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Numerical Analysis of Industrial Roll Cooling using FEM

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Abstract:- *In a hot strip mill, the quality of the rolled products and the productivity of the mill depend on the efficiency of roll cooling to a great extent. To study the influence of the cooling system on roll performance, a good understanding of the thermal aspects of roll cooling is essential. Mathematical models to predict temperature development in the work roll induced at the roll surface during rolling were developed. The models were used to predict temperatures in the roll under various cooling conditions, thus examining the efficiency of the existing roll cooling system and exploring the scope of optimizing it.*

Keywords**—** Roll Wear, Roll; Hot Strip Mil, Roll Cooling;

1. INTRODUCTION

To meet the high quality requirements of nowadays steel production, it is vital that the rolling takes place in the prescribed temperature range. Moreover, the temperature largely influences the yield stress and thus the rolling force and torque. Therefore, the temperature evolution of the plate has to be considered when planning the roll passes and scheduling the whole production process. In the following, the different production steps are outlined by means of an overview of the considered rolling mill shown in Figure 1 and their influence on the temperature evolution of the plate is briefly described. In hot rolling, wear of the work roll takes place mainly because of:

I. Abrasion of the roll surface due to contact with the strip, and in a four high mill, due to contact with the back-up roll also

II. Fatigue of the surface layers due to the variable nature of mechanical stresses applied by the strip and the back-up roll

III. Thermal fatigue of the roll surface due to the temperature cycles undergone by the outer layers as those are alternately heated by the strip and cooled by the coolant from the spray headers.

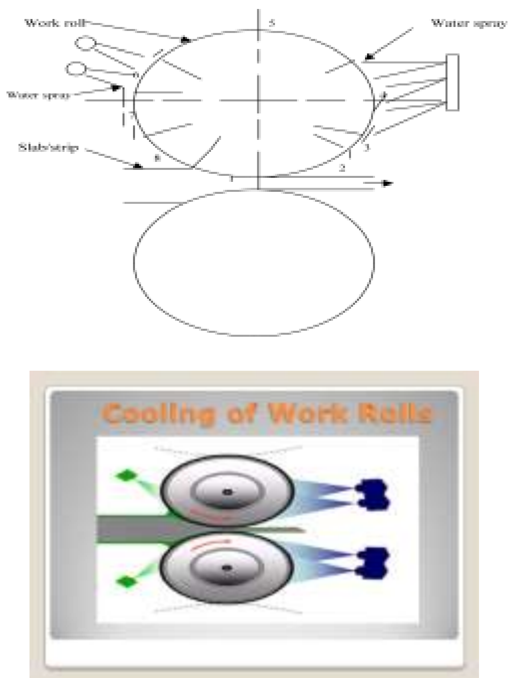

Fig. 1. Cooling arrangement for work rolls rolling a slab/strip (Back-up rolls and cooling of the lower work roll not shown).

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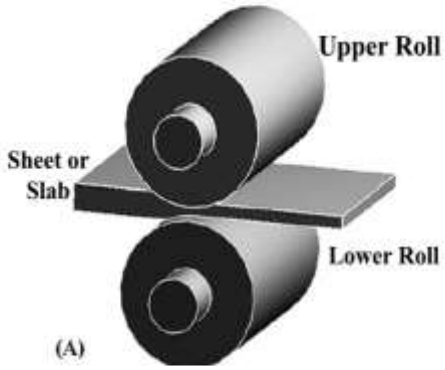
When the slab is reheated in a furnace up to 1450K, primary scale grows on the surfaces of the slab, which has to be removed prior to the rolling process because it would otherwise affect the surface quality of the rolled plate.



