Synopsis

The Water-Quench System developed by NKK has an advantage of producing high strength cold rolled steel sheet with low cost. However, when it is used for the production of drawing quality (DQ) cold rolled steel sheet, the process can not prevent the excess cooling. Therefore, additional energy cost is necessary to raise the strip temperature to the temperature required for the overaging treatment. To overcome this disadvantage, NKK has newly developed the Roll Quench (RQ) process which does not produce this reheating energy cost.

The RQ process consists of cooling the steel strip by contact with internally water-cooled rolls. For the development of RQ process, various basic heat transfer data were requested for the design of system. Contact thermal conductance between the surface of strip and roll were investigated. Thermal behaviors of roll shell were analyzed through theoretical simulation. Mathematical model of the RQ process was established, which is useful for both the design and operation of RQ process.

I. Introduction

The continuous annealing process with a water quenching system (abbreviated to WQ) known as the NKK-CAL WQ process, was introduced in 1971. It is used in the production of drawing quality (DQ) cold rolled steel sheet used for the manufacture of automobile parts, electric appliances, and other products. The CAL process has been appreciated in the industries.

The NKK-CAL WQ process, which cools the strip at a very high rate, can produce high strength cold rolled steel sheet with tensile strength ranging from 40 to 140 kg/mm² at low cost, and can also manufacture drawing quality cold rolled steel sheet with superior aging properties with only 1 min overaging treatment. However, because of the very high cooling rate, this process had a disadvantage when it was used for the production of drawing quality cold rolled steel sheet. It is difficult to stop over cooling due to the fast cooling rate with previous cooling system. This necessitated additional energy costs to raise the strip temperature to the temperature required for the overaging treatment, approximately 400 °C. Due to the rise in energy prices in recent years, NKK has recently developed the Roll Quenching system (RQ) to overcome this disadvantage. As shown in Fig. 1, the RQ process cools down the steel strip water-cooled rolls. The cooling rate of this process is lower than that of WQ; however, it is rapid enough to precipitate supersaturated solid solution carbon (above 100 °C/s). Depending on the line speed or the strip thickness, the control of the strip temperature at the termination of the cooling is easily made by adjusting the contact length of the strip with the water-cooled roll. The cooling ability of the RQ process is much affected by the contact thermal conductance between the steel strip and the shell of the roll. There are fluctuations of the contact thermal conductance, due to the
change of the normal pressure between the strip and the roll-shell arising from line tension. It is very important to keep the cooling ability of RQ process constant, and to cool the strip uniformly across the direction of strip width. Moreover, contact and non-contact between the roll shell and the strip are repeated periodically. It is important to predict the final cooling ability of the RQ process because the cooling process is an unsteady process. Therefore, we carried out the basic experiment for the contact thermal conductance and simulated the thermal behavior of roll-shell by theoretical analysis in order to obtain the important information necessary for design and operation of the RQ process. The knowledge about contact thermal conductance and the model for the cooling ability of water-cooled roll which are shown in this report are very profitable for operation of our RQ process. A full commercial scale RQ system has been installed in No. 2 CAL of the Fukuuyama Works, and the outline of this system is also presented in this report.

II. Basic Research for Contact Cooling with Water-cooled Rolls

1. Theoretical Considerations

The process of cooling the strip with water-cooled rolls was planned using a simplified model of a roll quenching system with one roll as shown in Fig. 2. The strip is cooled through heat transfer on its contact surface with the roll, conduction heat transfer in the roll shell, and convection heat transfer to the cooling water. In such a case, the overall heat transfer coefficient $U_0$ between the cooling water and the strip can be defined using their actual measured temperatures.

$$ U_0 = \frac{pC_dpV}{\ln \left( \frac{\theta_e - \theta_w}{\theta_i - \theta_w} \right)} $$

where, $U_0$: overall heat transfer coefficient (kcal/m²·h·°C)
$p$: density of strip (kg/m³)
$C_d$: specific heat of strip (kcal/kg·°C)
$V$: line speed (m/h)
$\theta_e$: outlet strip temperature (°C)
$\theta_i$: inlet strip temperature (°C)

In Eq. (1), $\theta_e$ and $\theta_w$ are the mean temperature in strip thickness. $U_0$ in Eq. (1) is the significant parameter in designing the RQ process, and it would be very profitable if, in advance, $U_0$ could be estimated from the conditions of the facilities and the operation. When thermal resistances exist as layer-by-layer, equation for the overall heat transfer coefficient $U_0$ is known in general. To apply this equation for the shell of the water-cooled roll and the strip in Fig. 2, the following equation is obtained.

$$ U'_w = \frac{1}{\frac{1}{h_w} + \frac{1}{\lambda_s} + \frac{0.5d_r}{\lambda_s}} \text{(2)} $$

where, $d_r$: thickness of roll shell (m)
$h_w$: contact thermal conductance (kcal/m²·h·°C)
$\lambda_s$: thermal conductivity of roll shell (kcal/m·h·°C)
$\lambda_i$: thermal conductivity of strip (kcal/m·h·°C).

