Wear of Roll Surface in Twin-roll Casting of 4.5% Si Steel Strip

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The rolls are one of the most important components of the twin-roll casting process, determining not only strip quality, but due to their expense, add to the price of the as-cast strip. The potential for reducing operational cost and ensuring required strip quality may be achieved through a reduction in wear of the roll surface and hence reduced frequency of roll surface reconditioning and replacement. To achieve this, it is imperative to understand the mechanisms of roll surface wear which occur during casting operations.

2. Problem Description

The advantages inherent in the twin-roll casting process do not in itself ensure a competitive advantage in the production of strip if the strip is not of a commensurable price and acceptable surface quality. The efficiency of the twin-roll casting process and the quality of the as-cast strip are considerably influenced by roll surface topography and its stability.

The rolls are one of the most expensive components in twin-roll casters, thus strongly influencing the price of the as-cast strip. The potential for reducing operational cost may be achieved through a reduction in the wear of the roll surface and hence a reduction requirement for reconditioning.

Production of this as-cast strip drastically increases the demands on cast quality. Since the surface to volume ratio of the as-cast strip increases with a decrease in thickness, even a slight surface defect causes a serious reduction in the as-cast strip quality, hence the need to increase control of the roll surface topography.

The surface topography of the roll is the most important factor in formation of the strip quality insofar as it influences heat transfer at metal-roll interface, the metallographic structure of the as-cast strip, its surface roughness and inhomogeneous cooling and surface crack formation on the strip surface.

The as-cast strip is a semi-product which requires some post treatment. The surface roughness of as-cast strip, determined by the topography of the roll surface in the casting process, is important in post treatment operations of the strip insofar as it influences the cold rolling process, the stamping process, annealing operation, surface coating and painting.

To be able to ensure the required quality of the as-cast strip, it is necessary to control the topography of the roll...
surface. To achieve this, it is imperative to understand the mechanism of roll surface wear which occurs during casting operations. It is of particular interest to relate the influence of liquid metal attack, roll separation force and effect of strip incline to the roll surface wear.

The term wear remains a subject of some debate, so to avoid confusion in this discussion the term wear in this work is accepted as “damage to a solid surface, generally involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances”.

3. Experimental Equipment and Procedure

3.1. Twin-roll Casting Process

An experimental investigation was carried out on a twin roll caster schematically showed in Fig. 1. Steel melt was prepared from 50 kg ingots which were melted under an argon atmosphere in an induction furnace, yielding the following composition: 4.5% Si, 0.0013% Cu, C<0.007%, P<0.010%, Ni<0.07%, Ti<0.02%, Co<0.02% and Al<0.01%.

The superheat was maintained at ~30°C and the melt entered the gap between the rolls through a slot in a ceramic nozzle. The cylindrical, water-cooled rolls constructed from Cu–Cr sleeves were ~440 mm in diameter and 150 mm in length. The casting speed was 7 m/s and the thickness of the as-cast strip 0.1–0.2 mm.

The roll surface before casting was treated with an emery wheel. The roll surface obtained in this manner was further treated with fine emery paper to obtain a roughness of the roll surface, 𝑅𝑎 = 0.4 μm.

The roll separation force per unit length of the roll was varied between 0.5 and 3.0 kN mm⁻¹.

The influence of strip slip on wear of the roll surface was estimated by the variation of the angle of the strip incline from the vertical as shown on Fig. 1. The angle was increased from 0 to 50 degrees. Strip tension was applied during casting operation.

For chemical analysis, samples were cut off at the same position of as-cast strips. Samples surface was cleaned by emery papers and then cleaned in an ultrasonic cleaner.

3.2. Proceeding of Surface Roughness Measurements

Surface roughness of the roll and the as-cast strip were characterised by the amplitude parameters 𝑅𝑎 (arithmetic mean deviation of profile irregularity); 𝑆𝑝 (mean spacing of profile irregularity) and hybrid parameter 𝑇𝑝 (profile bearing length ratio).

Measurements were done on an area of 10×10 mm² for each sample. The measurements were done with accuracy of 90% and reliability of 0.9. The accuracy and the reliability were estimated by published methods.

Reproducibility was estimated by comparison between the value of each measurement obtained by two different profilograph profilometers, a Kalibr Works, and a Surtronic-3P Rank Taylor Hobson. The measurements were obtained with 0.8 mm of cut-off value. If the variation between the compared results were more than 10%, the surface was remeasured.

Additionally the roughness of the roll surface was measured by a optical non-contact device.

