**Enhanced paper:**

“Frequently Asked Questions about Hot Strip Mill Work Roll Surface”
(wear, oxidation, firecracks, sticking and fiction)

This was originally presented at the WMSP, New Orleans, 2004.

Dr. Karl Heinrich Schroeder
With British Rollmakers (China) Ltd.

Keywords: rolls, wear, oxidation, firecracks, sticking, friction

**Abstract**

The roll surface is crucial for work rolls in hot rolling mills. We have to deal with wear, oxidation, firecracks, sticking and friction. This paper starts with temperature simulations on and below the roll surface during rolling and takes common experience into consideration. The result/intention is to give help for new and better understanding of the changes on the roll surface. Rolling conditions including descaling and cooling are of similar - in some respect even higher - importance as the work roll quality.

**Introduction**

There are some frequently discussed questions between roll users and roll makers concerning the surface of work rolls. I will discuss here wear, oxidation (banding/peeling), firecracks, sticking and friction. There are a lot of practical experiences on either side about all these fields of troubles, but the reasons, explanations, excuses or “theories” to explain certain phenomena are often doubtful to say the least. The worst of all, many of the existing theories give nothing or even wrong hints for the development of roll grades and rolling technology.

The process of rolling, the contact of the roll with the rolled material is almost out of our reach: we cannot visibly watch, not measure anything in the roll gap and the process is very fast. Even easy questions – as “is this or that a result of one or many repeated contacts”, fatigue or not – is hard to answer. The only way to approach the roll gap is by computer simulation and by critical evaluation of well-known facts.

In the next chapter, I will explain the simulation calculations and summarize the results. In the following chapters, I will deal with five FAQs, always going back to experiences, followed by the results of simulation calculations to introduce my ideas and compare these with traditional theories.

At least for wear, oxidation, and firecracks I can offer something (as far as I know) totally new. The future will tell whether it is right or wrong.

**Simulation calculation**

Mill builder use different simulation calculations to build up the right model for rolling procedures. J. Seidel, from SMS-DEMAG, Germany, helped me out with the calculations of temperatures on and below the roll surface during hot rolling. The results are proven to be effective for hot rolling models, what gives me good confidence is that the achieved figures are reliably describing the situation in the rolls.

The calculations used a rolling schedule of a 6-stand CSP-mill, Figure 1, (rolling schedule and rolling parameters). Figure 1 also contains some calculated information, which I reckon are very interesting. “Contact time” is a big issue for oxidation.
**General information:**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR material</td>
<td>CR</td>
<td>CR</td>
<td>CR</td>
<td>AIC</td>
<td>AIC</td>
<td>AIC</td>
</tr>
<tr>
<td>WR diameter [mm]</td>
<td>760.0</td>
<td>770.0</td>
<td>750.0</td>
<td>500.0</td>
<td>450.0</td>
<td>480.0</td>
</tr>
<tr>
<td>Delivery thickness [mm]</td>
<td>15.9</td>
<td>7.0</td>
<td>3.9</td>
<td>2.3</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Relative reduction [%]</td>
<td>67.0</td>
<td>56.0</td>
<td>44.0</td>
<td>39.0</td>
<td>32.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Speed [m/sec]</td>
<td>0.9</td>
<td>2.0</td>
<td>3.6</td>
<td>6.0</td>
<td>8.9</td>
<td>11.3</td>
</tr>
<tr>
<td>Rolling force [kN]</td>
<td>22 200</td>
<td>16 400</td>
<td>22 800</td>
<td>12 600</td>
<td>11 800</td>
<td>9 400</td>
</tr>
<tr>
<td>Specific pressure [N/sqmm]</td>
<td>170.0</td>
<td>230.0</td>
<td>560.0</td>
<td>550.0</td>
<td>750.0</td>
<td>860.0</td>
</tr>
<tr>
<td>bite angle [degree]</td>
<td>17.0</td>
<td>9.0</td>
<td>5.0</td>
<td>4.5</td>
<td>3.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Contact length [mm]</td>
<td>110.0</td>
<td>58.0</td>
<td>34.0</td>
<td>19.0</td>
<td>13.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Contact time [msec]</td>
<td>120.0</td>
<td>30.0</td>
<td>9.0</td>
<td>3.0</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Calculated strip length [km]</td>
<td>7.8</td>
<td>17.6</td>
<td>32.0</td>
<td>52.0</td>
<td>78.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Contact revolutions</td>
<td>3 200</td>
<td>7 400</td>
<td>13 400</td>
<td>33 000</td>
<td>49 000</td>
<td>64 000</td>
</tr>
<tr>
<td>Total contact time [sec]</td>
<td>384</td>
<td>220</td>
<td>120</td>
<td>100</td>
<td>75</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 1: Rolling schedule of a 6-stand CSP-mill (SMS-DEMAG) and diverted figures.

