Improving thermo-mechanical rigidity of caster rolls in continuous casting machines

By M O El-Bealy*

A mathematical model has been developed to predict the deflection of caster rolls – and hence the resulting internal quality of cast slab – under various conditions of temperature, roll material and ceramic insulating coating on the roll. It predicts the minimum thickness of coating required and shows that while cast-iron rolls require a thicker coating than steel their deflection is less.

The concept of thermo-mechanical rigidity has been developed to optimise caster roll resistance to thermo-mechanical and friction stresses in continuous casting machines. The idea behind this concept is to maximise the roll resistance against the various stresses by using two approaches. One is by minimising the heat flow from the cast steel slab to the roll by insulating the roll surface. The other is to improve the mechanical properties of the roll material. A mathematical model of thermal, solidification, stress analysis and cooling conditions has been developed based on earlier approaches. The model predicts that increasing the insulating layer thickness or decreasing its thermal conductivity decreases the peak surface temperature of the roll at in the contact area with the slab and results in a decrease in roll deflection and surface wear. The model predictions also show that improving roll mechanical properties increases roll performance and life.

The design of continuous casting machines has entered a new era to meet the demands for improved product quality, higher productivity, reduced energy use and the need for a clean environment[1,2]. The design of the mechanical parts of casting machines requires careful attention to prevent defects in the cast product[3]. One of the most important mechanical parts affecting the slab inner quality is the caster roll[4]. Therefore, to achieve these gains, the process has been mathematically modelled to improve the design of this component.

Several designs[5-7] and mathematical models[8-10] have been developed to improve the performance of the caster roll by minimising its deflection, optimising its life and reducing maintenance costs. The problem which arises is that the design of the roll should provide high performance and a long life while ensuring good slab quality. Because the roll is heated during casting due to contact with the slab, the roll is subjected to large differences in its resistance to the mechanical forces experienced.

Design methodology & Thermo-Mechanical rigidity

In the model, the roll is treated as a simple distributed and composite beam Fig1(a). The beam is subjected to mechanical stresses produced by the ferrostatic head under different roll temperature distributions due to the unsteady heat flow between the surface of the slab and the supporting roll. Consequently, the elastic line of the system can be formulated from the following equation Fig 1(a) [11-13];

$$y = \int_{0}^{l} \frac{M}{EI_R} dx^2$$  

(1)
where $y$, $M$, $E$ and $I_R$ are deflection, bending moment, modulus of elasticity and roll moment of inertia, respectively.

The author previously proposed design methodologies based on an approach for rigidity[14]. The method was designed to improve the elastic limit of thermo-mechanical and dynamic systems (TMDS) by minimising the deflection of TMDS by using three techniques. These techniques are explained in details in Reference 14. In this study, the second technique will be used to explain the details of mechanical components working in such unsteady thermal fields. There is a need to optimise the internal thermal fields by minimising the temperature gradients. Therefore, equation (1) for composite beam becomes:

$$y = \int_0^l \frac{M}{EI_R} \, dx^2$$  \hspace{1cm} (2)

where $E$ is the average modulus of elasticity of a composite roll and is equal to;

$$\bar{E} \approx \frac{1}{R} \sum_{i=1}^{n} E_i(T_i) \Delta r$$  \hspace{1cm} (3)

where $R$, $E_i$, $T_i$ and $t_i$ are the radius, modulus of elasticity, temperature and thickness of element $i$, respectively.

and $E_1(T_1) \ll E_2(T_2) \ll \ldots \ll E_n(T_n)$   \hspace{1cm} (4-a)

This is due to $T_1 \gg T_2 \gg \ldots \gg T_n$   \hspace{1cm} (4-b)

For symmetry, non-uniform roll temperature distributions, can be calculated by using the following equation[11-13]:

$$I_R = \sum_{i=1}^{n} \sum_{k=1}^{N} f_k \left[ \Pi_i \right] \Delta r$$  \hspace{1cm} (5)

Equations (2) to (5) show that the roll core temperature distribution controls the value of average modulus of elasticity. Therefore, the thermal methodology was designed to add a surface insulated layer with low thermal conductivity and low friction coefficient as shown in the roll section Fig 1(b).