2. DEVELOPMENT OF THE MATHEMATICAL MODEL OF ROLL TEMPRATURE

A typical roll cooling arrangement is shown in Figure 1. As the roll surface comes in contact with the hot slab/strip, it receives heat from the slab/strip at a high rate. After the surface comes out of the roll bite, it is subjected to cooling by water sprays. As observed for long and wide strip rolling, the mills often operate near cyclic steady state conditions and the axial heat flow is usually not significant.2)With these assumptions, the equation of heat transfer in the work roll, with respect to a fixed Eulerian reference frame, becomes:

$$-\frac{\omega\delta T}{\alpha\delta\theta} = \frac{\delta 2T}{\delta r2} + \frac{1}{r}\frac{\delta T}{\delta r} + \frac{1}{r}\frac{\delta 2T}{r2\delta\theta 2}$$

Since the work rolls rotate at a high speed, the heat transfer in the circumferential direction by conduction can be neglected compared to the heat transfer by convection (rotation of the rolls). The above equation, then, can be simplified as:

$$-\frac{\omega\delta T}{\alpha\delta\theta} = \frac{\delta 2T}{\delta r2} + \frac{1}{r}\frac{\delta T}{\delta r}$$

Employing the relationship, *q* =*wt*, the above equation becomes:

$$-\frac{1\delta T}{\alpha\delta\theta} = \frac{\delta 2T}{\delta r2} + \frac{1}{r}\frac{\delta T}{\delta r} \text{.......................(1)}$$

Where t is the time taken for an elemental volume of the roll to rotate through an angle q measured from the reference point

This equation is subject to the following boundary conditions:

(i) At the roll surface, For t>0 and r=R,

$$-k\frac{\delta T}{\delta r} = h(t)\{T\text{-}T_\infty\}\text{.......................(2)}$$

For h(t) and T_∞, the ambient would be different in different zones. For example, in the roll bite, the strip surface is the ambient whereas in the zone where water is impinged on the roll surface, the cooling water is the ambient.

(i) As rolling proceeds, the temperature of the roll gradually increases. In a typical rolling operation where the roll is rotated rapidly, if rolling takes place continuously (without any interval between rolling of two consecutive slabs), the major portion inside the roll achieves a nearly steady and uniform temperature after a certain time from the commencement of rolling and temperature variations are localized in a very thin layer near the surface. Therefore, this thin layer only needs to be considered in the model.2)

For t>0 and r=R—d ,

$$k\frac{\delta T}{\delta r} = 0 \quad \text{.................................(3)}$$

According to Tseng,3)d can be found from the following equation:

$$d = 7RPe^{-1/2} \text{ where } Pe = w\,R^2/a\,.$$

'd ' was calculated for the work rolls of Stand No. 1 of the finishing mill of the Tata Steel HSM and was found to be about 7.2 mm.The accuracy of the model depends considerably on the values of the heat transfer coefficients used for different zones.

2.1.1 Roll Bite Zone

From the measurements of work roll temperature in a roughing mill, Stevens et. al.1) estimated that the heat transfer coefficient (HTC) within the roll bite (zone 1 in Fig. 1) was 37.6 kW/(m2 K) during the first 30 ms in the arc of contact and 18 kW/(m2 K) thereafter. These values of HTCs were used for the roll bite zone in the present model. To get the strip surface temperature, heat transfer in both the roll and the strip have to be modeled together. However, in the present study, modeling of strip heat transfer was avoided by assuming strip surface temperature on the basis of plant data and literature.

2.1.2. Water Impingement Zone

The work rolls are cooled by spraying water on the roll surface (zones 4 and 6 in Fig. 1). Devadaset al.,[4] in their work, determined the heat transfer coefficients in the water impingement zones from Yamaguchi et al.'s correlation [5]:

$$\dot{q}_{sp} = (1.11)(1.163)(10^5)\dot{W}^{0.521} \quad \text{..................(4)}$$