Figure 2a: Work roll boundary conditions

Figure 2a shows one roll with the general information about the different zones for rolling gap, air-and-water-cooling and the contact with the backup roll.
Figure 2 b: Variation of Exit Side Cooling

Figure 3: Surface temperature of the roll during one revolution

Figure 3 gives for stand F 1 the circumferential temperatures of the surface of the roll, high temperature in contact with the hot strip, decreasing temperature during air-and-water-cooling with a sharp drop during contact with the back up roll.
Figure 4: Circumferential distribution on the roll of “maxima temperature minus surface temperature” (creating tensile stress)

Figure 4 shows for F 1 the difference between maxima temperature below roll surface and temperature at the roll surface – thermal tensile stress at the roll surface! In case the maxima temperature is at the surface, the difference is zero, which means compression stress at the surface or no thermal stress. The changes on the surface temperature (dT/dt) and the changes on the load (dP/dt) are very fast; the change speed of the resulting strain per time is in the range of impacts!

Figure 5: Roll temperatures (radius) for different angles.

Figure 5 represents the radial temperature distribution at different angles, the gradient of the temperature with distance from the surface is very high (dT/dr).
Similar calculations have been performed for all stands. For stand 1 – for academic interest – we applied some variations in the positioning of the cooling, of the heat-conductivity of work roll material and of the rolling speed. I took some important figures out of all these calculations and put them together in Figure 6; and these figures will deliver the base for our further considerations about firecracks.

<table>
<thead>
<tr>
<th>Stand number</th>
<th>max. temp. [°C] - at roll surface</th>
<th>max. temp.[°C] - 1 mm below surface</th>
<th>max. temp. minus surface temp. due to cooling water [°C]</th>
<th>max. temp. minus surface temp. due to b.u.r. [°C]</th>
<th>depth below surface in mm with tensile stress</th>
<th>depth below surface in mm with temp. variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 1</td>
<td>600</td>
<td>260</td>
<td>112</td>
<td>75</td>
<td>4</td>
<td>8.0</td>
</tr>
<tr>
<td>F 2</td>
<td>620</td>
<td>180</td>
<td>80</td>
<td>70</td>
<td>3</td>
<td>6.0</td>
</tr>
<tr>
<td>F 3</td>
<td>680</td>
<td>170</td>
<td>65</td>
<td>74</td>
<td>2</td>
<td>4.0</td>
</tr>
<tr>
<td>F 4</td>
<td>700</td>
<td>150</td>
<td>62</td>
<td>85</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>F 5</td>
<td>680</td>
<td>130</td>
<td>58</td>
<td>75</td>
<td>0.5</td>
<td>1.2</td>
</tr>
<tr>
<td>F 6</td>
<td>600</td>
<td>120</td>
<td>42</td>
<td>55</td>
<td>0.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Figure 6: Summary of important figures from the simulation calculations**

Remarkable results of simulation calculations, Figure 6, conclusions:

1. Roll surface temperature in contact with strip is similar for all stands and varies around 600 to 700°C depending on the rolling conditions.
2. 1 mm below the surface, the temperature does not exceed 260°C under normal rolling conditions. Temperature gradient along a radius (dT/dr) is very high; the temperature change at the surface with time (dT/dt) is even higher. Roll surface reaches contact temperature almost spontaneously (less than one msec. after contact!)
3. From stand F 1 to F 6 decrease:
   a. contact time (from 120 to 0.8 msec) and
   b. contact length (from 110 to 9 mm) between roll and strip
   c. bite angle (from 17 to 2.1 degree) and
   d. the zone/depth, where the temperature varies, (from 8 to <1 mm).
4. The total contact time of work roll surface and strip during a campaign of 100 km finished strip length is just about 6 minutes for stand F1 decreasing to less than 1 minute in F 6!
5. Low heat conductivity of work roll material or “early” cooling reduces the zone of temperature variations; late cooling or low rolling speed do the opposite.
6. “Skin cooling/roll gap anti-peeling cooling” - see chapter wear – reduces the roll surface temperature in the gap significantly and consequently the zone with varying temperatures during revolutions.

The stress situation on the roll surface is 2- dimensional, below is 3- dimensional. Pressure due to contact between roll and strip or back up roll (Hertzian pressure) acts in radial direction. Thermal stresses due to temperature gradients (of any kind) show high axial- and tangential/circumferential-stress, which are equal in size and sign, while the radial stress is zero at the roll surface and increases slowly with increase in distance from the surface. Residual stresses, stable within the working layer and of some importance for fatigue crack initiation and propagation, are compression stresses in axial and circumferential direction and they are equal in size and sign; the radial stress is 0 at the surface and increases slowly as tensile stress with the increasing distance from the surface.

I would like to show the stress distribution on the roll surface and below during one revolution, however, I am still waiting for someone to do the FE-calculations. The easy calculation to estimate the stresses does not give any figures of relevance.

**Wear**

Work roll in hot strip mills *wear due to friction* between roll surface and hot strip. (Back up rolls wear as well, but under pressure with elastic deformation, the friction is much less.) The wear is uneven from one end of the barrel to the other. We all know the various wear pattern curves for different work roll materials - many papers published these curves quite often. However, a nice shining, dark oxide layer always covers the roll surface, (almost?) from the beginning to the end of a campaign (as long as there is no banding/peeling – and we will cover this issue later in chapter "oxidation"). The only way that this, wear and a perfect oxide layer, can happen - in my imagination – is:

The oxide layer of the work rolls shears off more or less completely at least on the strip entry and exit side. Only in the neutral phase - there is no relative motion/friction between strip and roll surface – “lose” strip oxides (see chapter “oxidation”) are between everywhere. When the oxides are sheared off, there is direct friction between roll and strip material, the work roll wears! The oxide particles may increase the wear. After the rolling gap, the oxides are still “somehow” sticking to the roll surface. The cooling water - with relative low pressure - does not wash the oxides away. In the gap between work and back up roll, the back up roll” irons” the oxides onto the work roll surface to a smooth surface finish.

Now, after I imagine/understand how the work roll material gets into contact and friction with the strip despite the oxide layer and wears, the rest is easy: wear is similar to that of cutting tools and the development of roll materials for hot rolling mills follows the development of *cutting tools*. Wear of hot-mill work-roll material depends *strongly on the type and content of carbides, rather than on hardness*, (of course, there is a little bit what you can expect from higher hardness of a material but this is incremental compared with the potential improvement due to more and harder carbides). In the past, it became evident how effective especially very hard carbides are. Figure 7 compares the hardness of various roll materials, which – as everybody knows – have totally different wear performances. The hardness is in the same range for all of these materials, the carbide content is decreasing, however, the type, and amount of carbides varies widely.
Figure 7: Hardness, carbide content and carbide nature of typical work roll qualities

Figure 8: The influence of different alloying elements on wear

(Range of alloys: 0.30-0.44% C, 0.02-0.35% Si, 0.31-0.83% Mn, 1.18-4.03% Cr, 0.08-3.04% Mo, 0.26-1.92% V and 1.42-5.85% W) [13]
Fig 8 shows the dependence of wear from alloying elements and introduces an **alloy-equivalent**, which allows to rate the importance of the various elements.

