Rolling conditions in hot strip mills and their influence on the performance of work rolls

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**Summary.** The mechanical rolling conditions in hot strip mills are precisely defined by various variables, which are taken directly from the rolling schedule (separation force, torque, speed, strip thickness) or calculated from figures of the rolling schedule and dimensions of the mill (strip reduction, roll diameter etc.). These variables allow to describe the mechanical rolling conditions of all passes in roughing and finishing mills. These variables should be supplemented by the metallurgical rolling conditions. They then give basic information on the conditions which determine wear (specific load, wear speed) and firecrazing (co-efficient of heat penetration etc.).

There is a good chance to use the experiences of other mills with various roll grades by analog comparison - as long as the rolling conditions are similar. This method is limited by “abnormal rolling conditions”, which require totally different roll grades, although if it would be much better to eliminate the abnormal conditions.

**Introduction.** In hot strip mills, slabs of 1.50 to 250 mm thick are rolled to strip 1.5 to 12 mm thick. Conventional hot strip mills consist of roughing and finishing stands. The configuration of the roughing mills varies widely. A mill with one reversing stand is called a semi-continuous mill. A mill with one reversing stand and one or two continuous roughing stands is called a % continuous mill and a mill with 4 to 6 continuous roughing stands is called a continuous mill.

In 3/4 continuous and continuous mills, the first stands are usually two high stands while the remainder are 4 high stands. In addition to these horizontal stands, several edgers are also used. The finishing mills have a minimum of 4 stands but normally have 6 or 7 stands.

Rolling conditions vary from mill to mill, stand to stand and pass to pass. Mill configurations are designed for a desired total strip (thickness) reduction, however, each stand is limited in strip reduction by the maximum separation force, maximum torque, risk of slippage etc.

In order to supply the correct roll for each mill, roll makers ask for details of the rolling conditions and any special circumstances. However, how to use this information? How to compare the conditions of pass No. X and No. X + ??? There have been many discussions over the years but rarely any really good results with these comparisons. For example, looking at roughing mill work rolls, there are so many roll grades being used in different mills that it is evident that the optimum grade to yield the maximum quality for all applications has not yet been found.

To date, no theories have been proved. In fact, in many instances the combination of experience and roll performance in the mills is totally contrary to the theories of yesterday and today.

Even the finest theory does not help if a roll grade fails:

- Banding in roughing stands never created problems. The handing problem in finishing mills has not been solved by any roll grade. And there is little hope for change in future.
- There is no single outstanding quality for roughing mills which out-performs all other qualities in every application. This is because rolling conditions vary widely.

In this paper an attempt is made to identify some variables which are independent of the mill and the passes in the mill, and then to analyse the “rolling conditions”. The bases for these analytical studies are actual rolling schedules for similar strip dimensions and qualities from different mills and experience with different roll grades in these mills. We have to identify the different variables for every stand and for every pass and then try to find the relationship between these variables and the performance figures for different roll grades. All information about special practices in the mills for producing good strip profile and flat strip, which are of high importance for mill people, are not considered because they probably have no influence on the choice of the correct roll grade. The initial idea was to answer all questions, to solve all problems by having rules for roll wear and firecrazing. We very quickly found that this was impossible. Even with the most sophisticated methods, because we can only study “normal rolling conditions” and very often the so called “abnormal conditions” are every day occurrences. And only the simple figures from the rolling schedules are available and no actual information on loads, torque or the real temperature distribution on strip and rolls, nothing about change of roll surface during service (wear, oxide layer), nothing of the total rolling programme (length, coffin shape etc.).

Therefore, we will try to define the rules for normal conditions and the other problem, to eliminate the “abnormal” conditions, is up to the mill people. Finally, we have to prove how good our variables for rolling conditions are and how they are affected by the “abnormal conditions”.

**Rolling conditions and theoretical background.** The rolling conditions are directly related to the mill configuration of the mill.
a) The mill configuration consists of:
- number of stands,
- type of stands (two; four-high) and for each stand
- maximum separation force, - maximum torque,
- speed ranges,
- roll dimensions and
- cooling system;
b) the rolling practices consist of:
- strip grade,
- slab and strip temperatures.
- slab and strip dimensions,
- gap tulle and
- draughting practices/ load distribution.

