates). Friction during plastic deformation is described by complicated relationship, and it varies from classic friction with its dependence on l/h during rolling and upsetting. If l/h relationship is less than 0.5, seizing area spreads along whole length of curve seizing and tangential friction forces don't reach the maximal values. If l/h relationship is 0.5–2.0, seizing areas spreads along whole length, while tangential forces reach maximal values in the entrance and exit of a roll area. It is necessary to differ average contact temperature, volumetric and temperature burst owing to discreteness of a contact area. The formulas for temperature calculation in friction conditions, depending on technical conditions, thermal, physical and mechanical properties of materials and contact geometry for parabolic case of variation of friction intensity by time, are concluded in the paper based on solution of Fourier parabolic equation of heat conductivity. The formula for calculation of the contact temperature between a roll and rolled strip is concluded. Recommendations for use of the formulas are given. If we know the optimal and experimentally found rolling temperature (it is individual for each metal), we can solve the backward task, i.e. determine the rolling procedures via presented formulas.

Introduction

The process of lengthwise rolling is characterized by elastic-plastic deformation, slipping friction, seizing friction, rest friction arising in the contact area between rolls and strip. During deformation process the rolls are subjected to deformation resistance from metal named as rolling force. The rolling stand is an elastic system, so rolling force originates elastic deformation of its components and, consequently, increases of initially preset roll gap [1–4].

The following forces are acting from each roll in the contact plane with rotating rolls: reaction force F (oriented in radial direction) and friction force T (oriented perpendicular to radial direction). Correlation between horizontal projections of the a.m. forces from both rolls determines of bite possibility [5, 6].

Friction during plastic deformation is described by complicated relationship, and it varies from classic friction with its dependence on l/h during rolling and upsetting. If l/h relationship is less than 0.5, seizing area spreads along whole length of curve seizing and tangential friction forces don't reach the maximal values. If l/h relationship is 0.5–2.0, seizing areas spreads along whole length, while tangential forces reach maximal values in the entrance and exit of a roll area. If l/h relationship is 2.0–5.0, slipping is observed in the beginning and in the end of bite curve, and this slipping is obeyed to dry friction $\tau = fp$ and dropping. And seizing area consists only of rest area. If l/h relationship is more than 5.0, three friction areas are observed on a bite curve: slipping, seizing and rest friction [7–12].

Materials and methods of investigation

Work of elastic-plastic deformation and friction is the source of contact heat forming during lengthwise metal rolling. The contact temperature can vary depending on its value from room level (at low energy values and small deformation rates) to high temperature (at high energy values and large deformation rates). It is necessary to differ average contact temperature, volumetric and temperature burst owing to discreteness of a contact area [13–21].

Generating temperature is considered as secondary relating to rolling and has multi-valued effect on friction coefficient (**Fig. 1**). Its maximal value can be observed at 700–800 °C.

Let's consider power balance of the process.

Total heat amount that is generating during rolling is determined via the following formula.

$$W = PfVt = Q. \tag{1}$$

On the other hand, this heat amount will heat during the contact (the process is considered to be adiabatic one) some volumes of rolls and rolled strip up to some definite temperature:

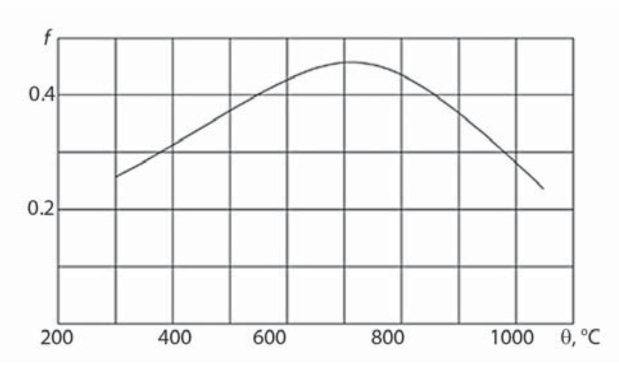

Fig. 1. Relationship between friction coefficient and temperature [3]

$$Q = Q_1 + Q_2 = C_1\rho_2 Ab_1\theta_1 + C_2\rho_2 Ab_2\theta_2, \quad (2)$$

where C_1, C_2 is specific heat conductivity of material (sample and roller); ρ_1, ρ_2 are densities of materials of contacting bodies; A is contact area; b_1, b_2 are efficient depths of heat impulse penetration; θ_1, $\theta_2$is average temperature of roll and rolled strip.

$$b_1 = 2\sqrt{a_1 t}\ , \quad (3)$$

where a is temperature conductivity, t is duration of roll and strip contact.