![Alloy-Equivalent Table]

**Figure 9: Carbide- and extra hard particle forming elements**

Figure 9 gives more information about the effectiveness of the different elements.

![Wear vs. Alloy Equivalent Graph]

**Figure 10: Wear and roll grades**
The whole wear story for work rolls is put together in Figure 10, from the past to the far future. The wear performance of work rolls will further increase beyond HSS for big factors!

However, wear is only one - but not the only factor to make a “good roll”: wear, “strength” of roll material and residual stresses in the roll have to fit together. Compound rolls are a wonderful solution with different materials and properties for the working layer and the rest of the roll. Centrifugal casting (horizontal or vertical) of work rolls for hot rolling mills is state of the art. However, centrifugal casting magnifies segregations due to the high g-factor. Therefore, heavy- or light-weighted elements/particles may concentrate close to the outer or inner part of the liquid metal of the working layer after casting. This can be an advantage - but normally it is a disadvantage, creating gradients of properties where uniform material is required.

Strip “skin-cooling”, called “roll gap cooling or anti-peeling cooling” (see: Iron & Steel Technology, May 2004, p.27 ff) that is a high-pressure water-cooling of the strip surface directly before entering the roll gap, improves roll performance, reduces roll wear. We know this method since long (even people almost forgot this procedure for many years) and there is a standard explanation: reduced wear due to “soft oxides” on the strip. I do not know, whether this explanation is valid/right. In this very limited time (a fraction of a second) between water quench and entering into the roll gap, the oxides have to transform into the stable structure equivalent to balanced conditions. (Occasionally, in discussion some doubt came up) However, Voest Alpine (CCR’04, Hot rolling Seminar-Paper No. 11.6/Page 3 of 6) reported about layers of different oxides on the coiled hot strip, which they had investigated. The reason for better roll wear performance – in my opinion – should be suspect in the changed temperature distribution in the strip and related strain – nothing to do with the oxide structure or the roll material – and an additional descaling. However, for sure, skin/anti-banding cooling helps to reduce “oxidation” and wear!

**Oxidation**

Oxide layers cover the surfaces of work rolls in hot strip mill and give them a colorful appearance, somehow between yellow and black, especially in the early stand. This is typical for 4-high stands.

Figure 11: The prove that oxide layers need the b.u.r. in 4 high stands.

Without a back up roll the shiny oxide layer on the work rolls does not develop. We observed a work roll surface, picture 11, where the back up roll has had a circumferential groove (the back up roll barrel edge was repaired after a spall by a shrink fitted ring). Opposite this groove, there was no black oxide layer! This circumferential area was somehow metallic shining and very rough. This means the high specific pressure between work- and back up roll “irons” the oxides onto the work roll surface.
Plate mill b.u.r. are frequently repaired in this way, however, there was never a complaint about the “oxide layer inconsistency” like it is shown in picture 11. The reason could be, that in plate mills the work rolls are used for all passes and the oxide layer, which might build up in the first passes will disappear in later passes.

These oxide layers may have different thickness for various roll grades. This raised the question again and again, whether these oxides are originating from the sheet or the rolls. Many people/institutions carried out tests to prove the oxidation rates of different roll materials. However, we have to keep in mind:

1. The oxide layer builds up already after the first revolution(s)
2. In the rolling gap oxygen has no access to the roll surface
3. The temperature of the roll surface in the rolling gap does normally not exceed 700 C
4. The time in the rolling gap at “high” temperatures is only a fraction of a second in each revolution, see Figure 6.
5. The time when the strip is between descaler and F 1 or between the stands is much longer than in the rolling gap.
6. Oxygen has access to the strip everywhere outside the rolling gap.
7. Strip temperature is normally in the range of 900 to 1100 C.