3.3. Roll Surface Wear

The roll surface wear was evaluated by as follows

\[ ΔP = P_{\text{after}} - P_{\text{before}} \] ...........................(1)

where \( P_{\text{after}} \) and \( P_{\text{before}} \) are parameters of roll surface roughness after and before the process of the casting respectively.

Parameters of the surface roughness between the Roll 1 and Roll 2 were compared as per Eq. (2)

\[ ΔP = P₁ - P₂ \] .................................(2)

where \( P₁ \) and \( P₂ \) are the surface roughness parameters which were measured on surface of Roll 1 and Roll 2 respectively (see Fig. 1).

Index of the roll wear intensity \( w \) was estimated as

\[ w = \ln \left( \frac{Ra_{\text{after}}}{Ra_{\text{before}}} \right) \] ..........................(3)

where \( Ra_{\text{after}} \) and \( Ra_{\text{before}} \) are surface roughness.

4. Results and Discussion

4.1. Influence of Melt on Roll Surface

Molten steel is fed into a gap between two rotating rolls, water cooled from the inside. As the melt enters the roll gap, it forms a melt bath as shown in Fig. 2. Solidification of the molten steel begins on the roll surface in the region which is very close to the meniscus of the melt bath.

The high velocity of the roll surface, the presence of impurities and oxidation on the melt/roll surface interface and roughness of the roll surface give rise to non-uniform wetting of the roll by the melt and formation of micro areas of non wetting and micro areas of direct contact between the melt and the roll surface. In the micro areas of direct contact the molten steel impinges on the roll surface causing the surface to melt and be washed away with the liquid steel as shown in Fig. 3.

Chemical analysis reveals small quantities of copper (the material of the roll surface) in the as-cast strip as seen in
Fig. 4 which may be interpreted as the effect of the melting and washing away of the roll surface by the steel melt. This micro melting and subsequent washing away of the roll surface leads to roughening. The amplitude and the distance between the micro peaks are increased as seen in Fig. 5. The profile of the micro-peak becomes with bigger radius of the tip as seen in Fig. 5. Schematic illustration of the micro-peak profile before and after interaction of the roll surface with the melt is shown in Fig. 3.

The profile of the micropipes of the roll topography during casting operation becomes more stable than the initial surface, due to the bigger cross section areas of the micropipes. The increased area of every single micropipe reduces the thermal load on the micropipe and as a result decreases the probability of it melting and being washed away by the steel melt. Probably the redistribution of the surface topography and the more stable profile obtained in the beginning of the casting process lead to the same slow down of changing of the roll surface roughness during further casting operation.34).

During further solidification, the roll surface separated from melt by the solidified shell. At this stage of solidification, the roll surface may lift off from the roll surface due to depression and distortion as shown in Fig. 2, which are attributed to thermal stresses exceeding the yield point of the material. As there is not enough contact between the shell and the roll surface to cause wear at this stage, the influence of shell growth on roll surface wear may be neglected.

4.2. Influence of Roll Separation Force on Roll Surface
4.2.1. Special Feature of Hot Rolling Process in Twin-roll Casting

Immediately after complete solidification, the steel undergoes a degree of hot rolling in the deformation area before leaving the roll bite. The metal starts to deform plastically when the pressure reaches the yield stress. By plastic deformation the metal is displaced from one location to another, as a result two directions of metal flows appear relative to the roll surface as shown in Fig. 2. On the entrance side, the metal flow is in the direction of melt bath and at the exit side in the casting direction. In the neutral section, the metal and the rolls move at the same speed. Metal at the entrance side to the neutral section moves slower and at the exit faster than the surface speed of the rolls.37,38)

The real area of contact between the as-cast steel strip and the roll surface is determined by the roughness of the surfaces, mechanical properties of the metals and the force applied to the interface.39)

Each single spot of real contact between two surfaces under the action of friction force may be represented as an ellipse shaped area of dimensions \(a\) and \(b\), along and across the direction of the movement, respectively. The normal compressive stress for each local small area can be given by

\[
\sigma_n = \sigma_{\text{along}} \frac{a}{a+b} + \sigma_{\text{across}} \frac{b}{a+b} \tag{4}
\]

where is the stress \(\sigma_{\text{along}}\) and the stress \(\sigma_{\text{across}}\) the direction of movement. According to the theory of plasticity by Sokolovskii,40)

Fig. 2. Schematic diagram of strip formation between rolls and distribution of specific pressure along the arc of the deformation zone. The shape of the specific pressure was drawn in accordance with direct measurements done by Boichenko et al.37)
Substituting Eqs. (5) and (6) into Eq. (4) gives the normal compressive stress $\sigma_n$ between two solid bodies with rough surfaces, in contact under a friction force:

$$\sigma_n = k \left( \frac{2 + \pi - 2\mu}{a + b} \right) \left[ 2 + \pi - \left( \frac{1}{2} \right) \mu \right].$$

where $k$ is the resistance to shear, $\mu$ is coefficient of plastic friction.