The same correlation was used in the present study for the water impingement zones. The water fluxes (W˙) were calculated from the spray configuration. The above correlation is based on experimental measurements of the thermal response of a heated plate to spray cooling. The plate temperature was in the range of 100 – 400°C and water fluxes varied from 5 000 to 50 000 L/m2/min. The heat transfer coefficient was obtained from the relationship as follows:

$$\dot{q}_{sp} = h(t)\times(T_S - T_\infty)$$

To get the heat transfer coefficient in this zone for roll surface temperature less than 100°C, the relationship for heat transfer from a rotating cylinder[6] was used as below:

$$h(t) = 0.11(0.5Re^2 + Gr\,Pr)^{0.35}\times k\,/D \quad \text{............(5)}$$

The values of Rew and GrD can be obtained from the following equations:

$$Re_W = pD^2 w/n$$

$$\text{and } \; Gr_D = g\,b\,(T_s - T_\infty)D^3/n^2$$

The properties Pr, k_S, n and b at the mean fluid temperature T_f can be used in the above equations, where $T_f = (T_S + T_\infty)/2$.

2.1.3. Water Streaming Zone

In this zone, the surface of the rolls is covered with a film of water streaming down from the spray zones above. In Fig.1 , these zones have been marked by 3 and 7. The heat transfer coefficient in these zones would depend on the roll surface temperature.

For surface temperature less than or equal to the saturation temperature of water (T_{sat}), the heat transfer coefficient was calculated from Eq. (5). For roll surface temperature above the saturation temperature of water, pool boiling[4] heat transfer equations were used as follows:

(i) For $T_{sat} < T$ ŠT_{max} (temperature of critical heat flux), Rohsenow's correlation for nucleate boiling was used.

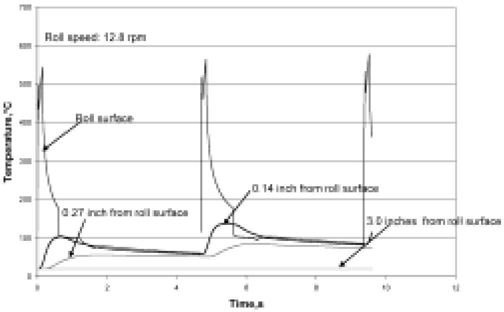


Fig. 2. Predicted variation of temperature of a point of the roll with time during rolling.

2.1.4. Other Zones

For the remaining zones (2, 5 and 8 in Fig. 1), the heat losses from the roll surface were assumed to take place by convection according to Eq. (5) and radiation.

Using the implicit technique, finite difference equations were developed to solve the governing equation of heat transfer (1) numerically along with boundary conditions (2) and (3). A value of 12 mm was chosen for d .To solve the finite difference equations, a computer programme in C language was written. The grid size and the time step were taken such that further refinement of those did not make any appreciable change in the output.

3. VALIDATION OF THE MODEL

To assess the accuracy of the model, it was employed to reproduce the conditions published by Stevens *et al.*[1)] for a roughing mill operation. Stevens *et al.* instrumented a work roll with thermocouples and measured the temperature response at different depths below the surface. With the operating conditions for the roughing mill work roll described in Stevens *et al.*'s paper, the work roll temperature variation was predicted with the present model. The results for the first two revolutions are shown in **Fig. 2**. It can be seen from the figure that the surface of the roll would reach a peak of 545°C during the first revolution and a peak of 565°C during the second revolution. The predicted temperature variation at different depths from the roll surface have also been depicted in the figure.

Table 1. Comparison of model predicted work roll tempera tures with published measured data.

Temperature, °C	During First Revolution		During Second Revolution	
	Predicted	Measured	Predicted	Measured
Maximum temperature at the surface	545	500	565	539
Maximum temperature at a depth of about 0.14 inch	105	100	138.5	117
Maximum temperature at a depth of about 0.27 inch	56	47	86	75

4. APPLICATION OF THE MODEL

The above model was applied to the upper work roll of Stand No. 1 of the finishing mill of HSM at TATA STEEL with the following inputs:

Parameter	Value
Slab thickness at entry side	33 mm
Slab thickness at exit side	18 mm
Slab temperature at entry	1040ºC
Average slab surface temperature in the bite zone	940ºC
Angular speed of the roll	45 rpm
Roll diameter	700 mm