On the other hand, the roll shell is heated by the strip at the contact area and cooled down by the cooling water at the non-contact area. This heating and cooling process is repeated periodically, so that $U_0$, which shows the cooling ability of the actual RQ system, is obtained at unsteady thermal states. Contrary to this, $U'_w$ of Eq. (2) is in steady thermal states. Therefore, $U_0$ and $U'_w$ are generally very different from each other, and it is impossible to predict the cooling ability of the actual process from Eq. (2).

Another difficulty in the prediction of $U_0$ is the uncertainty of the value of contact thermal conductance $h_c$ in Eq. (2). It is presumed that the term $1/h_c$ in Eq. (2) is major compared to the other terms $1/h_w$, $d_r/\lambda_s$, $0.5d_r/\lambda_i$ and affects mainly to $U_0$. Moreover, as the strip contacts the roll shell at a normal pressure caused by line tension. The degree of influence on $h_c$ is very important because it arises from the fluctuation of the normal pressure. For these reasons, a series of the basic experiments for contact thermal conductance was performed, and the cooling characteristics of the unsteady process with the rotation of the water-cooled roll were investigated.

2. Basic Experiments for Contact Thermal Conductance

I. Experimental Procedure

To measure the contact thermal conductance $h_c$, the experimental apparatus shown in Fig. 3 was prepared. The apparatus consists of a pair of axisymmetric metal blocks with the contact surfaces of 10 mm² for heat transfer. The upper block with the maximum diameter of 160 mm is made of steel and has an electric heater inside, corresponding to the high temperature strip. The lower ones with water-cooled fins are made of steel and copper to correspond to the water-cooled roll shell. These test
blocks are surrounded by bricks for thermal insulation. In the cylindrical parts of both blocks with 10 mm diameter, one-dimensional steady heat flux is generated, and the temperature gradients of both cylinders are measured by C-A thermocouples which are inserted into the center of the test blocks.

The temperatures of the contact surfaces of both blocks are obtained by extrapolation of these measured values. Further, the heat flux \( q \) and the contact thermal conductance \( h_c \) are calculated from the following equations (3) and (4), respectively:

\[
q = -\lambda_0 \left( \frac{\partial T}{\partial x} \right)_n = -\lambda_1 \left( \frac{\partial T}{\partial x} \right)_l \quad \text{(3)}
\]

\[
h_c = \frac{q}{(\theta_n - \theta_l)} \quad \text{(4)}
\]

where, \( (\partial T/\partial x) \): vertical temperature gradient in the cylindrical part \( (°C/m) \)

\( \theta \): temperature \( (°C) \)

\( \lambda_0, \lambda_1 \): thermal conductivity of test blocks \( (\text{kcal/m·h·°C}) \)

\( u, l \): suffix indicating upper or lower block.

The normal pressure at the contact surface was varied by the screw 4 in Fig. 3 being monitored by the load cell 5. The temperatures of the contact heat transfer surfaces of each of the blocks were controlled by the heater current. In this experiment, the roughness of contact surface has been kept constant; 5 \( \mu \text{m} \) as \( R_z \) (maximum height of peak to peak in surface profile). To prevent the oxidation of the contact surfaces, a small amount of nitrogen gas was injected near the contact surfaces.

2. Results of Experiment

An example of the temperature distribution measured in the test blocks is shown in Fig. 4. In the cylindrical part near the contact surface, the temperature distributions are linear. Therefore, it is clear that the one-dimensional heat flux has been realized. In the case of Fig. 4(a), which is supposed to be a steel roll, the same temperature gradient in the cylindrical part is obtained in both blocks. However, when the materials of the two blocks are different, the temperature gradient is not the same. The values of the heat fluxes calculated from this data coincided well with each other, and reliability of the experiments were confirmed.