The researchers Charroha, Haseegrubera, Chichinadze and Ginzburg [8] displayed that contact generating heat is distributed among contacting bodies depending on their geometry and thermophysical properties. Additionally, depth of heat impulse penetration has maximal effect on distribution of heat flows in non-stationary processes. So, contact generating heat flow is proportional to deformation work, while coefficient of heat flows distribution should be proportional to distribution of deformation power values between contacting bodies.

The F. Sharron formula [9] can be used for determination of heat flows distribution coefficient in impulse processes (such as rolling), meaning short duration of the process:

$$\alpha = \frac{\sqrt{\lambda_2 C_2 \rho_2}}{\sqrt{\lambda_1 C_1 \rho_1} + \sqrt{\lambda_2 C_2 \rho_2}}, \quad (4)$$

where α is a part of heat transferred to the second element; λ is a material heat conductivity coefficient.

Based on (1) and taking into accout (2) and (3) and supposition about equality of temperatures in “roll – billet” contact, the contact temperature can be determined.

$$\theta = \frac{PfVt(1-\alpha)}{2A\sqrt{t}\left(C_1\rho_1\sqrt{a_1} + C_2\rho_2\sqrt{a_2}\right)}\ . \quad (5)$$

As soon as normal stress is equal to:

$$\sigma_n = P/A. \quad (6)$$

We insert equations (3) и (6) in (5), and get

$$\theta = \frac{\sigma Vf\sqrt{t}(1-\alpha)}{2\left(C_1\rho_1\sqrt{a_1} + C_2\rho_2\sqrt{a_2}\right)}\ . \quad (7)$$

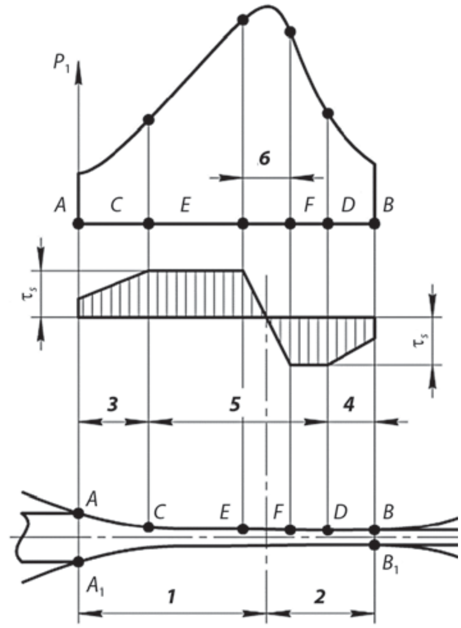

Fig. 2. Distribution of contact normal and tangential stresses along the bite curve at $l/h_{av} > 5$:
1 — backward slip zone; *2* — forward slip zone; *3* — backward slipping zone; *4* — forward slipping zone; *5* — banding zone in the areas CE, EF, FD; *6* — obstructed deformation zone in the area EF

Formula (7) is suitable for preliminary evaluation of the contact temperature, but it can’t determine the temperature in each time period on the surface and at some distance from the surface, what is very important in any cases. Intensity is characterized by deformation source in the most complete way, thereby we shall examine the most general case when rolling intensity is varying in time according to parabolic law at $l/h = 5{,}0$.

If the current pressure P varies along the contact curve according to parabolic law, it looks like the following sight (**Fig. 2**) and is described by the following equation:

$$P = P_0\left(\frac{t}{\Delta t} + \frac{t^2}{\Delta t^2}\right),$$

where speed along the rolling curve is considered to be constant (though it is different in forward and backward slip zones), i.e. $V = \text{const}$.

Specific rolling intensity in each contact time interval can be described as follows:

$$N_1 = P_0 Vf\left(\frac{t}{\Delta t} - \frac{t^2}{\Delta t^2}\right), \quad (8)$$

where P_0, V are maximal contact pressure and speed respectively; t is current time coordinate; Δt is time of roll contact along the billet curve.

Solving the task of heat forming and heat conductivity in rolling can be formalized in solving of the Fourier differential heat conductivity equation for linear heat flow.

$$\frac{\partial\theta}{\partial t} = a\frac{\partial^2\theta}{\partial x} \quad (9)$$

With initial condition:

$$\theta = 0 \text{ at } t = 0 \tag{10}$$

and boundary conditions:

$$-\lambda\frac{\partial\theta}{\partial X} = \frac{PfV\left(\frac{t}{\Delta t} - \frac{t^2}{\Delta t^2}\right)}{A} \tag{11}$$

$$\theta = 0 \text{ at } X = \infty. \tag{12}$$

Equation (9) was solved via the Laplace method of integral transformation.