Therefore, it is easy to understand that the oxidation of the strip for sure is relatively very much bigger than that of the roll, the relation of strip oxides to roll oxides might be 10,000:1 or even more! On the work roll there are oxides from the strip (as it was analyzed many times), no oxides from the rolls; forget the oxidation of the roll surface.

Why the oxides build up layers of different thickness on different roll grades is another open question, maybe related to the formation of fire cracks or various wear patterns. Both – fire cracks and wear – are influenced by the skin cooling/roll gap anti-peeling cooling. There is for sure some impact due to reduced temperatures on the strip surface entering the rolling gap and consequential on the work roll surface. At the same time, this cooling device operates as secondary descaler as well.

“Peeling” and “banding” of these oxide layers develop differently from mill to mill – even with the same/identical roll grade. Typically banding/peeling starts during rolling light gage with high reduction and slow rolling speed in the critical stands (most frequently on the bottom rolls of stands F 2 or F3) Interstand descaling and antibanding cooling should help because strip carries less oxides. In case the layers get too thick, the sheared off oxides may not stick any more to the surface or they are washed away from the roll cooling water, especially where the water flow is disturbed, for instance at the cross-points of the fire-crack network. Rolling heavy gauges with low reduction and high speed in the critical stands often repairs the oxide layers on the roll surface.

The Conclusion:
Rolling condition are more crucial for peeling and banding than roll grades.

Work rolls wear, with or without banding, peeling, and at the end, the worn rolls are thinner – but the oxide layer seems to be more or less unchanged from the beginning on.

Firecracks
Mill people know firecracks are forming during normal rolling in hot rolling mills for flat and long products. Fire-cracks appear in cold rolling mills only occasionally after rolling accidents. I will deal with hot rolling of flat products only, however, everything is valid for long products as well, only the stress situation in grooved rolls is more complicated. Fire-cracks on rolls develop only, when a “hot” roll surface is cooled/quenched rapidly, normally by cooling water. Fire-cracks are not “bad” in itself, but often they may cause spalls, initiate banding/peeling and change “friction” – see this chapter.

In hot strip mills:

1. Firecracks in the finishing mill decrease in depth and size of the network from the first stand to the last stand, they are almost invisible in the very last stand(s).
2. Firecracks develop during the first contact(s) with the strip, no fatigue problem, the most a (very) low cycle fatigue.
3. Firecracks form due to the maxima stress and are perpendicular to the surface (brittle fractures)
4. The worst condition for forming firecracks are mill stalls with strip in the stands; deep cracks and a coarse network pattern may lead to unproductive loss of roll stock. Procedures/strategies to reduce the firecracks due to mill stalls are available and often neglected.
5. Firecracks in AIC develop more easily into spalls (fatigue) than those in High Chrome rolls. HSS behaves probably similar to HCr in this respect.
6. The old theory for fire cracks based on plastic deformation and fatigue, however, evidence was never found or proved.

The most frequently used theory to explain the formation of fire-cracks is very old and was repeated again and again. Plastic deformations due to the thermal expansion at the roll surface in the rolling gap should cause whatever and finally create fatigue cracks. Nobody ever could verify any plastic deformation; nobody ever saw any sign of fatigue at firecracks! And everybody can calculate/show that the shear stress in the roll surface (respective close to the surface) in the rolling gap is not high enough for any plastic deformation. The surface is 3-dimensional under compression (thermal expansion stress plus rolling pressure) stress, which reduces the shear stress. Actually, the shear stress close to the work roll surface is higher in contact with the back up roll (thermal tension stress, see fig 6, high pressure) than in contact with the strip. Everybody knows: no firecracks – of course - in back up rolls! Furthermore, the critical shear stress is increasing with increasing speed of deformation and during rolling, the critical shear stress should be higher than tensile strength; this is the condition for brittle fracture and firecracks - for me - are brittle fractures. Furthermore, worst of all, the “old theory” (or call it speculations) does not allow to explain any of the above mentioned experiences and gives the wrong advice for developing better roll grades with finer fire-crack pattern.

