COOLING OF ROLLS USED IN HOT ROLLING OF LONG PRODUCTS

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ABSTRACT
This paper describes the processes of roll cooling design and optimisation. Knowledge of the cooling intensity of a variety of nozzles, and their spray parameters forms the basis for the design of a cooling system. The paper introduces the results of an extensive program of experiments, which provide a knowledge base for provision of cooling optimisation. The influence of pressure and flow rate, type and positioning of nozzle and nozzle spray parameters was measured. The results of experiments using nozzles with flat jet and full cone sprays are compared to results using systems without nozzles. The design of a cooling header starts with the analysis of the contact areas between the roll and the rolled material. Thermal load on the roll is used for computation of stress fields on the roll. This analysis produces critical points in the groove where thermal cracks are likely to originate. The resulting knowledge base of cooling intensity is subsequently used for selection of the best nozzles and their ideal positioning around the cooled roll. The final step in cooling design is the fine adjustment of nozzles in order to provide the best required cooling performance.

Keywords: spray cooling, rolls, long products, hot rolling, measurement of cooling intensity

INTRODUCTION
The cooling of rolls raises a variety of questions and this paper introduces the results of an extensive program of experiments to help answer those questions. The major topics covered are the following: optimum pressure and flow rate, types of nozzle, positioning of nozzles and proposed methods of further cooling intensification. The cooling intensity results of the use of nozzles with flat jet and full cone sprays are compared to results using systems without nozzles.

A measurement technique for the qualitative valuation and comparison of cooling configurations was developed [1], [2]. The description of cooling measurement technique is outside of the scope of this paper but can be found in [3], [4].

The experiments for this research focused on their application for use in spray cooling design. The characteristics of the cooling system utilised has an influence on both production quality and life duration of the rolls. The cooling design can be considered from two angles. The first includes roll wear, roll cracks, surface defects and oxidation of roll surface and the second is focused on thermal control of the roll shape for long products [5]. The first aspect is dominant for the design of roll groove cooling of the long products.

A numerical model is used for cooling optimisation and control with the application of measured cooling intensity information obtained from experiments. This paper concludes with an example of numerical model application for rolling simulation where roll temperature fields and thermal stresses are obtained.
COOLING INTENSITY & SPRAY PARAMETERS

Knowledge of cooling intensity for various cooling methods is the first step in the design of an optimal cooling system [6], [7]. A number of spray parameters affect the efficiency of roll cooling. The major parameters are listed here:

coolant pressure and flow rate,
type of nozzles and their positioning around the roll,
build material of roll,
roughness and speed of rolling.

The following paragraphs discuss the influence of some of the above parameters with special emphasis applied to the rolling of long products.

Influence of nozzle spray angle (30°, 60°, 120°)

The first example studies the influence of flat jet nozzle spray angle. Three groups of flat jet nozzles were used. All of the nozzles have identical flow rates but each type uses a different spray angle. Spray angles of 30°, 60° and 120° were used. The actual distribution of impinging water along the cooled roll can be seen in Fig. 2. Other cooling parameters are as follows: a spray height of 100 mm, pressure of 5 bar, flow rate per nozzle of 25 l/min (at 5 bar), circumferential velocity of 1 m/s. This spray configuration is schematically shown in Fig. 1 and direction of rotation is counter clockwise.
The average values of heat transfer coefficient along the roll length are plotted in Fig. 3. It is obvious that the nozzles with a narrow spray angle reach higher HTC values in the position of the nozzle axis. Comparison of Figs. 2 and 3 provides interesting information: water impingement density for a 30° nozzle is (in the position of nozzle axis) 6 times higher than for a 120° nozzle, but cooling intensity is higher by only 40%.

Further conclusions can be made by comparing the impact width, with the width of an effectively cooled area, see Fig. 2. Even the nozzles with a narrow spray angle can cool a much wider surface area than the nozzle impact area itself.