$$\begin{aligned}\theta(x,t) = {} & \frac{(1-\alpha)PfV}{A\lambda\sqrt{\pi}}\left(\frac{t}{\Delta t} - \frac{t^2}{\Delta t^2}\right)\times \\ & \times\left[2\sqrt{at}\exp\left(-\frac{x^2}{4at}\right) - x\sqrt{\pi}erfc\left(-\frac{x}{2\sqrt{at}}\right)\right] - \\ & -\frac{1}{2a}\left(\frac{1}{2} - \frac{t}{\Delta t}\right)\times \\ & \times\left[\frac{\left(2\sqrt{at}\right)^3\exp\left(-\frac{x^2}{4at}\right) - 4x^2\exp\left(-\frac{x^2}{4at}\right)\sqrt{at}}{3} + \frac{2}{3}x^3\sqrt{\pi}erfc\frac{x}{2\sqrt{at}}\right] - \\ & -\frac{1}{80a^2\Delta t}\left[\begin{array}{l}(2\sqrt{at})^5\exp\left(-\frac{x^2}{4at}\right) - \\ -\frac{2}{3}x^2(2\sqrt{at})^3\exp\left(-\frac{x^2}{4at}\right) + \\ +\frac{4}{3}x^4 2\sqrt{at}\exp\left(-\frac{x^2}{4at}\right) - \\ -\frac{4}{3}x^5\sqrt{\pi}erfc\frac{x}{2\sqrt{at}}\end{array}\right]\end{aligned} \tag{13}$$

where P is pressure; V is speed; Δt is contact time; t is current time; x is coordinate ; a is temperature conductivity; $erfc(x/2\sqrt{at})$ is a special function; α is the coefficient of heat flows distribution; λ is heat conductivity; f is friction coefficient.

Formula (13) allows to provide calculation of the average temperature at the contact surface and volumetric temperature in each moment of rolling process and for the depth.

As soon as the row is quickly damping, we can't take into account the 2nd and consequent components due to their small amount. Based on this consideration, the expression (13) can be formulated as follows:

$$\theta(x,t) = \frac{(1-\alpha)PfV}{A\lambda\sqrt{\pi}}\left(\frac{t}{\Delta t} - \frac{t^2}{\Delta t^2}\right)\left[2\sqrt{at}\exp\left(-\frac{x^2}{4at}\right)\right]. \tag{14}$$

To calculate the average temperature we take $X = 0$ in the formula (14)

$$\theta(0,t) = \frac{2(1-\alpha)PVf\sqrt{at}}{\sqrt{\pi}A\lambda}\left(\frac{t}{\Delta t} - \frac{t^2}{\Delta t^2}\right). \tag{15}$$

In the formula (15) $\Delta t = L/V$, where L is curve length, V is rolling speed.

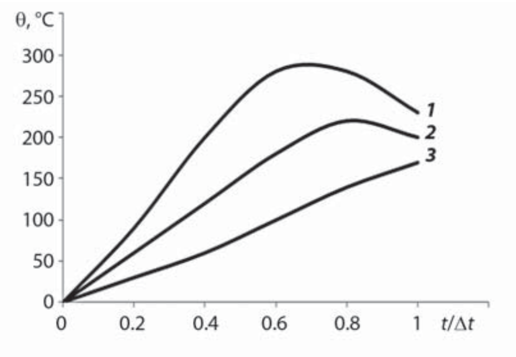

Fig. 3. Relationship between roll temperature during rolling and time of passing the deformation area:
1 — surface temperature; *2* — temperature at the depth 0.01 mm; *3* — temperature at the depth 0.1 mm

Calculations of the temperature conducted according to the formulas (14) and (15) displayed (**Fig. 3**) that the temperature on the roll surface rises to 300 °C. Its maximal value can be observed closer to exit from deformation area. If we examine the depth 0.1 mm from the contact surface, the maximal temperature value is reached only at the exit.

Conclusions

Thereby, based on solution of the Fourier parabolic heat conductivity equation, the formulas for temperature calculation in friction have been concluded depending on parameters of rolling conditions, thermal, physical and mechanical properties of material and contact geometry for parabolic case of friction intensity variation in time.

Calculation of the contact temperature between the roll and rolled strip can be done via the formula (15). If we know the optimal and experimentally revealed rolling temperature (it is individual for each metal), it is possible to solve the reverse task — to determine rolling conditions based on the above-mentioned formulas.

The program for checking the mathematical model should be developed and calculations based on this program should be done. Experimental investigations of rolling temperature should be conducted as well.