In my understanding fire-cracks develop,

1. When the heated roll surface after the rolling gap reaches the water cooling zone, the surface under equal axial and circumferential tensile stress creates cracks in axial and circumferential directions, a network.
2. The cracks release the stress next to the cracks in the surface, the more the deeper the cracks are.
3. Crack depth depends on the heat penetration in and after the rolling gap (and on the height of residual stresses). Heat penetration, the size of the zone with tensile stress decreases from stand to stand. (see fig 6)
4. Continuing turning of the roll brings the next surface area behind the cracks building up tensile stress until new cracks will form. This process will repeat on and on.
5. At given crack depth the distance from crack to crack – the size of the fire-crack pattern – is proportional to the strength of the roll material.
6. FE-calculations are still missing and should prove this idea.

**Conclusion:**
Rolling conditions are crucial on fire-cracks; roll material of low strength suffers a fine network – high strength induce coarse networks

**Sticking**
The specific pressure between work roll and strip increases from the first stand up to the very last stand, at the same time the thickness of any layer of oxides decreases. Strip temperature decreases in the mill. Sticking of strip material to the rolls happens – if at all - in general in the very last stand(s). Only Alloyed Indefinite Chill rolls (AIC/ICDP) “never” do pick up strip material, do not stick.

In the early stands of the finishing mill, rolling most steel grades a sticking problem does not exist. Rolling carbon steels always starts with austenitic microstructure of the strip but before the last stand(s) maybe the microstructure transforms. The probability for ferrite is not high, because the time for any transformation – especially the time where the strip is in contact with the cold work roll – is very short. For continuous cooling the TTT-diagrams show, that in time less than 10 sec with temperatures below 700 C there is now microstructure transformation. Rolling ferritic, very low C-steels is no problem either, because in the early stands there are always “enough” oxides on the strip (and rolls) to prevent sticking.

Rolling Carbon-steels at very low temperatures may create big trouble for High Chrome rolls. Picture 12 shows the surface of a High Chrome roll in F 4 of a narrow strip mill where rolling temperatures about 700 C were normal, only AIC solved this problem. Similar results were reported from another narrow strip mill, however, HSS solved this problem as well.
Rolling ferritic stainless steel (even at higher temperatures with ferritic microstructure) is a special problem: “no oxides” on the strip, “no oxide layers” on the rolls. Sticking may happen in all stands of the mill – only AIC/ICDP (classical or carbide enhanced) is safe.

I never heard any complaint from plate mills about sticking, whether High Chrome or AIC/ICDP rolls were used (Rolling temperatures during “TM” rolling are very low). However, of course, here the rolls are used for all passes (oxide layers on the roll surface after the first passes will more or less disappear during later –closer to finishing - passes) and the surface of plate is never considered as critical as that of strip.

It seems, a “good relation of the matrix-microstructure of roll and strip” (some ferrite/perlite on both sides) is essential for sticking. Why/how and what this means in reality is a frequently discussed question. AIC/ICDP is different from all other roll materials:

1. It contains free graphite
2. It has the highest content of carbides in comparison with HCr or HSS.
3. The matrix is highly alloyed with Nickel (>4%), different from the other roll grades.

I, personally, do not believe in “graphite” (the old clear chill rolls without graphite did not stick either; that is what I heard), argument 1. No other roll grade is available with similar carbide content yet, argument 2. Test with 4% Nickel in High Chrome rolls, did not perform well, argument 3.

HSS with very fine distributed carbides (the content is always lower than that of AIC/ICDP) and never “big” isolated areas of matrix sticks in the very last stand occasionally (even the Japanese mills use still today ICDP rolls), however much less than High Chrome rolls. Therefore, probably it is a combination of facts 2 and 3, what makes AIC/ICDP so unique.

