MINIMIZATION OF THERMAL CRACKS OF ROLLS BY COOLING OPTIMIZATION

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Abstract
Roll surface during rolling is periodically loaded by thermally and mechanically inducted stresses. This paper describes the processes of roll cooling design and its optimisation. Knowledge of the cooling intensity of different types of the nozzles and their spray parameters forms the fundamentals applied for a design of the cooling system. Distribution of the cooling around the roll influences total heat balance and influences the intensity of thermal cyclic stresses as well. These stresses are inherent features of the rolling process but their magnitude can be modified. The most critical factor for thermal cracks is a tensile stress appeared in a roll surface layer in cooling area.

The task can be divided into two parts – mechanical and thermal analysis. The thermal load on the roll is used for the computation of stress fields on the roll. The boundary conditions describing the cooling intensity are obtained from the laboratory measurements. The design of a cooling header continues with the analysis of the contact areas between the roll and the rolled material. Superposition of both loads, mechanical and thermal, provides information about stress-strain behaviour of the roll surface layer. The optimized design of the cooling minimizes elastic, in some cases even plastic, deformation of the material and provides a sufficient cooling in order to keep a reasonable temperature of the rolls.

Key words:
Spray cooling, rolls, hot rolling, measurement of cooling intensity, thermal cracks, cooling optimization

1. INTRODUCTION
A surface of rolls for hot strip rolling suffers considerable degradation due to high thermal shocks. These shocks produce a plastic strain and a residual stress. This necessarily leads to cracks and forced hot strip mill to temporary shutdown or even to roll elimination. Knowledge of optimal cooling configuration which produces the smallest amount of plastic strain will lead us to maximum production life of roll [1], [5], [9].

An optimisation of roll cooling is very difficult and problematic task. A determination of optimal cooling is consisted from many variables (cooling intensity, cooling position, spraying angles, temperature of water which is used for cooling et cetera) [2], [4], [6] and [7]. A separation of influence of individual variables is crucial for cooling optimisation. This paper is focused on finding of optimal configuration which will produce the smallest amount of plastic strain.

2. ROLLING SIMULATION
The software SimRoll®, designed by the Heat Transfer and fluid Flow laboratory, was used for rolling simulation. It has many simulation options related to hot strip rolling. One of them is calculation of a temperature field within a roll in a time period. The real rolling campaign recorded during previous work was used for all simulations presented in this paper [10].

Three different cooling configurations were created based on real hot strip mills [11], [13], and [14]. These configurations have the same cooling effect on the roll but they vary in cooling intensity and position from each other. In other words, the final temperature of the roll after several hours of rolling is the same for all
cooling configurations. The list of maximal cooling intensity is given in Table 1. The rolling campaigns with different cooling are simulated by SimRoll. Surface temperatures are exported from SimRoll and transformed to a boundary condition which is used in further FE simulations.

A heat transfer coefficient between the rolled strip and the roll is $30\,000\, \text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-2}$ and it is identical for every cooling configuration. A cooling performed by radiation and natural convection is identical for each configuration. Dimensions of the roll are same for all configurations (Table 1). All values are obtained from previous project work done at the Heat Transfer and Fluid Flow Laboratory [2], [3], [4] and [6].

**Table 1 – The cooling intensity summarisation**

<table>
<thead>
<tr>
<th>Cooling configuration</th>
<th>Maximum cooling intensity [W/(K·m²)]</th>
<th>Percent proportion of cooling intensity to 1st con. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>20800</td>
<td>100%</td>
</tr>
<tr>
<td>Second</td>
<td>49200</td>
<td>237%</td>
</tr>
<tr>
<td>Third</td>
<td>11580</td>
<td>56%</td>
</tr>
</tbody>
</table>

**Fig 1 – The roll dimensions (on the right side).** $D = 1500\, \text{mm}$, $d = 654\, \text{mm}$, $W = 2000\, \text{mm}$.

The first cooling configuration is exit-type cooling by one collector which is spraying on the roll. The maximum of cooling intensity is $20\,800\, \text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-2}$, position of collector is around $120^\circ$ and deviation angle from horizontal $10^\circ$ (Fig 2).

The second cooling configuration is enter-type cooling by one collector. The maximum of cooling intensity is $49\,200\, \text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-2}$, position of the collector is around $290^\circ$ and deviation angle from horizontal $-5^\circ$ (Fig 2).

The third cooling configuration is dual cooling with one collector in exit position and one in enter position. The maximum of cooling intensity is $11\,520\, \text{W} \cdot \text{K}^{-1} \cdot \text{m}^{-2}$, positions of the collectors are around $290^\circ$ (enter), $120^\circ$ (exit) and deviations angles from horizontal $10^\circ$(exit), $-5^\circ$(enter).