REFERENCES

1. Kolikov A. P., Romantsev B. A. Theory of metal forming: a manual. Moscow : Izdatelskiy dom MISiS. 2015. 451 p.
2. Belelyubskiy B. F., Gerasimova A. A., Khlamkova S. S. Machines and equipment for metal processing: a manual. Moscow : Izdatelskiy dom MISiS. 2019. 74 p.
3. Unksov E. P. Engineering theory of ductility. Moscow : Mashgiz. 1959. 328 p.
4. Gorbatyuk S. M., Sedykh L. V. Improving the durability of rolling-mill rolls. *Metallurgist*. 2010. Vol. 54. No. 5-6. pp. 299–301. DOI: 10.1007/s11015-010-9297-y.
5. Tyurin V. A., Mokhov A. I. Theory of metal forming: a manual for high schools. Volgograd : Volgogradskiy GTU. 2000. 416 p.

6. Albagachiev A. Yu., Mikheev A. V., Khasyanova D. Yu., Tananov M. A Tribological studies of lubricants. *Journal of Machinery Manufacture and Reliability*. 2018. Vol. 47. No. 5. pp. 464–468.
7. Albagachiev A. Yu., Keropyan A. M. Deformation processes within wheel-rail adhesion in contact area. *IOP Conference Series: Materials Science and Engineering. "International Conference on Mechanical Engineering, Automation and Control Systems 2017 — Processing Equipment, Mechanical Engineering Processes and Metals Treatment"*. 2018, 042048. DOI: 10.1088/1757-899X/327/4/042048.
8. Chichinadze A. V. Relationship between friction-wear and temperature parameters of loaded heteronymic and homonymic friction couples at stationary and non-stationary friction conditions. *Trenie i iznos*. 2000. Vol. 21. No. 2. pp. 158–167.
9. Gerasimova A. A., Radyuk A. G., Glukhov L. M. Applying coatings to the narrow walls of continuous-caster molds to improve the quality of the surface of slabs. *Metallurgist*. 2014. Vol. 58(5-6). pp. 397–400.
10. Keropyan A., Gorbatyuk S., Gerasimova A. Tribotechnical aspects of wheel-rail system Interaction. *Procedia Engineering*. 2017. Vol. 206, pp. 564–569. DOI: 10.1016/j.proeng.2017.10.517.
11. Holmberg K., Kivikyto-Reponen P., Harkisaari P., Valtonen K., Erdemir A. Global energy consumption due to friction and wear in the mining industry. *Tribology International*. 2017. No. 115. pp. 116–139.
12. Gerasimova A. A. Choosing the temperature conditions for the heavy plate rolling mill at Vyksa metallurgical works. *Vestnik BGTU im. V. G. Shukhova*. 2018. No. 10. pp. 126–131.
13. Keropyan A., Gerasimova A., Goloshapov K. Influence of the track gradient on the contact temperature at the wheel-rail zone for open-pit locomotives. *International Conference on Modern Trends in Manufacturing Technologies and Equipment (ICMTMTE 2017)*. MATEC Web of Conferences. 2017. 129. 06009.
14. Zakharov A. N., Gorbatyuk S. M., Borisevich V. G. Modernizing a press for making refractories. *Metallurgist*. 2008. Vol. 52. No. 7-8. pp. 420–423. DOI: 10.1007/s11015-008-9072-5.
15. Terentyev D. V., Ogarkov N. N., Platov S. I., Kozlov A. V. Effect of operating modes and contact surface oil absorption on lubricant film thickness in heavy-duty friction units of metallurgical plants. *Chernye metally*. 2018. No. 9. pp. 60–64.
16. Malikov A. A., Markova E. V., Fomicheva N. B., Chechuga J. V. Analysis of friction surfaces of structural steels after their hardening by methods based on electrical technologies. *Chernye metally*. 2019. No. 5. pp. 32–36.
17. Gee A. W.. Materials research and tribology. *T.N.O. news*. 1971. Vol. 6. No. 8. pp. 445–451.
18. Yongjian Yang, Yunfeng Shi. Single asperity friction in the wear regime. *Friction*. 2018. Vol. 6. No. 3. pp. 316–322.
19. Bast J., Gorbatyuk S. M., Kryukov I. Yu. Horizontal hcc-12000 unit for the continuous casting of semifinished products. *Metallurgist*. 2011. Vol. 55. No. 1-2. pp. 116–118. DOI: 10.1007/s11015-011-9399-1.
20. Gorbatyuk S. M., Pavlov S. M., Shapoval A. N. Experience in application of screw rolling mill for deforming the billets of refractory metals. *Metallurg*. 1998. No. 5. pp. 32–35.
21. Gerasimova A., Gorbatyuk S., Devyatiarova V. Application of gas-thermal coatings on low-alloyed steel surfaces. *Solid State Phenomena*. 2018. 284 SSP. pp. 1284–1290.