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Numerical Analysis of SurfaceStress in Hot Rolling

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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 compute thermal strain induced at the roll surface during rolling were developed and applied to the upper work. The models were used to predict thermal stresses/ strains in the roll under various cooling conditions, thus examining the efficiency of the existing roll cooling system and exploring the scope of optimizing it.*

KEY WORDS: roll cooling; roll; hot strip mill; roll wear.

1. INTRODUCTION

In a rolling mill, the efficiency of roll cooling is one of the main factors on which the quality of the rolled products and the productivity of the mill depend. Improper or insufficient cooling of work rolls can not only lead to roll break- age due to excessive differential expansions but can also significantly affect the shape or crown of the roll and result in buckled strips.

To study the influence of the cooling system on roll performance, a good understanding of the thermal aspects of roll cooling is essential.

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.

Therefore, to arrive at an optimum roll cooling system, the following methodology can be adopted:

- Development of a mathematical model to predict roll temperatures during rolling
- Analysis of thermal stress and strain induced at the roll surface
- Utilization of the model to assess the influence of various cooling parameters on the efficiency of roll cooling.

2. DEVELOPMENT OF THE MATHEMATICAL MODEL OF ROLL TEMPERATURE

A typical roll cooling arrangement is shown in Fig. 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.

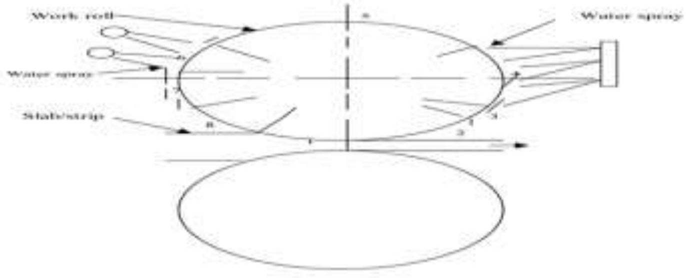


Fig. 1. Cooling arrangement for work rolls rolling a slab/strip (Back-up rolls and cooling of the lower work roll not shown).

3. MECHANISM OF THERMAL FATIGUE OF ROLL SURFACE

As discussed earlier, in each revolution, the roll surface attains a maximum and a minimum temperature, which gives rise to variation of thermal stress repeatedly, causing thermal fatigue. Compared to the peak temperature attained by the roll surface in each revolution, the temperature of the bulk of the inside of the roll, which may be called roll body temperature, is much lower.

The development of thermal fatigue can better be seen from **fig 2** . An element of the roll surface has been shown in the figure. As this element comes in contact with the hot strip (a) ,its temperature starts rising and it attempts to expand (b). But this expansion is prevented by the main body of the roll which is at much lower temperature. As a result , a circumferential stress in circumferential direction is induced in the element (c).

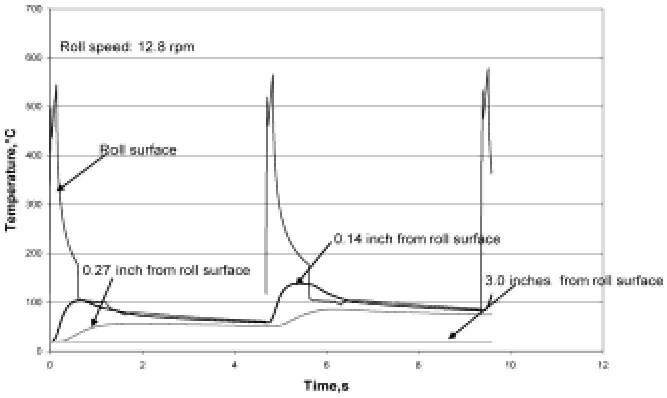


Fig. 2. Development of compressive thermal stress in roll surfaces.

4. ESTIMATION OF THERMAL STRESSES

A method for computing thermal stresses and strains was described by Stevens *et al.* in their article.1) The same method was used in the present study as follows:

When the temperature of the roll surface increases, equivalent strains are set up both circumferentially and axially and the elastic strain is given by:

$-\alpha_e . \Delta T = e' - m'e'$

i.e $\varepsilon' = -(1/1-\mu')\ \alpha_e . \Delta T$ and

⍰ $el = E.\varepsilon' = -(E/1-\mu')\ \alpha_e . \Delta T$

In the plastic regions, the stress at any temperature is assumed to be equal to the yield stress of the material at that temperature. The total strain at any temperature can be obtained from the general fundamental equations as follows:

$-\alpha_e . \Delta T = e'(1-- m') + e''(1-m'')$

$e = e' + e''$

The following properties of high chrome cast iron were used in computation of thermal stresses and strains at the roll surface:

