Conference Paper

Developing Effective Roll Cooling Systems Based on Computational Simulation

Yuri Lipunov[1], Sergey Shikhov[2], Evgeniy Kiselev[3], Konstantin Lipunov[1], and Valeria Kuznetsova[3]

[1]OJSC "Research Institute of Metallurgical Heat Engineering" (VNIIMT), Ekaterinburg, Russia
[2]JSC "KaturInvest," Ekaterinburg, Russia
[3]Ural Federal University (UrFU), Ekaterinburg, Russia

Abstract

In order to retrofit a roll cooling system at the JSC 'Katur Invest' rolling mill, computational simulation was carried out for a process of accelerated emulsion spray cooling the rolls heated during rolling. Initial and boundary conditions for the Fourier equation in the case of a body of infinite length and arbitrary cross-sectional shape were determined for the thermal state conditions of rolls in mill stands No. 1, 2, 5, 7. After model adaptation, a comparative analysis of the roll temperature field dynamics in different cooling conditions was made based on experimental data. The analysis revealed that extending the time of emulsion cooling, even without any further cooling process intensification, allows to significantly reduce both the maximum temperature level in a roll and its penetration depth, which results in required roll surface temperature reduction. Based on computational simulation, cooling parameters and conditions for the retrofitted cooling system are selected. Experimental data on roll surface temperature as measured before and after retrofitting the cooling system proved its effectiveness.

Keywords: rolling, rolls, accelerated cooling, temperature field, simulation

Corresponding Author:
Yuri Lipunov
vniimt1@yandex.ru

Received: 6 June 2018
Accepted: 15 June 2018
Published: 17 July 2018

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the TIM'2018 Conference Committee.

1. Introduction

During a process of rolling, the surface layer of rolling mill rolls is cyclically heated in areas of contact with a workpiece and cooled with emulsion on leaving the contact. In a single revolution a roll goes through a heating-cooling cycle. While continuously rolling the workpiece, temperature on the surface of the roll as well as at a certain depth below the surface is constantly rising [1, 2]. The interfacial temperature rise due to roll heating by workpiece rolling is a big problem. The rolls get worn out and change their shape quicker at increased interfacial temperatures [3]. Operational life of the rolls gets shorter. In 2008 OJSC 'VNIIMT' retrofitted roll cooling collectors in stand No. 3 at the JSC 'Katur Invest' copper wire rod rolling mill, which is the largest copper wire rod

How to cite this article: Yuri Lipunov, Sergey Shikhov, Evgeniy Kiselev, Konstantin Lipunov, and Valeria Kuznetsova , (2018), "Developing Effective Roll Cooling Systems Based on Computational Simulation" in *VII All- Russian Scientific and Practical Conference of Students, Graduate Students and Young Scientists on "Heat Engineering and Computer Science in Education, Science and Production"*, KnE Engineering, pages 177–184. DOI 10.18502/keg.v3i5.2667

producer in Russia. The retrofitting resulted in extending the lifetime of rolls in that mill stand from 26 000 t to 33 000 t. In 2017 retrofitting a roll cooling system in mill stands No. 1, 2, 7 was carried out under agreement with AO 'Katur Invest'. The cooling system retrofitting provides for an increase in the rate of heat extraction from the roll surface after it has been in contact with a workpiece due to installing a new cooling system, which increases the rate of heat exchange, and prolonging the emulsion cooling time as well. As a result, the roll surface temperature is expected to be 6–10°C less. In order to predict results of the cooling system retrofitting, numerical simulation of the roll heating and cooling processes during a rolling operation was carried out.

A cross-sectional temperature field in a roll was calculated using a program module developed by OAO 'VNIIMT' for solving a two-dimensional heat conduction problem under corresponding boundary and initial conditions. The computational module is based on solving the differential heat conduction equation for a two-dimensional problem

$$\rho \cdot c(t)\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(t)\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(t)\frac{\partial t}{\partial y}\right), \tag{1}$$

where t –temperature of a roll; $c(t)$, $\lambda(t)$ –specific heat and heat conductivity of a metal; ρ – density of a metal; x, y – coordinates in a cross-section of a roll; τ – time. The program module is intended for calculating dynamics of a temperature field in an arbitrarily shaped cross-section of an infinitely long body. It is known that, when rolling, a rise of temperature only penetrates outer layers of a roll, thus, it could be admitted that the roll is an infinitely long body. Hence, in case a cross-section profile of the roll is properly specified, the initial condition and conditions of heat transfer at the roll surface boundary are specified, numerical solution of equation (1) performed by the program module allows to calculate the dynamics of a temperature field in the cross-section of the roll.