Where $T_1^{\prime} \gg T_2^{\prime} \gg \ldots \gg T_n^{\prime}$   \hspace{1cm} (6-a)

but $T_1^{\prime} \ll T_1$, $T_2^{\prime} \ll T_2$, $\ldots$, $T_n^{\prime} \ll T_n$   \hspace{1cm} (6-b)

However, in the case of changing the mechanical properties of complete system, the deflection equation is;

$$y = \int_0^l \frac{M}{E_m I_R} \, dx^2 = \frac{1}{E_m} \int_0^l \frac{M}{I_R} \, dx^2$$  \hspace{1cm} (7-a)
whereas in the case of changing especial areas in the mechanical system, it can be formulated as follows;

\[ y = \int_0^l \frac{M}{E_j I_R} \, dx^2 = \frac{1}{E_1 I} \int_0^{s_1} M + \frac{1}{E_2 I} \int_{s_1}^{s_2} M_2 + \cdots + \frac{1}{E_{n-1} I_{n-1}} \int_{s_{n-1}}^{s_n} M_n + \frac{1}{E_n I_n} \int_{s_n}^l M_n \, dx^2 \]  

(7-b)

In the case of changing the material or modulus of elasticity of complete mechanical system;

\[ y = \int_0^l \frac{M}{E_m I_R} \, dx^2 = \frac{1}{E_m I} \int_0^l M \, dx^2 \]  

(8-a)

whereas in the second case of changing the material type, the modulus of elasticity \((E_m)\) changes in some regions modifying the deflection equation to be formulated as in (8-b);

\[ y = \int_0^l \frac{M}{E_j I_R} \, dx^2 = \frac{1}{E_1 I} \int_0^{s_1} M_1 + \frac{1}{E_2 I} \int_{s_1}^{s_2} M_2 + \cdots + \frac{1}{E_{n-1} I_{n-1}} \int_{s_{n-1}}^{s_n} M_{n-1} + \frac{1}{E_n I_n} \int_{s_n}^l M_n \, dx^2 \]  

(8b)

Subsequently, the thickness of the roll coating \((\delta)\) is seldom known exactly. Therefore, it is customary to determine the minimum layer thickness \((\delta_{min})\) as a function of process variables and the following equation (9) can be used;

\[ \delta_{min} = \frac{D_R}{A} \left[ \frac{\lambda_{ins}}{\lambda_R} \right] \left[ \frac{2l}{D_R} \frac{A_c}{A_R} \right] \left[ \frac{T_{RS} - T_{room}}{T_S - T_{RS}} \right] \]  

(9)

It is proposed to calculate the maximum deflection of simple distributed and composite beam \((y_{max})\) (Fig1a) as follows[11-13];

\[ y_{max} = \frac{5P_x l^4}{384EI_R} \]  

(10)

However, it is well known that roll life is inversely proportion to friction energy \((E_f)\) and the following equation was used[11];

\[ E_f = ff_cP_z A_c v \]  

(11)

where \(f, f_c[16], P_z, A_c\) and \(v\) are the friction coefficient, correction factor, total specific pressure at level \(z\), roll contact area and casting speed, respectively. In this system, equation (11) can be rewritten as;

\[ E_f = f (1 + \frac{T_{room}}{T_{RS}})(P_z + w_g) R^2 v \]  

(12)
where $T_{\text{room}}$, $T_{\text{RS}}$, $p$, $w_g$, $R$ and $\theta$ are room temperature, roll surface temperature, ferrostatic pressure, slab weight force, roll radius and contact angle, respectively. In the case of vertical position, $w_g$ is equal to zero. The values of different friction coefficient contacts are summarised in Refs[15-18]. A new approach to test the improvement in the quality of thermo-mechanical systems by using non-dimensional parameter[19] is proposed and can be calculated as;

$$T_{MR\text{Roll}} = \left( \frac{I}{I_1} \right) \left( \frac{D_R}{IP_z^2} \right) \left( \frac{1}{\nu_m(n_c)_m^2} \left( \frac{E_R}{E} \right) \right)$$  \hspace{1cm} (13)