$a_e=10.9\times10^{-6}/°C$, $m'=0.28$, $m''=0.50$,

$E=2.1\times10^5\ N/mm^2$

5. DEVELOPMENT OF TEMPERATURE AND THERMAL STRESS IN THE ROLL UNDER VARIOUS COOLING CONDITIONS

The temperatures of the work roll and the resulting thermal stresses depend on many factors. Some of the major factors are mentioned below:

a) Amount of flow of cooling water

b) Location of the water spraying zones

c) No. of rows of spraying nozzles

d) Distribution of cooling water at the work roll circumference

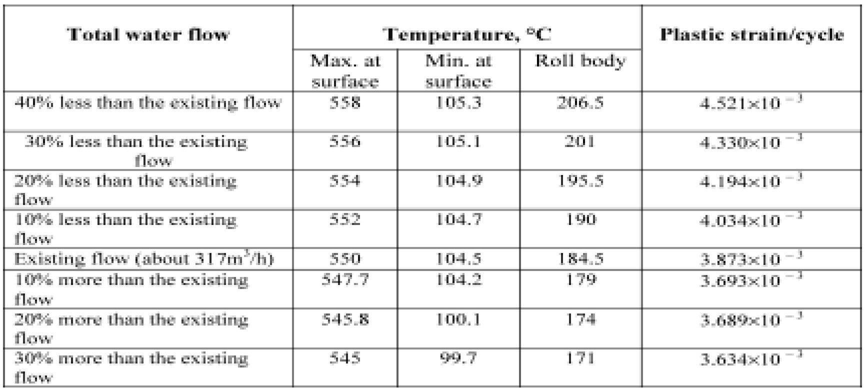
e) Strip lubrication.

The model was utilized to assess the influence of different factors on roll cooling and thus arrive at an optimum cooling system.

6. 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. The effects of variation in cooling water flow on roll temperature as well as on thermal strain at the roll surface are depicted in **Table 1**.

Table 1. Variation of temperature and thermal strain of the work roll with amount of cooling water (two and three rows of spraying nozzles at entry and exit sides respectively).

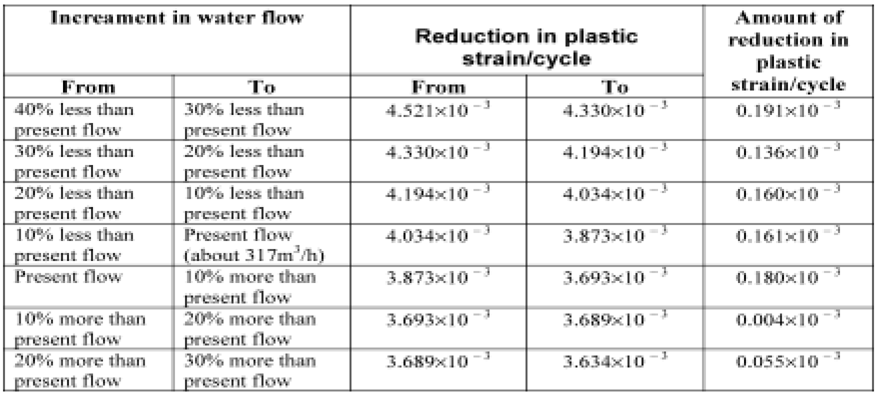


Total water flow	Temperature, °C			Plastic strain/cycle
	Max. at surface	Min. at surface	Roll body	
40% less than the existing flow	558	105.3	206.5	4.521×10^{-3}
30% less than the existing flow	556	105.1	201	4.330×10^{-3}
20% less than the existing flow	554	104.9	195.5	4.194×10^{-3}
10% less than the existing flow	552	104.7	190	4.034×10^{-3}
Existing flow (about 317m^3/h)	550	104.5	184.5	3.873×10^{-3}
10% more than the existing flow	547.7	104.2	179	3.693×10^{-3}
20% more than the existing flow	545.8	100.1	174	3.689×10^{-3}
30% more than the existing flow	545	99.7	171	3.634×10^{-3}

It can be observed from the Table that by increasing the total water flow from 40 % less than the existing flow to 30 % less than the existing one, it is possible to reduce the plastic strain/cycle from 4.521× 10—3 to 4.330×10—3, i.e., by 0.191×10—3. The observations from this Table on thermal strain have been summarized in Table 2

Table that by increasing the total water flow from 40 % less than the existing flow to 30 % less than the existing one, it is possible to reduce the plastic strain/cycle from 4.521× 10—3 to 4.330×10—3, i.e., by 0.191×10—3. The observations from this Table on thermal strain have been summarized in Table 2