Initial condition:

$$t(\tau_0) = t_{ini} = const. \tag{2}$$

Boundary conditions for emulsion spray cooling

$$\begin{cases} \lambda(t)\dfrac{\partial t}{\partial x}\mid_{x=0} = \begin{cases} q\ at \quad t_{sur} \geq 100^{\circ}C \\ \alpha\left(t_{sur} - t_{env}\right)\ at\ t_{sur} < 100^{\circ}C \end{cases} \\ \lambda(t)\dfrac{\partial t}{\partial C}\mid_{y=0} = \begin{cases} q\ at \quad t_{sur} \geq 100^{\circ}C \\ \alpha\left(t_{sur} - t_{env}\right)\ at\ t_{sur} < 100^{\circ}C \end{cases} \end{cases}, \tag{3}$$

where t_{sur}, t_{env} – temperature of the roll surface and the environment, respectively; $\alpha(t)$ –convective heat transfer coefficient depending on temperature of the roll surface, q –the rate of heat transfer removed from the roll surface.

The boundary conditions for cooling in air correspond to natural radiant and convective heat transfer.

During one heating-cooling cycle, that is, a single revolution of a roll, the boundary conditions are changing in time and over the roll surface. Figure 1 shows the cross section of the roll of stand No.1 and the scheme of partitioning its surface into zones for which the cooling conditions are different. The surfaces of the rolls of the other stands are zoned in the same way. The boundary conditions for different zones are given in Table 1.

Table 1: Boundary conditions at the roll surface.

Zone No.	Cycle stage			
	Heating when in contact with metal	Emulsion cooling	Air cooling during a process of rolling	Air cooling after rolling
1	Heat transfer when in contact with metal	Heat flux density	Convective heat transfer	Convective heat transfer
2	Convective heat transfer			
3	Zero heat transfer			

The initial roll temperature was taken to be equal to the coolant temperature. Mill stands are supplied with emulsion at a temperature of 47 ÷ 51°C for stands No. 1, 2 and 41 ÷ 45°C for stands No. 5, 7.It is known that, when a roll and a workpiece get in contact, their surface temperature may be considered, with a reasonable degree of accuracy, as identical and equal to the mean temperature of the roll and the workpiece before the contact [1]. The workpiece temperature decreases during a process of rolling. Since stands from No. 1 to No. 8 are covered with protective housings when the mill is running, the actual temperature of semi-finished rolled product at the entry and exit sides can only be measured at a few points. According to temperature gauging by 11.07.2017, the workpiece temperature at the entry side of stand No.1 was 918°C, between stands No. 4 and No. 5 it was 761°C, at the exit side of stand No. 8 it was 602°C. At a first approximation, the workpiece temperature was assumed to be 920°C at the entry side of stand No.1, 875°C at the entry side of stand No.2, 760°C at the entry side of stand No.5, 680°C at the entry side of stand No.7. The roll temperature after rolling was measured using a thermal imager (Figure 2).

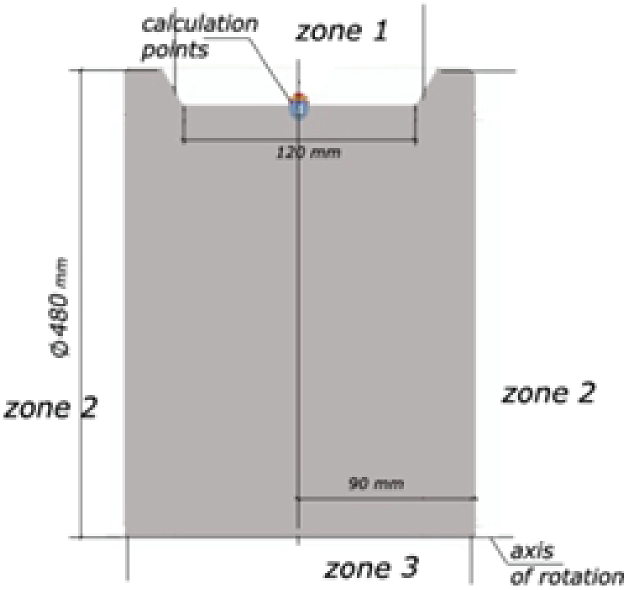


Figure 1: An example of the partitioning of the roll surface into zones with different boundary conditions (Stand No. 1).