Equation (13) describes the roll thermo-mechanical rigidity and consists of two main parts. The first part is the thermo-mechanical part and the second is thermo-material part. The first part includes the ratio between the actual moment of inertia of the roll which can be calculated for room temperature[11-13] as;

$$I_R = \frac{\pi D_R^4}{64}$$ \hspace{1cm} (14)

Also, this part contains the roll geometry such as roll diameter ($D_R$), roll length ($l$) and ferrostatic head at level z ($P_z$) in the dominator of equation of equation (13). The second part consists of process variables and material factors. In the nominator of this part of equation (13) the roll contact area ($A_c$) appears whereas in the dominator, they appear as, casting speed ($v$) and time spent in the roll contact area ($t_c$). Also, ($m^k$) is the exponent of solid phase ($k$) determined experimentally from uniaxial creep tests. The modulus of elasticity ratio appears also between the modulus of elasticity at the average temperature of the roll core and the ideal modulus of elasticity as shown in equation (13).

Heat flow & solidification models

The mathematical models have been developed from the first principles based upon the general frame-work for governing equations of heat flow, solidification, and cooling conditions. These models are to simulate casting 0.12%C steel and the caster roll steel. The equations are summarised in Refs[8-10,19] and the reader is referred to the original references for the details of the mould, the assumptions, properties of the steel and nomenclature made in the derivation. The validation of these models experimentally was published in the series of Refs[7,8,16] where good agreements were found.

A 2-D mathematical model for the long transverse cross-section of the slab shown in Fig. 2 is used with explicit finite-difference mesh. Relying on symmetry, a uniform grid was adopted for a slice across one quarter of the slab cross section as it moves downward as the steel shell forms at the slab casting speed. The initial and boundary conditions employed to simulate different thermal fields in the slab and caster rolls are illustrated in Refs[8-10,19]. The effect of various cooling conditions especially for the upper spray cooling zones on the Newtonian heat transfer coefficient profile between a pair of rolls was simulated by using El-Bealy’s approach[8,9,19].
Predicted results

The effect on roll deflection of the characteristics of the sprayed insulating layer on the roll surface caused by modifying the heat flow is illustrated in Fig 3(a) for variations of the heat transfer coefficient (h) between a pair of rolls located 0.8-1m from the meniscus for low, and medium thermal conductivity coatings. The results are summarised in Table 1. The predicted results illustrate that there is no difference in the h profiles except in the roll/slab contact area. This is due to a significant change in the thermal resistance of the roll surface. Fig 3(b) demonstrates the effect of different surface layer thickness on friction energy. Not surprisingly, the only difference in h appears in the roll contact areas where h increases with decreasing coating thickness ($\delta_c$)[4,8,18].

Table 1 Characteristics of the roll coating and roll material properties[13,14,15]

<table>
<thead>
<tr>
<th>COATING MATERIAL</th>
<th>Thermal Conductivity (W/mK) ($\lambda_c$)</th>
<th>Friction Coefficient (f)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK) ($\lambda_c$)</td>
<td>1.25</td>
<td>1.67</td>
</tr>
<tr>
<td>Friction Coefficient (f)</td>
<td>0.23</td>
<td>0.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ROLL MATERIAL</th>
<th>$E$ (N/m²)</th>
<th>$\lambda_R$ (W/mK)</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron</td>
<td>1.90x10⁹</td>
<td>23.0</td>
<td>0.29</td>
</tr>
<tr>
<td>Forged Steel</td>
<td>2.14x10⁸</td>
<td>31.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Special Treatment</td>
<td>2.45x10⁸</td>
<td>32.4</td>
<td>0.32</td>
</tr>
</tbody>
</table>

$E$ = modulus of elasticity  
$f$ = Friction coeff

The model was next applied to test the history of the roll surface temperature ($T_{RS}$) over a complete cycle as seen in Fig 4(a & b). This history reveals a steep reheating of the roll surface in the roll/slab contact area followed by rapid decreasing in $T_{RS}$ in the remainder of the roll circumference. Fig 4(a) illustrates the effect of the different thermal conductivities ($\lambda_c$) shown in Table 1. The predictions indicate that the roll surface temperature reaches a peak value in the roll contact area where it depends completely on the characteristics of the ceramic surface layer coating of the rolls. This peak decreases with decreasing coating thickness $\delta_c$[18]. The results shown in Fig 4(b) reveal the effect of various $\delta_c$ values on $T_{RS}$. The same trend appears with differences in the peak temperatures in the roll contact area where the peak value decreases with increasing $\delta_c$.