In influence of spray height

Three spray heights were tested within this group. The nozzles were moved closer and farther from the roll surface as schematically shown in Fig. 4. Distances of 50 mm, 100 mm and 200 mm were used. Flat jet nozzles with a spray angle of 60° were used for the tests. Test parameters were identical to the previous test examining spray angles. Fig. 5 shows the water distribution on the roll surface. Fig. 6 shows the cooling distribution for three spray heights. The most surprising outcome is that maximum HTC values were found using a distance of 100 mm, this being neither minimum nor maximum spray height.
The experiment with a spray height of 50 mm shows the following: if the nozzle is very close to the surface, HTC values are not the highest. This finding can be explained by the existence of a large amount of water in the impact area which prevents the jet reaching the surface at high energy, due to the spray contacting a water pool. Since this was not an expected conclusion the effect of spraying from close spray heights should be further studied. Total extracted heat is largest for the most distant spray height. This finding confirms previous experiment programs on roll cooling.

**Pressure dependence (increasing flow rate)**

Flat jet nozzles with a spray angle of 60° were used for all four experiments. The nozzle type and cooling configuration was identical to the measurements taken with variable spray angles. Spray configuration is schematically shown in Fig. 1. Pressure is increased in four steps: 2, 5, 8 and 12 bar. Flow rate grows with the square root of the pressure. The selected configuration is typical for plant conditions where the pressure varies for the given nozzles. Water distribution (spray angle) is not affected by the pressure.
The HTC plots in Fig. 7 show that cooling intensity grows with increasing pressure but HTC distribution on the cooled surface is not affected by pressure. Linear dependence can be observed between HTC and flow rate as shown in Fig. 8. Figure 8 shows average values of heat transfer coefficient for three positions on the roll surface – in relation to the nozzle axis.

**Fig. 7 Heat transfer coefficient (HTC) for measurements using increasing pressure**

**Fig. 8 Average values of heat transfer coefficient as a function of flow rate**

**Influence of spray bar spacing**

Since spray bars can be placed in different positions around the roll, this group of measurements compares spray bar positioning using three different spacings. All experiments used identical conditions of pressure, nozzle type and spray height, the only variable parameter being "nozzle spacing angle". Positioning of the nozzle around the roll is shown in Fig. 9 and the nozzle spacing in Fig. 9, was at 7°, 15° and 30°.

Figure 10 shows heat transfer coefficient distribution on the cooled surface. The nozzles spaced at 7° and 15° form a single HTC peak. The peak is highest for the experiment with 7° spacing, where the nozzle configuration makes a "high density spot" of water on the roll surface. The maximum HTC values for 7° are about 40 000 W/m2K, for 15° about 30 000 W/m2K and for
30° about 15 000 W/m²K. The average values of HTC are plotted in Fig. 11. The nozzle spacing of 15° seems to be the most efficient.

Fig. 9 Scheme of configuration with nozzle spacing of 7°, 15° and 30°

Fig. 10 Distribution of cooling intensity for spray configuration in Fig. 9

It should be noted that total cooling efficiency does not depend only on HTC values but also on a combination of HTC and surface temperatures. Identical HTC distribution removes much more heat when the sprays are near to the exit from the rolling gap where the highest surface temperatures are found.

Fig. 11 Heat transfer coefficient (HTC) for three different nozzle spacings around the roll
Cooling using bored holes

Older mills still using drilled holes rather than the installation of nozzles for coolant distribution are still common so cooling intensity and distribution for this type of cooling was also measured. The nozzles used in the above measurements were replaced by drilled holes with diameters of 5 and 8 mm. An identical flow rate was used for the holes as for the nozzles. A single hole, a group of 4 holes and a group of 7 holes were tested.

All experiments of spraying made by drilled holes produced a narrow cooling pattern with a high HTC peak at the axis.

Surprisingly, the average HTC values in the position of the spray axis are about seven times higher for 7 nozzles than for a single hole. Cooling provided by the jets from drilled holes produce only a narrow HTC footprint. The comparison made between the use of flat jet nozzles at a spray angle of 60° to the drilled holes at an identical flow rate can be seen in Fig. 12.

When comparing the average HTC values of flat jet nozzles versus holes we find about a 10-25% higher efficiency when using the nozzles. However, the drilled holes can provide an advantage if cooling demands are to be concentrated in a small area. Even for this purpose, the solid jet nozzles would provide an advantage due to the poor repeatability shape of the jet formed by drilled holes.