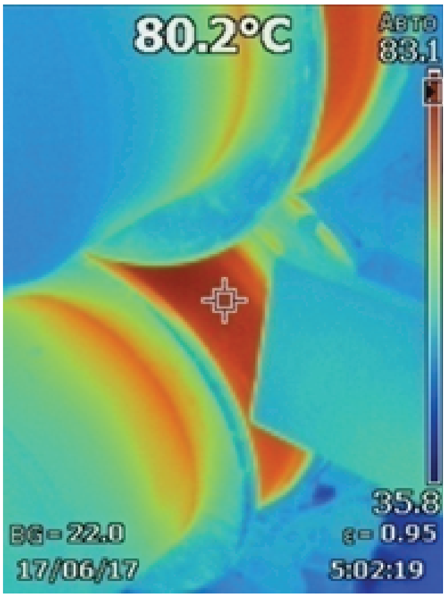


Figure 2: Example of measuring the temperature with a thermal imager. Stand No. 1, the lower roll.

Emulsion is sprayed onto the roll surface at high flow rate of 120 to 200 m^3/m^2h. Interpolation of the test data given in [4] and the experimental data obtained at the spray cooling of mill furniture provide reasons to assume that, when emulsion is cooling a roll, density of the heat flux removed from the roll surface falls in the range of 6.0–12.0 MW/m^2.

Rolls are made of steel 4X5MΦ1C or its analogs. When calculating, we used temperature dependences of specific heat capacity and heat conductivity known at present for steel P18 [R18], which is chemically similar to steel 4X5MΦ1C [5].

Computational simulation of dynamic changes in roll temperature during a process of rolling was carried out for:

- existing roll cooling systems and coolant properties involved in the mill stand operation;
- cooling systems under design provided with multi-version calculations. Cooling conditions were simulated for variable intensity cooling during a complete cycle as a whole (a single roll revolution) and variable rate of heat exchange (variable coolant flow rate) as well in different time and temperature intervals during a complete cycle.

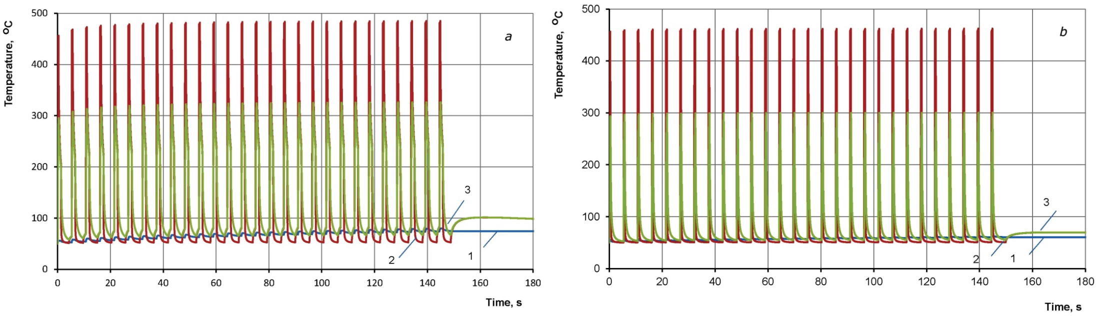
Time-related parameters of a heating-cooling cycle for rolls in the enumerated stands are presented in Table 2. In the retrofitted system, the cooling time was defined by a mill stand design and assigned to be as extended as possible.

Table 2: Stage duration for a single heating-cooling cycle.