The results discussed below will refer to the above work roll. The figure shows temperatures at the surface as well as at different depths from the surface. It is revealed from the figure that any point on the roll surface during its first working revolution attains a peak temperature of 490°C and subsequently cools down to a minimum temperature of 51°C. During the second revolution, the maximum and minimum temperatures attained by the roll surface are predicted to be 503 and 61°C respectively. The maximum and minimum temperatures attained by the roll surface during the sixth revolution are, as predicted by the model, 521 and 80°C respectively. The figure also reveals that at the end of the first working revolution of a point at a depth of 3.5 mm from the surface, the temperature would be about 49.5°C. The temperature at this point of the roll, at the end of the sixth revolution, would be about 95°C, as predicted by the model. The temperatures at a point of the roll at a depth of 7 mm from the surface would be about 35 and 71°C at the end of the first and sixth revolutions of the point respectively.

5. EFFECT OF LOCATION OF SPRAYING NOZZLES

The heat that can be taken out from the roll surface progressively diminishes as the surface moves further from the roll bite because the heat conducts towards the core and is not sufficiently available on the surface for removal. Therefore, cooling of the work roll by sprays should start as close to the roll bite as possible. The model was utilized to evaluate the influence of the position of the spraying nozzles on cooling of the work roll. All other conditions were taken same as the existing ones with the upper work roll at the 1st stand of the finishing mill.

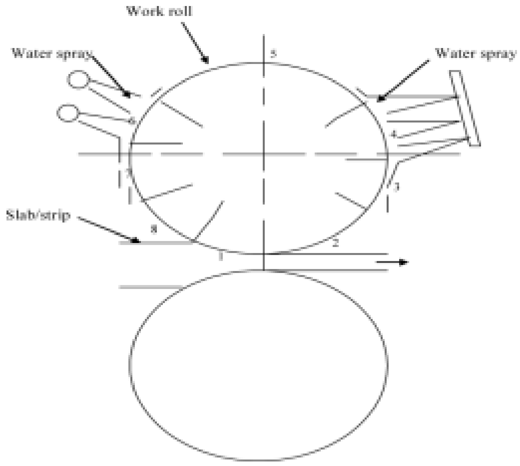


Fig.3. Cooling arrangement (earlier) for work rolls rolling a slab/strip (back-up rolls and cooling of the lower work roll not shown).

Earlier, the angular position of the lower most row of nozzles at the exit side of the work roll under study was about 100°, as shown in **Fig. 3**. A few years ago, the nozzles were shifted towards the roll bite to some extent and the new angular position was about 65°, as shown in Fig. 1. It was found that the maximum and minimum surface temperatures did not practically change. However, the roll body temperature reduced to some extent from 189 to 184.5°C. The plastic strain/cycle was predicted to reduce from 3.921×10^{-3} to3.873×10^{-3}.

5.1 Effect of Rate of Cooling Water Flow

The model was used to evaluate roll temperature and the consequent thermal strain for various rates of cooling water flow, all other conditions remaining same. Presently, the total rate of water flow (upper work roll, 1st stand) is about 317 m^3/h.

5.2 Combined Effect of Cooling Water Flow Rate and Number of Rows of Nozzles

The model was utilized to examine the effects of changing the number of rows of spraying nozzles at both entry and exit sides together with varying the rate of water flow. It was found that if the upper row of nozzles at the entry side was withdrawn and the water flows at all the other rows were unaltered, the maximum surface temperature and the roll body temperature would increase to 556 and 198°C respectively from the present values of 550 and 184.5°C respectively and the plastic strain/cycle at the surface would increase from 3.873×10^{-3} to 4.337×10^{-3}. The model also revealed that if all the cooling water at the entry side (100 m^3/h at present) were delivered through the lower row only, the exit side conditions remaining the same, the maximum surface temperature and the roll body temperature would increase to 554 and 194°C respectively from the present values of 550 and 184.5°C respectively and the plastic strain/cycle at the surface would increase from 3.873×10^{-3} to 4.177×10^{-3}. The findings are summarized in **Table 2**.