![Fig. 12 Heat transfer coefficient distribution for nozzles and drilled holes with identical flow rates](image)

Cooling optimisation

An example of cooling optimisation of a roll for U-beam rolling is given here. The design of cooling starts with an analysis of the contact areas between the roll and the rolled material. This is not a simple task because the initial material cross-section is plastically deformed and the shape of the groove can be complex. Figure 13 shows the initial shape and position of the rolls and the final position of the rolls with the final U-beam. The deformation of material and the shape of the contact area in the groove are computed by FEM (finite element method). There are areas in the groove that have prolonged contact with the rolled material, becoming highly thermally loaded. Other places in the groove are only in short contact with the deformed material and their thermal load is insignificant.
The thermal load of the deformation model is used as an input to a numerical thermo-mechanical model of the roll. This model uses the advantage of roll symmetry, as shown in Fig. 14. This thermo-mechanical model of the roll provides the temperature and stress fields in the roll during rolling.

The thermo-mechanical model is used for a study of thermal stresses in the roll during rolling. The model provides a comparison of cooling influences on thermal stresses in all important areas and critical points. It is known from the rolling practice that the critical point of a U-shaped groove is in the corner - see the red arrow in Fig. 14. Most of the cracks and fatal failures of the roll are initiated in this corner of the groove.

Two cooling strategies were compared for the cooling of the roll. The first strategy uses the most intensive cooling inside of the groove. The first case is schematically shown in Fig. 15 on the left. The thickness of the red beam schematically demonstrates cooling intensity. The second
case shows cooling at the roll head and side wall of the groove, as shown in Fig. 15 on the right. Case 1, as shown on the right of Fig. 15, is considered to be typical plant practice.

![Fig. 15 Scheme of two configurations of cooling intensity distribution; the thickness of the red bars represents cooling intensity](image)

Figure 16 shows the temperature field of the roll after a nine minute period of rolling. Case 1, on the left, shows where the bottom of the groove is cooled. The right of the figure demonstrates case 2, where the head and side surfaces are cooled.

![Fig. 16 Temperature fields in the cross-section of the roll for two cooling configurations](image)
Fig. 17 Plot of computed stresses in the corner of the U-shaped groove (see Fig. 14 for position identification). Lines in the picture represent the following stresses: cyan – radial, magenta – axial, red – circumferential, blue – maximal main

The result of computations show that overheating of the roll head, when using cooling configuration 1, causes an increase in tensile stresses in the corner of the groove with a tendency towards cracking in this position. Cooling configuration 2, (see Fig. 15 right), results in more favourable stress fields. Figure 17 on the right shows that only compression stresses are in the corner. This cooling configuration will prevent cracking and breaking of the rolls originating in the corner of the groove. The case study showed that optimal cooling must cover the head of the roll where there is no contact with the material. This result is contrary to usual mill practice.

The final step in cooling design is the fine adjustment of the nozzles in order to provide the best required cooling performance. The cooling setup is shown in Fig. 17. The laboratory groove is made to true scale and the selected nozzles are fixed to the headers. The steel sample is heated and the cooling intensity in the path below the spray is measured. The position of the thermocouples inside the material and the groove sample are shown in Fig. 18.

Fig. 18 Groove sample, showing embedded thermocouples for cooling tests used for final spray adjustment and the test sample
CONCLUSION

The design and optimisation of spray cooling of rolls is a complex heat transfer and mechanical task. There is no theoretical method available providing a description of heat transfer with acceptable precision. The only reliable data results from cooling measurements using a complete geometrical configuration.

These measurements show the advantages of the use of different nozzle types for roll cooling. The experiment examples included here, confirm that higher obtained values of heat transfer coefficient are found in the use of full cone nozzles when compared to those found in flat jet nozzles, when considering use in the application of long product rolling. The use of a combination of different types of nozzles should be considered for the most effective cooling results.

Clarification of the role of spray parameters on cooling ability is the first step in the design of efficient cooling. Headers for rolls used in long product rolling, are specifically designed to take account of groove shape and distribution of thermal load on the groove surface. The FEM model of rolled material deformation provided thermal load distribution data. The optimal cooling configuration minimises thermal cracks of the roll and distributes cooling compatible to the thermal load of the rolls.

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REFERENCES