Equation (7) shows that the normal compressive stress in metal being deformed equals

$$\sigma_n = \beta \sigma_y \ln \frac{F_o}{F_o - F_R} \quad \text{.........(8)}$$

where $\sigma_y$ is yield strength of the metal, $\beta$ is Lode’s coefficient, $F_o$ is the geometrical area of contact and $F_R$ is real area of contact induced by plastic deformation. In the case for plane strain where $\beta \sigma_y = 1.15 \sigma_y = 2k$, the equation for the normal compressive strain takes the following form:

$$\sigma_n = 2k \ln \frac{F_o}{F_o - F_R} \quad \text{.........(9)}$$

or

$$\frac{F_R}{F_o} = 1 - \exp \left( -\frac{\sigma_n}{2k} \right) \quad \text{.........(10)}$$

The average shear stress on contact for maximum friction force takes the following form:

$$\tau_s = k \left[ 1 - \exp \left( -\frac{\sigma_n}{2k} \right) \right] \quad \text{.........(11)}$$

where the coefficient of friction is

$$\mu = 1 - \exp \left( -\frac{\sigma_n}{2k} \right) \quad \text{.........(12)}$$

From Eq. (7) it follows that the normal compressive stress depends on friction force, and can not reach the maximum due to absence of full mechanical contact $F_R/F_o \ll 1$. The shear stress is not high enough to reach the maximum friction due to certain peculiarities of deformation in the twin-roll casting process.

The hot deformation in the twin-roll casting process is different from the usual rolling technology. The temperature gradient through the as-cast strip gives rise to non-uniformity of the yield stress between the centre and the surface layers. Plastic deformation in the strip thickness is localized in the strip centre due to the higher temperature and lower resistance to plastic deformation. The higher temperature layer in the centre of the strip thickness is squeezed out in the direction of the molten bath. Figure 6 illustrates the squeezing out of the centre layer in the strip thickness. The tips of the columnar crystals are bent opposite to the casting direction. Another difference between strip deformation in the twin-roll caster and conventional rolling is the unequal squeezing of metal along and across the roll length. In the twin-roll caster this squeezing out occurs by spreading metal along the roll length. The plastic deformation...
in the centre and the plastic deformation by spreading lead to a reduction in backward slip of the as cast strip on the roll surface and hence give rise to reduce friction in the early stages of plastic deformation. These effects differentiate the deformation of strip in the twin-roll casting from the conventional rolling processes where the strip is deformed through the strip thickness more uniformly and to a greater extent in the rolling direction.43)

### 4.2.2. Roll Wear

Increasing roll separation force leads to an increase in both the amplitude and the distance between the micro-peaks on the roll surface as shown in Fig. 5. This means that it is not only the roll surface but also the roughness of the as-cast strip that affect the roll surface. It is proposed that an increase in pressure along the deformation zone, as illustrated in Fig. 2, increases the heat transfer due to better strip/roll contact and consequently, increases the temperature of the roll surface. At some stage in the deformation zone it is therefore surmised that the temperature of the strip and roll surfaces reaches a value such that the roll surface becomes softer than the strip, and the strip begins to grind the roll surface. Conversely, in the earlier stages of deformation when the difference in roll/strip temperature is such that the roll is harder than the strip, slipping results in roll surface roughness imparting scratches upon the strip surface as shown in Fig. 7.

In general roll wear phenomena may be explained by two mechanisms, roll skidding on the strip surface at the entry to the deformation zone and then digging the strip surface in the area of the roll in the neutral section as illustrated in Fig. 3. The roll surface skids on the strip before entering the neutral section in the deformation zone due to relatively low friction. This suggestion agrees well with the theoretical calculation mentioned above. Scratches on the strip surface imparted by the roll in the casting direction are evidence of roll skidding on the strip surface, see Fig. 7. Imprinting of the highest micropeaks on the strip into the surface of the roll in the neutral section also influences surface roughness of the roll surface. During the shell growth and shrinkage as well as roll skidding, the strip surface moves relative to the roll surface, so the highest micropeaks of the strip surface dig into “new” areas of the roll which leads to an increase in the roll surface roughness.