Table 2. Effect of roll cooling parameters on roll temperature and thermal strain (No. of rows of nozzles at the entry side = 2).

No. of rows(exit)	Total water flow (entry + exit)	Temperature, °C			Plastic strain/cycle
		Max. at surface	Min. at surface	Roll body	
2	18% less	558.2	105.3	206	4.506E-3
	Existing	554.4	104.9	196	4.210E-3
3	40% less	558.5	105.5	206.5	4.521E-3
	30% less	556.5	105.0	201.0	4.330E-3
	20% less	554.0	105.0	195.5	4.194E-3
	10% less	552.0	104.5	190.0	4.034E-3
	Existing	550	104.5	184.5	3.873E-3
	10% more	547.5	104.0	179.0	3.693E-3
	20% more	546.0	100.0	174.0	3.689E-3
	30% more	544.5	100.0	171.0	3.634E-3
4	Existing	546.0	102.0	174.5	3.629E-3
	10% more	544.0	100.0	169.0	3.548E-3
	20% more	543.0	99.3	166.0	3.466E-3
	30% more	542.0	99.0	163.0	3.416E-3
5	Existing	543.0	99.5	167.0	3.483E-3
	10% more	541.0	99.3	162.0	3.331E-3
	20% more	540.5	99.2	161.0	3.294E-3
	30% more	540.0	99.1	159.0	3.259E-3

It can be noted here that the mathematical model developed predicts temperatures when roll temperatures have stabilized after a certain time of continuous rolling (without any interval between rolling of two consecutive slabs). This is useful in comparing roll performance under various conditions and in having basic information about the merits and demerits of different cooling systems.

Therefore, to evaluate the actual effects of different cooling conditions on roll temperature and the consequent thermal strain, a separate model was developed in which, the effect of intermittent rolling was taken into care. For this, the entire radius of the work roll had to be considered in the model. It was done by taking the interior boundary condition as follows:

For $t>0$ and $r=0$

$$k\frac{\delta T}{\delta r} = 0 \quad \text{................................(7)}$$

Difference of material properties between high chrom iron (roll shell material) and e.g. iron (core material) were considered in the model. It can be mentioned that the heat transfer coefficient at the bite zone would depend on the condition whether the rolls are in the process of rolling any slab or at the stage of idling between rolling of two consecutive slabs.

To get the actual situation, the full radius model was applied to the work roll under two different conditions as follows:

- Condition A (present condition)

  No. of rows of nozzles at the entry side: 2

  No. of rows of nozzles at the exit side: 3

  Total cooling water flow: 317 m^3/h

- Condition B

  No. of rows of nozzles at the entry side: 2

  No. of rows of nozzles at the exit side: 4

  Total cooling water flow: 380 m3/h (20 % more than at present)

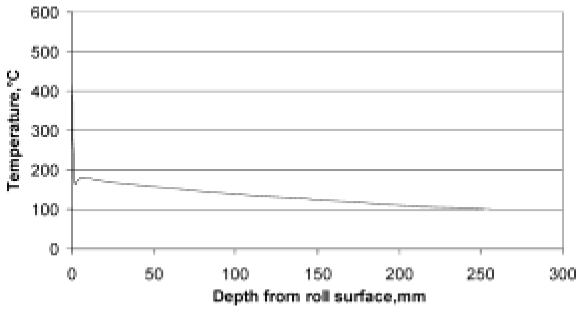


Fig. 4. Roll temperature at different depths from the surface at or nearly at the end of roll bite after 45min. from the start of rolling.