Figure 5 shows the relation between contact thermal conductance and surface temperature of the upper block (supposed to be strip) obtained by Eqs. (3) and (4). The example corresponding to the copper roll is Fig. 5(a), and the example of the steel roll is Fig. 5(b). In Fig. 5(a), the heat flux can not depend on the capacity of the heater. Therefore, the maximum temperature of the contact surface of upper block has been limited to below 400 °C. Normal pressure is a parameter in both figures.

The contact thermal conductance is higher in copper than in steel, and is dependent much on the normal pressure. This should be explained by the difference of hardness between copper and steel.

The relation between contact thermal conductance and normal pressure is shown in Fig. 6. Contact thermal conductance was expressed by Tachibana as follows when the surface roughness of both materials are same.8)

\[
h_c = \frac{10^4}{(\delta + 23)} \cdot P \left( \frac{\lambda_N \cdot \lambda_L}{\lambda_N + \lambda_L} \right)^{10^6} \cdot \frac{10^6}{\delta} \quad \text{(5)}
\]

where, \( H_v \): Vicker's hardness of smaller one \( (\text{kg/mm}^2) \)

\( P \): normal pressure \( (\text{kg/cm}^2) \)

\( \delta \): peak-to-peak roughness of contact surface; \( R_z \) (\( \mu \text{m} \))
The term \( \frac{P}{H_v} \left[ \frac{\lambda_H \cdot \lambda_L}{\lambda_H + \lambda_L} \right] \) in Eq. (5) is calculated from the thermal conductivity and the Vicker's hardness of copper and steel at various temperatures, and is shown in Fig. 7 in relation to the contact thermal conductance. It is evident from Fig.

7 that the form of Eq. (5) is applicable to both the copper rolls and the steel rolls. The calculated value of \( h^- \) from Eq. (5) is also shown in Fig. 7.

Tachibana has obtained Eq. (5) from the data of over 15 kg/cm² normal pressure. Nevertheless, the results of our experiments showed a tendency to agree very well with it. Most research works on contact thermal conductance reported hitherto are concerned with the case of fairly large normal pressures. In continuous annealing line of steel strip, where the unit tension in the strip is \( \sigma \) kg/mm², and the radius of water-cooled roll is \( R \) mm, the normal pressure \( P \) kg/mm² is expressed by the following equation (6):

\[
P = 100\left(\frac{d_s}{R}\right) \cdot \sigma
\]

As \( P \) is lower than about 0.6 kg/cm², because \( \sigma \) is about 3 kg/mm² at most and \( R \) is about 500 mm, but there is little data of \( h^- \) with such a low normal pressure.

From the results described above, the following Eq. (7) is obtained. It predicts the contact thermal conductance at low normal pressure which has not been reported.

\[
h^- = K_1 \left( \frac{P}{H_v} \right) \left( \frac{\lambda_H \cdot \lambda_L}{\lambda_H + \lambda_L} \right) + K_2
\]

where, \( K_1, K_2 \): constants determined by the surface roughness of the roll and the strip \((-\).

Our experimental results and Eq. (7) are very useful in predicting the cooling rate of the strip while designing the RQ process.

### III. Overall Heat Transfer Coefficient of the Water-cooled Roll

1. Analysis of Unsteady Heat Transfer with the Rotation of the Roll

In the cooling process of RQ system, the roll shell
is heated and cooled periodically. Therefore, the cooling characteristics of the RQ process can not be predicted exactly from Eq. (2), because the roll shell is in an unsteady thermal state. The theoretical calculation of the unsteady heat transfer process of a single water-cooled roll was carried out, and the overall heat transfer coefficient $U_0$, which should be obtained in actual process, was estimated. The calculations have been performed for the heat transfer in the direction of the roll radius, by the finite difference method of the one-dimensional differential equation with a cylindrical coordinate. Basic differential equation is shown as Eq. (8):

$$
C_p \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial r} \left( \lambda \frac{\partial \theta_i}{\partial r} + \frac{1}{r} \frac{\partial \theta_i}{\partial r} \right) \tag{8}
$$

where, $C_p$: specific heat (kcal/kg·°C)
$r$: radial co-ordinate (m)
$t$: time (h)
$\theta$: temperature (°C)
$\lambda$: thermal conductivity (kcal/m·h·°C)
$\rho$: density (kg/m³)
$i$: suffix indicating roll shell or strip.