Stand No.	Linear speed of rolling, [m/s]	Mean roll diameter, [mm]	Cycle stage duration, [s]						
			Contact with metal	Air	Emulsion	Air c	Contact with metal	Emulsion	Air c
			Before retrofitting				After retrofitting		
1	0.24	409	0.3539	0.9467	3.0081	1.0446	0.3539	4.9994	–
2	0.39	390	0.2796	0.6349	2.1287	0.0985	0.2796	2.8621	–
5	1.55	310.85	0.0333	0.1383	0.2449	0.2135	0.0333	0.4725	0.1243
7	3.08	314.35	0.0151	0.0757	0.1113	0.1185	0.0151	0.2405	0.0650

Figure 3 shows a roll temperature curve during 28 cycles for the existing and retrofitted cooling systems of stand No. 1. During a cycle the heating of a roll takes place due to the contact heat exchange. After going out of the contact the roll goes through three stages in the existing cooling system: air cooling – emulsion cooling – air cooling. In the case of this system the roll surface is heated between the emulsion cooling and getting into the contact with a workpiece. New cooling manifold design involves negligible air cooling and does not involve surface heating-up.

When rolling, the roll surface temperature rises after every cycle. Interpolation of the surface temperature rise after going out of emulsion cooling in a single roll revolution reveals that in the retrofitted system the temperature rise ceases much earlier and is significantly lower than in the existing one (Figure 4).



a *b*

Figure 3: Roll temperature curve during 28 cycles for existing (*a*) and retrofitted (*b*) cooling systems. Stand No1. 1, 2, 3 – average mass temperature, surface, at a distance of 1 mm from the surface, respectively.

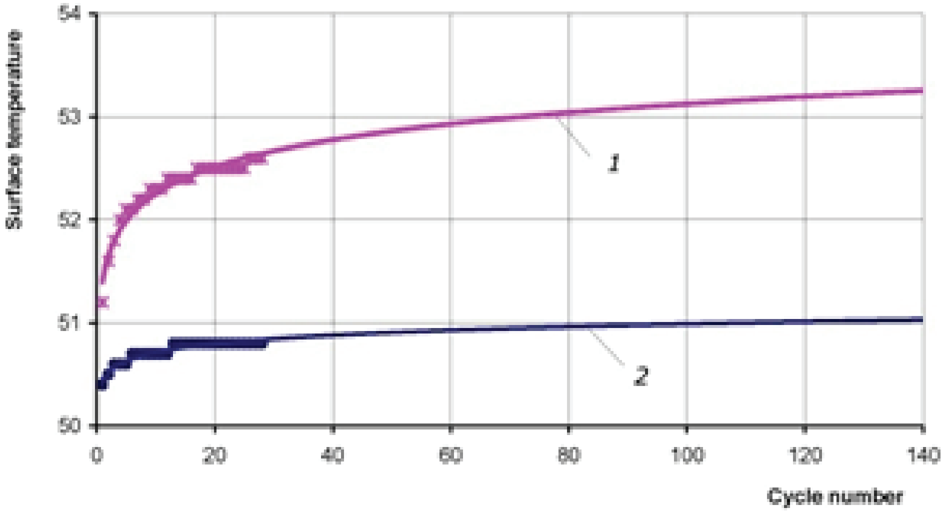


Figure 4: Interpolation of the calculated values of the surface temperature on each roll revolution when leaving the cooling stage with an emulsion: 1 – existing, 2 – retrofitted cooling systems.

After rolling, the surface temperature keeps rising during air cooling owing to the heat accumulated in inner roll layers. However, surface heating-up is significantly lower in the case of the retrofitted system due to less amount of the accumulated heat (Figure 5). Table 3 contains calculated and experimental surface temperature values.

Table 4 contains experimental values of roll surface temperature before and after retrofitting the cooling system. The retrofitting of stand No. 5 is scheduled in future.

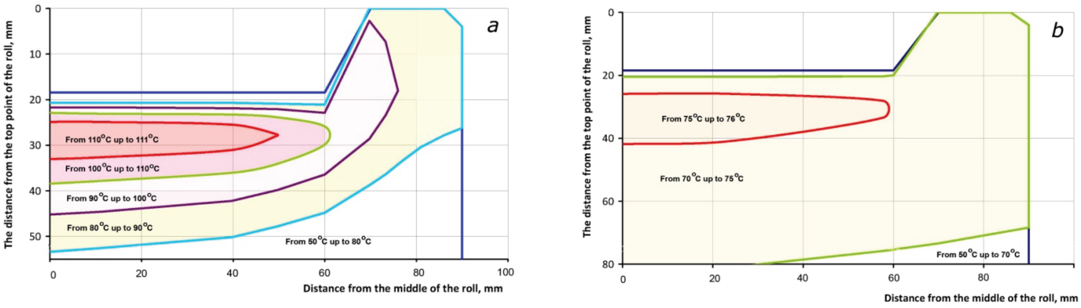


Figure 5: Temperature isotherms in the surface layers of the roll for the existing (a) and retrofitted (b) cooling systems.