Roll performance and roll life analysis

Fig 5(a) shows that the effects of coating thermal conductivity ($\lambda_c$) and coating thickness ($\delta_c$) on the maximum deflection of the roll ($y_{max}$) are significant. Also, it is concluded from these results that the effect of $\delta_c$ is higher than the effect of $\lambda_c$ and maximum roll deflection ($y_{max}$) depends completely on the effect of the heat transfer from roll surface to roll core. The effects of $T_{RS}$ on friction energy ($E_f$) are plotted in Fig 5(b). The same trend of different effects of $\lambda_c$ and $\delta_c$ on $E_f$ appear in Fig. 5(b) where these affect vitally the roll wear and therefore, its life. The predictions shown in this figure illustrate also that $E_f$ and roll wear is inversely proportional to roll surface temperature ($T_{RS}$). Roll wear decreases steeply blow 350°C and decreases with increasing roll coating thickness $\delta_c$ especially when $\delta_c$ is greater than 50µm as shown in Fig. 5(b).
Roll thermo-mechanical rigidity

Fig 6 reveals a gradual decrease in the roll’s thermo-mechanical rigidity (TMR\textsubscript{Roll}) with increasing roll surface temperature (T\textsubscript{RS}). Another interesting result arises from comparisons between TMR\textsubscript{Roll} and both maximum deflection \( y_{\text{max}} \) from one side and friction energy \( E_f \) from the other at the same temperature. The comparisons illustrate that thermal mechanical rigidity of the roll (TMR\textsubscript{Roll}) increases with a decrease of both \( y_{\text{max}} \) and \( E_f \) as shown in Figs 5(a & b), respectively, and (Fig 6).

Roll Materials Properties

Roll performance and roll life analysis

Figs 7(a-c) show the results come from examination of values of computed \( y_{\text{max}} \) for cast iron, forged and special treated roll steels, respectively, where \( y_{\text{max}} \) behaves similar to the preceding examinations at different roll operating conditions. It can be seen that the contact area of the ceramic roll surface coating has a significant effect on the value of \( y_{\text{max}} \) under steady state thermal conditions. However, the results in the case of a ceramic roll surface layer indicate that \( y_{\text{max}} \) is lower in the case of an uncoated cast iron roll than in the cases for the two uncoated steels as shown in Figs 7(a-c). This is due to the effect of the different thermal conductivities. Also, it arises from the different roll surface temperatures experienced by the various roll materials and their effects on the magnitude of the heat flux from the roll surface into the roll core. These predcitions agree quite well with experimental observations[1,4].

Fig 8 shows a comparison of the computed friction energy \( E_f \) for different operating conditions. The results point out that the ceramic layer on the roll surface has a vital effect on the value of \( E_f \). The predictions demonstrate that while the \( E_f \) of the special treated steel is lower than that for the forged steel at the various roll surface temperatures examined as seen in Fig 8, the \( E_f \) of the special treated steel is still higher than for cast iron.

Thermo-mechanical rigidity

Fig 9 illustrates that TMR\textsubscript{Roll} decreases if there is no ceramic coating on the roll or with increasing roll surface temperature. The results show that TMR\textsubscript{Roll} depends completely on the thermal conductivity of the roll material, roll surface temperature, roll core temperature distribution and therefore on the heat flux from the slab into the roll core. This affects directly the change in the average roll core temperature with time. However, an insulating ceramic surface layer on the roll increases TMR\textsubscript{Roll} for each of the different roll materials. The value of TMR\textsubscript{Roll} is highest for the coated cast iron roll compared to the forged or special treated steels. The greater TMR\textsubscript{Roll} value for coated cast iron is due to the significant differences in core temperature distribution with time and therefore the effect of this temperature gradient on the average modulus of elasticity as shown in equation (3).