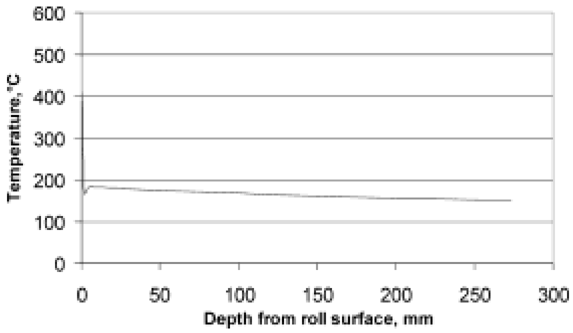


Fig. 5. Roll temperature at different depths from the surface at or nearly at the end of roll bite after 90 min. from the start of rolling.

Time after commencement of rolling	Condition	Location	Temperature, °C at different depths				
			Surface	7mm	87mm	175mm	Centre
About 1h 1min. -	Rolling a slab	End of roll bite	498	160	106	95	84
		Just before roll bite	140	160.3	106	95	84
About 1h 2min.	Idling	End of roll bite	55	72	107	95.6	84.8
		Just before roll bite	54	71	107	95.6	84.8

Table 3.Roll temperatures at surface and at different depths at different times from the commencement of rolling under the present condition Table 3.Roll temperatures at surface and at different depths at different times from the commencement of rolling under the present condition.

However, to capture the maximum benefits available with possible modifcation, the following cooling arrangement for the upper work roll of the 1st stand of the finishing mill can be under- taken:

No. of rows of spraying nozzles at the entry side: 2

No. of rows of spraying nozzles at the exit side: 4

Rate of cooling water flow

1st (Lower most) row at the exit side: 110 m3/h (same as at present)

2nd row at the exit side: 50 m3/h (same as at present)

3rd row at the exit side: 57 m3/h (same as at present)

4th (uppermost) row (additional row) at the exit side:44 m3/h

Upper row at the entry side: 77 m3/h Lower row at the entry side: 42 m3/h Total flow of cooling water: 380m3/h

Location of the exiting rows: Same as at present

5.3 Effect of Strip Lubrication

Some lubricants used during rolling have a significant effect on heat transfer in the roll bite. Thus, strip lubrication can have a marked effect on roll temperature. C. Devadas*et al.*[4] examined the influence of strip lubricants on work roll temperatures using the data obtained by Murata *et al.*[7] in laboratory experiments. Murata *et al.* calculated the heat transfer coefficients that would apply to hot rolling under a variety of conditions by measuring the thermal response of a high temperature (780°C) specimen in contact with a low temperature specimen in compression.

6. SUMMARY

A computer programme was developed to compute thermal strain induced at the roll surface during rolling. With the above models, roll temperatures and thermal stresses generated at the roll surface during rolling under various cooling conditions can be predicted and thus an optimum cooling system can be arrived at. The above models were applied to the upper work roll of the 1st stand of the finishing mill of HSM at Tata Steel to assess the efficiency of the existing roll cooling system and optimize it, if required. The major findings are as follows:

1) The model predicted the amount by which the thermal fatigue of the roll would increase if any row of spraying nozzles from the entry or exit sides of the work roll were withdrawn, thus justifying the provision of the existing rows.

2) For the present cooling arrangement, the optimum total water flow may be taken as 350 m3/h, which is 10 % more than the present flow.

3) The model revealed that by increasing the number of rows of nozzles and the water flow rate, it was possible to decrease the plastic strain/cycle in the roll and hence in- crease roll life. However, the increase in roll life over the present one may not be much.

4) Some modification in the existing roll cooling sys- tem was recommended to capture the maximum benefits available with possible modification.

5) There are some lubricants for strip lubrication which can reduce the maximum temperature attained by the roll surface during rolling by a considerable extent. It was found that if 40 % CaCO3 in hot rolling oil was used for lubrication of the strip, the maximum roll temperature would reduce to 407°C from the present 550°C. The model also revealed that if an inorganic salt such as KPO3 were used as a lubricant, the peak roll temperature would de- crease to222°C.

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