Table 3: Surface temperature after rolling.

Stand No.	1	2	5	7
Mean value according to experimental data over a period since April to June 2017, °C	74,8	70,9	59,2	53,8
Experimental mean square deviation, °C	3,4	4,9	6,4	5,1
Calculated value for the existing design after 180 s air cooling, °C	79,4	69,3	56,3	52,3
Calculated value for the retrofitted design after 180 s air cooling, °C	61,8	59,5	48,9	47,2

Table 4: Experimental values of roll temperature before and after retrofitting the cooling system.

Temperature, °C	Tongue/distant roll		Bottom/near roll			
	Stand No.					
	1	2	7	1	2	7
Mean before retrofitting according to data over the period from 08.06.17 to 12.12.17	73.23	71.74	58.30	74.14	71.22	57.28
Mean after retrofitting according to data over the period from 13.12.17 to 25.01.18	65.67	66.78	52.83	67.43	64.33	51.17
Mean temperature difference	7.56	4.97	5.47	6.71	6.89	6.11
Max. before retrofitting	80.0	78.0	65.0	82.0	78.0	65.0
Max. after retrofitting	71.0	72.0	55.0	72.0	70.0	53.0
Max. temperature difference	9.0	6.0	10.0	10.0	8.0	12.0

2. Summary

The carried out numerical simulation of the temperature field dynamics of stands No. 1, 2, 5, 7 in the ‘Katur-Invest’ rolling mill shown that the amount of heat inside the roll after rolling for retrofitting the cooling system has been significantly reduced, allowed to select the parameters of retrofitting a cooling system which gave the required reducing of the roll surface temperature. Experimental data showed that after the cooling system was modernized, the surface temperature of the rolls decreased by 6–10°C.

References

[1] Kushner, V. S., Vereshchaka, A. S., Skhirtladze, A. G., et al. (2009). *Materialovedenie i Tekhnologiya Konstrukcionnyh Materialov [Materials Science and Technology of Structural Materials]*, pod red, p. 520. Omsk: OmGTU.

[2] Grechnikov, F. V. and Uvarov, V. V. (2003). Analiticheskoye issledovaniye temperaturnogo polya poverkhnostnogo sloya valkov goryachey prokatki alyuminiyevykh splavov [Analytical study of the temperature field of a roll outer layer in the hot rolling of aluminum alloys]. *Mechanics and Machinery. Bulletin of the Samara Scientific Centre of the Russian Academy of Sciences*, vol. 5, no. 2.

[3] Vorobey, S. A. and Prikhodko, I. Yu. (2005). Modelirovaniye temperatunogo rezhima rabochikh valkov shirokopolosnogo stana goryachey prokatki [Simulation of the temperature mode for work rolls in wide-strip hot rolling mill]. *Scientific News. Modern Issues of Metallurgy. Metal Flow*, vol. 8, pp. 232–235. Dnepropetrovsk.

[4] Eismondt, K. Yu. (2011). Razrabotka i vnedreniye v proizvodstvo ustroystv termouprochneniya prokata reguliruyemym okhlazhdeniyem na osnove analiza protsessov teploobmena [Elaboration and manufacturing application of rolled metal thermohardening by controlled cooling based on heat transfer process analysis]: Extended abstract of Cand. Sci. (Eng.) dissertation: 05.16.01; 05.16.02. Scientific Research Institute for Metallurgical Thermal Engineering, Ural Federal University named after the first President of Russia B. Yeltsin. Ekaterinburg.

[5] Vargaftika, N. B. (ed.) (1956). Thermophysical Properties of Substances: A Reference Book, p. 367. M.-L.: State Energy Publishing House.