### 4.3. Influence of Grinding of Roll Wear by Strip

#### 4.3.1. Mathematical Formulation

A micro-peak of the strip may be represented as a cone with semi angle \( \alpha \) which as shown in Fig. 8. Under load \( N \) this micro-peak cone intrudes into the softer roll surface to
a depth, \( H \) and makes a cone mark with radius \( r \) on the roll surface. The depth of penetration \( H \) depends on surface smoothness of the surfaces and friction force between them.\(^{43}\) The force \( N \) induces on normal force \( \sigma \) and shear stress \( \tau \) on the elemental area of the cone surface \( dS \) (as shown in Fig. 8). These stresses compensate the force \( N \) over the total surface area of the cone. Under equilibrium the load may be written as a sum of the forces;

\[
N = \int \sigma \sin(\alpha) dS + \int \tau \cos(\alpha) dS \tag{13}
\]

where \( dS = rd\ell/2 \sin(\alpha) \); \( d\ell = r d\varphi \); \( dS = r^2 d\varphi/2 \sin(\alpha) \).

Since \( \tau = \mu \sigma \), Eq. (13) may be rewritten as

\[
N = \frac{\pi r^2 \sigma}{\sin(\alpha)} [\sin(\alpha) + \mu \cos(\alpha)] \tag{14}
\]

In Eq. (14) the multiplier before the bracket gives the sum of the normal forces acting on the contact surface of the cone. Increasing the contribution of the tangential force \( T \) causes the cone to move and the tip rises to the surface by a distance \( z \) (see Fig. 8). This movement causes some volume of the metal to be placed outside of the cone, inducing an additional friction force, \( t_r \), which in turn reduces friction force \( T \). The actual movement of the cone begins when the value of \( T \) exceeds the static friction and kinematic friction occurs. At this point, the ratio between \( T/N \) may be written as

\[
\frac{T}{N} = \frac{1 - \mu \tan(\alpha)}{\tan(\alpha) + \mu} \tag{15}
\]

with the coefficient of friction, \( \mu \), given by:

\[
\mu = \frac{1 - T}{N} \frac{\tan(\alpha)}{\tan(\alpha) + \mu} \tag{16}
\]

Hence or \( T/N < 1 \) or \( (1 - \mu \tan(\alpha))/\mu (\tan(\alpha) + \mu) < 1 \), when \( \alpha \) is large.

Taking into account surface hardening due to the surface scratches by the cone, the condition of the equilibrium stress can be expressed as

\[
n N = \frac{f}{\pi r^2} = 0.5 \pi r_0^2 \tag{17}
\]

where \( f = N - t_r \cos(\alpha); \) \( r = H \tan(\alpha); \) and \( r_o = (H-z) \tan(\alpha); \)

for the condition of \( t_r = \mu R \cos(\gamma) \).

Substituting \( f, r, r_o \) into Eq. (17) gives

\[
n N \frac{H^2}{2} = 2 \frac{N - \mu R \cos(\gamma) \cos(\alpha)}{(H-z)^2} \tag{18}
\]

Substituting Eq. (15) into Eq. (18) and rearranging gives the final equation for the cone tip displacement, \( z \)

\[
z = H \left[ 1 - \frac{2 \tan \alpha}{n(\mu + \tan \alpha)} \right] \tag{19}
\]

where \( n \) is a coefficient of the deformation characteristics of the metal.\(^{43}\)

This movement of the cone leads to a scratch in the soft roll surface by the cone with displacement of the cone tip up to the surface and the formation of a chip at the front of the movement as illustrated on Fig. 8. The displacement of the cone tip leads to a reduction in the contact area between the two sliding metal surfaces. Only the highest micropeaks of the strip surface remain in contact and may grind the roll surface.

4.3.2. Experimental Measurements

To separate the influence of the strip slipping on the roll surface wear in the area where the strip leaves the roll bite, the strip was inclined relative to one of the rolls as illustrated in Fig. 1. The strip inclination combined with an applied forward tension, leads to asymmetrical rolling.\(^{45}\) One feature of this asymmetrical rolling is a difference in the extent of strip slip on the different surfaces of the roll pair.\(^{46}\) The slip zone on the roll to which the strip is tilted is increased and reduced on the roll from which the strip is tilted away. Comparison of the surface wear on the respective rolls after casting with an asymmetrical hot rolling deformation zone may elucidate the effect of strip slipping on roll wear.