Minimum Thickness of Ceramic Layer

The predicted results illustrated in (Fig 10) generally show that the minimum roll surface layer thickness \( \delta_{\text{min}} \) needed to be effective increases with the increasing thermal conductivity ratio as presented in equation (9). Also, it is concluded that this ratio should not exceed 0.1 to achieve a significant effect on the roll performance, roll life and therefore, on the inner quality of the continuously cast steel slab.
It is interesting to note that cast iron rolls require a greater minimum coating thickness than both types of steel rolls. This arises from the conclusion from Figs 7(a-c), and it is due to the difference in roll design. In the case of Figs 7(a-c), the design base depends only on the thermal conductivities of the roll material and the average modulus of elasticity whereas in the case of (Fig 10), the design depends on the ratio between these two values. The effect of temperature differences appears in the last part of equation (9) but it is still the difference between the two designs approaches which is negligible.

Summary and Comment

A new approach to maximise the thermo-mechanical rigidity of caster rolls has been proposed. Two dimensional (2-D) mathematical models have been developed to simulate the surface temperature of the slab and that transferred to the caster rolls as well as to optimise the design of an insulating surface layer on the roll. The following main conclusions can be drawn from this investigation:

• A ceramic insulating coating on the roll surface has a significant effect on reducing heat transfer in the contact region between the roll and slab and thus reduces the surface temperature of the roll.

• The maximum deflection of the roll ($y_{max}$) and friction energy ($E_r$) depends significantly on the surface temperature and material type of the roll.

• Roll thermo-mechanical rigidity and the minimum required thickness of the insulating coating on the roll surface depend significantly on the insulating properties of the ceramic coating and on the mechanical properties of the roll material.

Acknowledgement

The authors are indebted to Companies' Chair for Materials Processing and Technology of the Swedish Iron Masters Association (Jernkontoret), Stockholm, Sweden, for financial support of this investigation.

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Nomenclature

\( A_R \) Roll contact area

\( D_R \) Roll diameter

\( E \) Modulus of elasticity

\( E_F \) Friction energy

\( f \) Frictional coefficient

\( f_c \) Correction factor

\( h \) Heat transfer coefficient

\( I_R \) Roll moment of inertia

\( I \) Roll length

\( M \) Deflection of roll

\( m^k \) Exponent of solid phase k of slab

\( p \) Ferro-static pressure

\( P_z \) Total specific ferro-static pressure

\( R \) Roll radius

\( t_c \) Time in roll contact area

\( T_{MRoll} \) Thermo-mechanical regidity

\( T_{MDS} \) Thermo Mechanical Dynamic System

\( T_{Room} \) Room temperature

\( T_{RS} \) Roll surface temp

\( v \) Casting speed

\( w_g \) Slab weight force

\( y_{max} \) maximum roll deflection

\( \delta_c \) Coating thickness

\( \kappa_c \) Coating conductivity

\( \lambda_c \) thermal conductivity of coated Material
Continuous casting

Fig 1 Schematic drawing of simple distributed composite beam

Fig 2 Schematic of caster roll and grid for computation on quarter cross section of slab

Fig 3 Variation of heat transfer coefficient (h) for different a) coating thermal conductivity $\lambda_c$ and b) coating thickness ($\delta_c$).

Fig 4 Variation of roll surface temperature ($T_{RS}$) with time for different a) coating thermal conductivity $\lambda_c$ and b) coating thickness ($\delta_c$).

Fig 5 Variation of a) maximum roll deflection ($y_{max}$) and b) Friction energy ($E_f$) under various surface conditions.
Continuous casting

Fig 6 Variation of thermo-mechanical rigidity $TMR_{roll}$ of roll under different roll surface conditions

Fig 7 Variation of maximum roll deflection ($y_{max}$) for different roll materials a) cast iron, b) forged steel c) Special treated steel at various roll surface temperatures

Fig 8 Variation of Friction Energy ($E_f$) for different roll substrate materials and ceramic coatings

Fig 9 Variation of thermo-mechanical rigidity of roll ($TMR_{roll}$) for different roll materials and ceramics coatings

Fig 10 Variation of minimum coating thickness $\delta_{min}$ for different roll materials and ceramics coating