**Fig 2 – The first cooling conf. – the exit cooling (on the left side); the second cooling configuration – The enter cooling**
3. **FINITE ELEMENT ANALYSIS**

The finite element analysis (FEA) was used for determination of a plastic strain. The FEA was accomplished with the well-known engineering simulation software ANSYS. The whole task is divided into two coupled simulations – transient thermal and structural. A material deformation caused by non-uniform temperature field is calculated in structural analysis. The temperature field itself is obtained from transient thermal analysis calculated first. The boundary conditions for thermal analysis are taken from SimRoll. Each cooling configuration was calculated separately.

A FE model represents 1° angular cylindrical sector and is created like a surface layer with a thickness of 27 mm or in other words a 27 mm thick tube. This simplification has several reasons. The simulated roll is rotationally symmetric, that means that an angular cylindrical sector is equivalent to the whole model. Most of thermal fluctuation happens in a subsurface layer with a thickness of 500 µm, i.e. it is not really necessary to model the whole cylindrical section (in this particular situation). In addition, the mapped mesh can be used and numerical stability of the simulation is highly increased. A thickness of FE model is one element with regard to axial symmetry of the roll and it is similar situation as with the rotational symmetry [8].

**Fig 2 –** The third cooling configuration – The exit and enter cooling (on the left side); the surface temperature for all three cooling configurations obtained from the SimRoll. The blue/green/red line – The 1\textsuperscript{st}/2\textsuperscript{nd}/3\textsuperscript{rd} cooling conf.

**Fig 3 –** The preview of the FE model mesh (on the top). The subsurface layer detail (on the bottom). A linear element type SOLID70 was used for thermal analysis, SOLID185 for coupled structural analysis.
There was just two boundary condition for the thermal analysis – model uniform temperature = 70 °C and applied surface temperature taken from SimRoll. The structural analysis has several boundary conditions (Fig 4). The FE model has two set of nodes in Z-axis. Nodes with coordinate Z = 0 is fully constrained and nodes with coordinate Z ≠ 0 are coupled together.

The material model and all used quantities for FEA are thermal depended from 20°C to 600 °C.

**Fig 4** – Applied boundary conditions for thermal and structural analysis (on the left side); the material model used for FEA. Stress – strain curves for temperatures from 20 °C to 600 °C (on the right side).

4. **RESULTS**

The results from simulations are presented in charts below. Each chart has three curves for each cooling configuration. The blue curve – The 1st cooling conf.; the green curve – The 2nd cooling conf.; the red curve – 3rd cooling conf. This colour theme is same for each chart.

The Fig 13 shows plastic strain curves over time period. The roll is affected by the rolling strip around 7.7 sec. The roll is heated from its actual temperature around 70 °C to 370 °C to 390 °C. This thermal shock leads to an immediate increase of the plastic strain which is slightly decreased when surface is cooled down. The plastic strain is increased again within next revolutions and total amount of the plastic strain slowly arises with the following additional revolutions.

The stress-strain curves of tangential components (Y-axis) for 1st and 2nd evolution after the first contact between the rolled strip and the roll are presented in Fig 6. The second cooling configuration produces the smallest amount of the plastic strain due to the lowest surface temperature which is applied (the smallest thermal shock).

Firstly, the compressive stress is induced. The subsurface layer has higher temperature than the rest of the volume, it tries to expand but the symmetric boundary condition does not allow expanding in tangential direction. That leads to commutations of compressive stress on the both sides of the model. The tensile stress is induced by cooling. The subsurface layer temperature rapidly drops and thus produces a contraction. The symmetry boundary condition does not allow contracting in tangential direction either, so the tensile stress is produced (Fig 6).
5. CONCLUSION

All configurations produce the plastic strain in the subsurface layer (Fig 5). The second cooling configuration produces the smallest amount of the plastic strain (about 19% less than other two configurations in the revolution 11) despite of the highest cooling intensity. The second cooling configuration has the lowest maximal surface temperature (Fig. 5), so the smallest thermal shock on the surface of roll is induced. The second cooling configuration produces the smaller thermal shock because of two following facts. The first fact is that the roll surface temperature falls at least at a half of its surface by convection to the roll core, nature air convection and radiation. The surface temperature is significantly decreased (to ~75 °C) before the main cooling. The second fact is that time between cooling and heating surface is the smallest. The surface layer does not have time to reheat itself by convection from the roll core.

The first and third cooling configurations produce almost the same amount of the plastic strain (about 0.26 mm in the revolution 11) despite the fact that the third cooling configuration has over 2 times lower cooling intensity than the first cooling configuration (Table 1). We can see that the cooling position has a higher impact on the thermal degradation than the cooling intensity and that is the significant conclusion of this paper.
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6. REFERENCES