Roll wear on the roll pair is illustrated in Fig. 9. Strip slip on the roll surface leads to an increase in the amplitude of the surface roughness and to a reduction in the distance between the micropeaks. The shape of the average micropeak profile becomes steeper.
Increasing concentration of copper in the strip with an increase in the roll separation force (see Fig. 4) may be explained by formation of chips at the moving micro-peaks front (see Fig. 8). The chip formation depends on the ratio $H/\alpha$ and chips are easily formed when the value of the ratio is high. Presumably some of the chips are melted as soon as they reach the steel bath on roll rotation while other stick to the strip surface.

### 4.4. Intensity of Wear

The relative contribution to the roll wear of the liquid metal, roll skidding on the as-cast strip as well as strip surface digging into the roll surface and strip slipping on the roll surface may be estimated by comparison of the change in the roll wear with variation of the roll separation force and the angle of strip inclination.

The contribution of liquid metal to roll surface wear is estimated by casting strip at the lowest value of roll separation force ($0.5 \text{kN mm}^{-1}$) because this minimizes the influence of the hot rolling deformation process on roll surface wear. In this case the roll wear $w_1$ depends only on wear causes by liquid metal melt $w_{\text{melt}}$ and may be written as:

$$w_1 = w_{\text{melt}} \quad \text{(20)}$$

It is difficult to measure roll skidding from strip digging and to separate these two mechanisms. The contribution of roll skidding and strip digging in the deformation zone may be separated from other parameters by casting the strip with a known value of the roll separation force (1.5 kN mm$^{-1}$ in this instance) and with a pre-set angle of strip inclination (%45 degree in this instance). The strip inclination leads to asymmetry reduced slip zone on Roll 1 and an increased slip zone on Roll 2 (see Fig. 1). Wear $w_2$ on the Roll 1, consists of wear caused by liquid metal, $w_{\text{melt}}$, as well as the roll skidding and strip digging, $w_{\text{skid+dig}}$.

$$w_2 = w_{\text{melt}} + w_{\text{skid+dig}} \quad \text{(21)}$$

The contribution of strip slip in the deformation zone may be estimated by using the same roll separation force (1.5 kN mm$^{-1}$) but without strip inclination. In this case the roll wear $w_3$, consists of wear caused by liquid metal $w_{\text{melt}}$, roll skidding and strip digging, $w_{\text{skid+dig}}$, and by strip slipping on the roll surface, $w_{\text{slip}}$.

$$w_3 = w_{\text{melt}} + w_{\text{skid+dig}} + w_{\text{slip}} \quad \text{(22)}$$

Finally the contribution of each parameter to roll surface wear may be calculated:

- the melt contribution is equal to
  $$w_{\text{melt}} = w_1 \quad \text{(23)}$$
- the contribution of the roll skidding and the strip digging is equal to
  $$w_{\text{skid+dig}} = w_2 - w_1 \quad \text{(24)}$$
- and the contribution of the strip slipping is equal to
  $$w_{\text{slip}} = w_3 - w_2 \quad \text{(25)}$$

Comparing the index of roll wear intensity caused by the melt, roll separation force and the strip forward slipping on the roll surface is shown in Fig. 10. The main wear of the roll surface occurs in a very short time (several milliseconds) when the roll surface interacts with the steel melt in the early stages of solidification. Application of roll separation force increases the intensity of the roll wear which is mainly caused by roll skidding on the strip surface and the digging of the strip surface into the roll. Forward strip slipping on the roll surface in the area where the strip leaves the roll bite causes the lowest wear of the roll surface (Fig. 10). The small effect of the strip forward slip on roll wear may be explained by the small strip elongation in the twin-roll casting process.

### 5. Conclusion

Roll wear phenomena in the twin-roll strip casting process was investigated by measuring parameters of the roll surface roughness.

Roll wear is an inherently complex process which accompany both removal of material from the roll surface and a redistribution of topography on the roll surface. The roll wear depends on the interaction of the roll surface with the steel melt during solidification as well as with the strip during hot rolling deformation.

Application of a high roll separation force leads to increase in removal of the material from the roll surface and coarsening of the roll surface topography. During hot rolling deformation, the mechanism of the roll surface wear may be represented in the form of two processes imprinting the strip surface on the roll surface in the neutral section, and grinding the roll surface by the strip surface both before and after the neutral section. The grinding of the roll surface before the neutral section occurs by “roll skids”, as a result of a low friction force. The grinding of the roll surface after the neutral section is attributed contact slipping of the strip surface on the roll, as a consequence of strip elongation.

The effect of asymmetrical rolling a twin-roll casting operation shows negligible influence of the strip elongation caused by the hot rolling deformation on the wear of roll surface.

Even by application of high roll separation forces, the most intensive wear of the roll surface occurs by interaction of the steel melt with the roll surface in the very early stages of solidification.
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