Boundary conditions are as follows:
1) Strip surface not contacted with water-cooled roll radiative and convective heat transfer to surroundings.
2) Contact surface of strip and roll shell heat flux $q$ kcal/m²·h is given by Eq. (9):

$$
q = h_c(\theta_s - \theta_r) \tag{9}
$$

where, $\theta_s$: temperature of contact surface of roll shell (°C)
$\theta_r$: temperature of contact surface of strip (°C)

3) Outer surface of roll shell of non-contact with strip same as the outer surface of the strip in the case of non-contact strip.

4) Inner surface of roll shell heat flux $q_w$ kcal/m²·h is given as convective heat transfer by cooling water; Eq. (10):

$$
q_w = h_w(\theta_i - \theta_w) \tag{10}
$$

where, $\theta_i$: temperature of inner surface of roll shell (°C)
$\theta_w$: temperature of cooling water (°C).

This calculations were performed with the rotation of the roll, adjusting the heat balance of the system. The flow of the calculations is illustrated in Fig. 8. Figure 9 shows an example of the calculated results. Under the calculating condition in Fig. 9, the temperature change of the roll shell with every rotation converged in a constant pattern about 3 min after the start of the cooling. This corresponded to about the 80th rotation of the water-cooled roll, which is a stational thermal cycle. In Fig. 9, the temperature distribution profiles of the radial direction in the roll shell at this stational thermal cycle are shown when the contact angle with strip is 45 and 90 deg, at the starting point of contact (inlet) and the end point of contact (outlet), respectively. The temperature of the outer surface of the roll shell varies about 30 °C between inlet and outlet in this case.

2. Influence of Conditions of Installation and Operation on $U_0$

From the simulation results mentioned above and Eq. (1), the overall heat transfer coefficient $U_0$ of both the single roll and the plural rolls were obtained. This should correspond to that of actual process.

Hence, we studied the degree of influence which should be affected by each parameter of the actual process on $U_0$.

1. Material of Roll Shell and Normal Pressure

The relations between $U_0$ and the contact thermal conductance $h_c$ are shown in Fig. 10, with the roll shell of copper and steel. $U_0$ nearly coincides with $h_c$ in the copper roll, but in the steel roll, $U_0$ is lower than $h_c$ owing to the smaller thermal conductivity of steel.
In practical operation, the factor which affects $U_0$ is normal pressure, so the relationship between $U_0$ and the normal pressure $P$ is shown in Fig. 11. From Fig. 6 and considering that the normal pressure $P$ in the continuous annealing process should be under 0.6 kg/cm² or so, the variation of $U_0$ will be about 2.0% at the copper roll and about 0.7% at the steel roll at most, if the strip is assured to be in contact with the water-cooled roll. Therefore, the fluctuation of the normal pressure is not so important to $U_0$, but rather a minor factor.

Further, in Fig. 10, $U_0$ calculated by Eq. (2) are also shown which are much different from the simulation results, indicating that Eq. (2) is not proper to predict $U_0$.

2. Heat Transfer Coefficient of Cooling Water

Figure 12 shows the influence of the heat transfer coefficient $h_w$ of cooling water on $U_0$. As in the total thermal process, $h_w$ is large enough and not a major factor, the variation of $U_0$ is only about 7.0% even if $h_w$ is varied from 5 000 to 10 000 kcal/m²·h·°C.

3. Thickness of Roll Shell

Figure 13 shows the relationship between the thickness $d_r$ of the roll shell and $U_0$. The degree of change in $U_0$ is larger in the steel roll, which has a lower thermal conductivity, than in copper roll.

4. Roll Contact Angle of Strip

The larger the contact angle becomes, the lower $U_0$ decreases as shown in Fig. 14, and the degree of change in $U_0$ is larger in the steel roll than in the copper roll. This is because the ratio of the cooling time for the roll shell decreases with the increase of contact angle, and the mean temperature of the roll shell becomes higher. Thermal behavior like this is due to the unsteady cooling mechanism of the Roll Quench process. Further, some other parameters have been studied, like the starting temperature of the cooling, the roll diameter, the line speed, etc. From these results, we summarized as conclusions:

1) The major factors of $U_0$ are as follows:
   i) material of the roll shell,
   ii) thickness of the roll shell,
   iii) contact angle, and
   iv) starting temperature of cooling.

(2) If the contact angle is constant, $U_0$ is not so much changed by the roll diameter and the line speed. Consequently, in actual process, as the contact angle becomes smaller when the roll diameter is large and the line speed is low, $U_0$ becomes larger.

(3) In the major factor described above the con-
tact angle is variable in operation, and much attention shall be paid to the apportionments of the contact angle. From this information, we have simplified the model equations of $U_0$ for practical use as Eqs. (11) and (12).