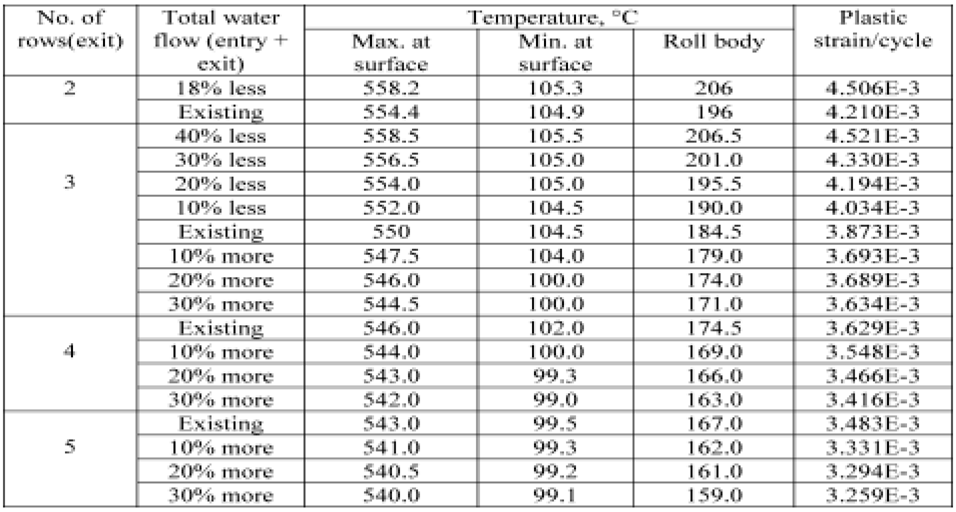
Table 2. Effect of roll cooling parameters on roll temperature and thermal strain per cycle



Increament in water flow		Reduction in plastic strain/cycle		Amount of reduction in plastic strain/cycle
From	To	From	To	
40% less than present flow	30% less than present flow	4.521×10^{-3}	4.330×10^{-3}	0.191×10^{-3}
30% less than present flow	20% less than present flow	4.330×10^{-3}	4.194×10^{-3}	0.136×10^{-3}
20% less than present flow	10% less than present flow	4.194×10^{-3}	4.034×10^{-3}	0.160×10^{-3}
10% less than present flow	Present flow (about 317m^3/h)	4.034×10^{-3}	3.873×10^{-3}	0.161×10^{-3}
Present flow	10% more than present flow	3.873×10^{-3}	3.693×10^{-3}	0.180×10^{-3}
10% more than present flow	20% more than present flow	3.693×10^{-3}	3.689×10^{-3}	0.004×10^{-3}
20% more than present flow	30% more than present flow	3.689×10^{-3}	3.634×10^{-3}	0.055×10^{-3}

The roll temperatures and the thermal strains at the roll surface were determined for vari- ous water flow rates with two rows of nozzles at the entry side and different numbers of rows at the exit side. The findings are summarised in **Table 3**. It can be seen from the Table that if the uppermost row at the exit is withdrawn (resulting in reduction in the total water flow by 18 %), the maximum roll surface temperature and the roll body temperature would increase to 558 and 206°C respectively .

Table 3. 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

6.1 Effect of Water Distribution at the Roll Circumference

Water is sprayed on the work rolls at both exit and entry sides, as can be seen in Fig. 1. In order to optimise the cooling effect of a given water flow rate, the header on the exit side should distribute more water than entry side. It is recommended that 70 % of the water should be applied from the exit side and 30 % from the entry side in case of high chromium iron rolls.8) In the present as well as the recommended cooling system, this ratio has been maintained closely. Some have suggested the water to be distributed in the ratio of 1 : 2 on the entry and exit sides for each stand.

7. ROLL WEAR BY ABRASION

Apart from thermal or mechanical fatigue, wear of the roll surface takes place by abrasion also. In order to resist abrasion, the working surfaces of the work rolls are made as hard as possible. However, as temperature increases, there is loss of hardness in the roll material. When the roll surface comes in contact with the hot strip, it gets softened; on leaving the roll gap, the hardness increases again as the roll surface gets cooled. The higher the roll surface temper-ature attained in the roll bite, the higher is the loss in hard- ness and hence the greater is the rate of roll wear due to abrasion.1) If by improving the roll cooling practice, the maximum surface temperature is reduced, the roll wear through abrasion also will reduce.

8. SUMMARY

Two mathematical models to predict work roll temperatures during rolling were developed:

i. A surface layer model which is applicable to continuous rolling and a situation when roll temperatures have stabilized.

ii. A full radius model which is applicable to intermittent as well as continuous rolling and any time after the commencement of rolling.

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 m^3/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.

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