- The microstructure of roll material and strip are crucial for sticking
- In my understanding, sticking happens when under high pressure (favorable low temperatures of the strip) matrix material under friction welds to the strip. The smaller the areas of homogeneous matrix material are the lower the risk of sticking becomes.
- Carbides and graphite interrupt the matrix areas. HSS does stick less than High Chromes because the “little content” of carbides is connected with a very fine distribution of these carbides, which reduces the size of homogenous matrix – more carbides (finely distributed) would be even better against sticking. Austenizing temperatures beyond
1250 C (normal for cutting HSS) would for sure create more secondary carbides of MC type – however this is impossible with cast HSS with nodular core material.

- HSS should not stick with smaller areas of homogeneous – carbide free – matrix, so what is needed is HSS with “more, fine, equally distributed” carbides, either quenched from temperatures above 1250 C or with higher C-content and by optimized inoculation finest carbides.

**Friction**

Without friction – rolling is impossible. Friction between metal follows a law of nature, no discussions. The coefficient of friction between steel and any roll grade is very similar, no big variations! Lubrication of the rolling gap – of course – reduces friction.

For normal ground rolls, friction dictates the maximum bite angle as a function of rolling speed. In case the bite angle for a given rolling speed is too high, (or v.v. the rolling speed is too high for a given bite angle) shatter will happen. Experienced rollers know how to improve the roll bite: they create a wonderful fire crack pattern on the rolls by changing normal roll cooling. Some roller told me: After rolling some strips without water-cooling, they turn on cooling water and a nice fire-crack pattern develops immediately. The friction improves, not the materials are changed but the roughness is increased and this increases friction as well.

Therefore, the answer to all the discussions about coefficient of friction of different materials – often it is the comparison of HCr and HSS – is the change of the surface during rolling, mainly it is the development of the fire-crack pattern. Some mills do have - others do not have problems with changing friction (increasing separation force is necessary with higher friction). This means in one mill the roll surface suffers from the rolling process much more than the same type of roll in an other mill, what is just a question of rolling and cooling conditions. Lubrication helps to overcome actual friction problems, but it is the wrong way to attack this issue. As soon, as the fire-cracks are under control, discussions about the coefficient of friction will stop. The conditions for fire-cracks were discussed before.

- The coefficient of friction of different roll materials is very similar
- The roll surface in the mill has high impact on friction between roll and strip, which is something different from a coefficient of friction of roll materials
- The rolling conditions are crucial for the roll surface.

**Conclusion:**

1. Roll material has a high impact on wear and sticking, and less (but some) on firecracks.
2. Rolling conditions determine oxidation and to some extend fire-cracks (the influence of the rolling conditions is more important than that of the roll material).
3. Friction changes with the surface appearance of the work rolls, which changes continuously during each campaign, the roll material itself is of minor influence.
4. Material with high content of very hard particles (carbides, or....) give best wear results.
5. Roll material with low thermal conductivity reduces temperature penetration into the roll and the depth of firecracks.
6. Roll material with “low strength” give a finer fire-crack pattern than high strength material.
7. Skin cooling of strip reduces roll wear and gives better performance, what is known and practices since 40 years or so.
8. Banding/peeling is caused by sheared off strip oxides from the roll surface under certain rolling conditions, only in 4-high stands. Inter-stand strip cooling/descaling is very useful to reduce/avoid it.
9. To create the “everlasting” work roll for hot strip mills, we need some fantasy:

    - Hard particles create high wear resistance (1).
    - Low strength and low heat conductivity reduce fire-cracks and give a very fine pattern (5, 6)
    - Of course – with no thermal expansion, there would be no thermal stress and no fire crack at all.
    - This material, hopefully, does not tend to stick to the strip (not even to ferritic stainless steel).
    - When the rolling conditions will fit, there will be no wear, no banding, no sticking, and no problem with firecracks and no change of friction.
• I reckon the best would be the “right HSS coated with hard metal”.
• Let us dream!