For steel roll; $U_0 = 20.1h_\theta^{0.80}d^{-0.22}g^{-0.28}$ .......(11)
For copper roll; $U_0 = 3.15h_\theta^{0.90}d^{-0.052}g^{-0.052}$ .......(12)

where, $d$: thickness of roll shell (mm)  
$h_\theta$: contact thermal conductance (kcal/m²•h•°C)  
$U_0$: overall heat transfer coefficient (kcal/m²•h•°C)  
$\theta$: contact angle (deg)

IV. Cooling Characteristics in Roll Quench Process

1. Outline of Roll Quench Process in Actual Production Line

A full commercial scale RQ system has been installed in the No. 2 CAL of Fukuyama Works in February, 1982 (cf. Fig. 1). The number of water-cooled roll is five, with roll diameter of 800 mm.$^6$ At first, the combination of the copper roll and the steel roll was adopted.

However, it was revealed that cooling rate obtained by the steel roll was higher enough to assure the mechanical property of the products with short over-aging time. Therefore, from the standpoint of the cost of installation and endurance, all the water-cooled rolls are now installed with steel. Table 1 shows the specifications of the water-cooled roll equipment of the actual production line. The strip thermometers have been equipped at the inlet and outlet of the Roll Quench section, and the water-cooled roll is fitted with a lifting device to vary the length of its contact with the strip. This makes automatic control of the outlet strip temperature possible.

2. Cooling Characteristics

The overall heat transfer coefficients $U_0$ obtained in the actual line are shown in Fig. 15 in comparison with those predicted by Eq. (11). Both values coincide very well, showing the reliability of Eq. (11). The relation between the cooling rate and the strip thickness is shown in Fig. 16. In the thickness range of 0.4 to 1.6 mm, the cooling rates are obtained 100 to 450 °C/s.

3. Product Quality

The cooling rates, obtainable by this quenching system, vary depending upon the strip thickness as shown in Fig. 16.

Figure 17 shows the relations of the cooling rate and the aging index (A.I.) and the time required for the overaging treatment. Basically, the time required for the overaging treatment decreases with the increase of the cooling rate; however, there is little

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<thead>
<tr>
<th>Table 1. Specification of RQ.</th>
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<tbody>
<tr>
<td><strong>Line specification</strong></td>
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<tr>
<td><strong>Line speed (mpm)</strong></td>
</tr>
<tr>
<td><strong>Strip size</strong></td>
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<tr>
<td><strong>Thickness (mm)</strong></td>
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<tr>
<td><strong>Width (mm)</strong></td>
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<tr>
<td><strong>Number of rolls</strong></td>
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<tr>
<td><strong>Material of rolls</strong></td>
</tr>
<tr>
<td><strong>Overall heat transfer</strong></td>
</tr>
<tr>
<td><strong>coefficient (kcal/m²•h•°C)</strong></td>
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<tr>
<td><strong>Contacting length (m)</strong></td>
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<td><strong>Flow rate of cooling</strong></td>
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<td><strong>water (l/h, each roll)</strong></td>
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difference in the time required for the overaging treatment at the cooling rates from 100 to 400 °C/s. Thus, it can be said that the water-cooled rolls with respect to the cooling rate are satisfactory. Moreover, using low carbon capped steel and low carbon Al-killed steel as materials, the mechanical properties obtained by this quenching system have been investigated.

As a result, all the cold rolled steel sheets manufactured by the Roll Quench process employing various heat cycles (CQ, DQ, DDQ) have superior properties including surface finish and shape equivalent to those of the conventional WQ-CAL process or the batch annealed steel sheets.\(^5\)

V. Conclusions

To reduce the reheating energy cost for the overaging treatment in WQ-CAL process, a new quenching system with water-cooled rolls has been developed.

In the first stage of the basic research, contact thermal conductance, which was an important factor in the designing of the system, was studied by experimentation. Further, the calculation of the unsteady heat transfer with the rotation of the water-cooled roll was performed, and the thermal behavior of the roll shell has been cleared up. The model equation which predicts the overall heat transfer coefficient \(U_o\) of the actual process has been obtained also. A lot of phenomena observed in the actual process can be explained from this model of \(U_o\), which is useful for designing and controlling the system.

A full commercial scale RQ system installed in the No. 2 CAL of Fukuyama Works has been operating successfully, reducing the reheating energy cost of the drawing quality (DQ) of the WQ-CAL process.

REFERENCES