This basic information gives the limits for each mill and each stand, but does not directly give enough information about the rolling conditions. Only the actual pass design and the real rolling schedules show what happens in the bite of each pass and therefore basic information of the rolling conditions is obtained.

The rolling schedule used gives the actual figures for each pass and stand but not the ranges. It gives realistic numbers for each pass which fit together and are normally close to the rolling conditions in the mill rolling slabs to strip.

The schedules for roughing mills are often constant, varying little for different strip grades and strip dimensions. The schedules for the finishing mill may change from strip to strip, however, these variations are normally within relatively narrow limits.

Although rarely done, the rolling schedules can be used to calculate the variables for each pass. These variables can be divided into 3 categories:

**Category 1**
These variables are shown in the rolling schedule itself and can be directly measured. Figure 1:
- strip thickness \( H_t \) before and \( H_f \) after the pass
- speed of strip \( V_1 \) before and \( V_2 \) after the pass
- separation force \( P \)
- torque \( M \)
- strip temperature
- strip width \( b \), roll diameter \( D \).

**Category 2**
These variables are directly calculated from the first group of variables:
- strip reduction \( \Delta H = \frac{H_f - H_t}{H_t} \)
- bite angle \( \cos \alpha = 1 - \frac{\Delta H}{D} \)
- contact length between strip and work roll \( L = \frac{\pi}{360} \cdot \Delta H \)
- contact time between strip and work roll \( t = \frac{L}{v} \), \( v \) = roll speed
- average specific load on strip in the gap \( p = \frac{P}{b} \) (\( b \) = strip width)
- relative speed between the strip and work roll \( V^* = \Delta V = V_2 - V_1 \).

**Category 3**
These are a combination of the first and second categories of variables:
- Coefficient of heat penetration from strip to work roll \( W = z \cdot t \)
- Coefficient of work for reduction in the gap \( A = p \cdot L \).

**Actual mechanical rolling conditions.** To understand rolling conditions in hot strip mills, rolling schedules from different hot mills were analysed. The schedules were taken from two continuous mills (4 and 5 roughing stands respectively), one semi-continuous mill (one two-high rougher with 7 passes, plus two continuous roughing stands), and one semi-continuous mill (four high rougher with 6 passes). The finishing mills in these four mills each had 7 stands. Variables of the 1st, 2nd and 3rd categories were obtained and calculated from the rolling schedules and then plotted versus the different passes. The four to nine passes of the different roughing mills were somehow equally distributed.

Figure 2 shows the separation force \( P \), varying on a high level in the roughing mill and the first finishing stands but decreasing in the later stands of the finishing mill. The important average specific load \( p \) is low and almost the same.

![Figure 1. Roll gap](image1)

![Figure 2. Separation force P is high in the roughing mill and decreases in the finishing mill, while the average specific load p in the bite is at a low level in the roughing passes and increases in the finishing mill](image2)
Figure 3. Torque M and coefficient of work for reduction in the gap \( \Delta \) show the same characteristics.

Figure 4. Rolling speed \( V_2 \) in all analysed roughing mills and increases rapidly in the finishing mills. These variables are inverse because the contact length decreases very fast in the finishing mill. The coefficient of work for reduction it shows the same trend as the torque M. Figure 3.

Figure 5. Relative speed \( V^* \) between the strip and work roll.

Figure 6. Coefficient of heat penetration \( W \) varies widely in roughing and early finishing stands, where the specific load \( p \) is at a low level.

Figure 7 shows the relationship between the bite angle and the rolling speed \( V_2 \). \( V_2 \) is critical only for the critical bite.
angle at the moment when the slab or strip initially enters the pass; afterwards the slippage in the roll bite depends on \( V^* \). Figure 8 plots the size of firecrack pattern versus the coefficient of heat penetration \( W \). These figures show some direct results which are important for rolling mills. It is evident that it is possible to control the variables which influence the rolling conditions. In fact \( p \), \( W \) and \( V^* \) differ widely throughout the mill. The specific load \( p \) is within a narrow range - almost constant in the roughing mill and increasing in the finishing mill (for the four analysed rolling schedules from different mills). The coefficient of heat penetration \( W \) decreases in the roughing mill front pass to pass and there are significant differences between the mills. \( W \) decreases also in the finishing mill, but is very similar for the first four stands and is close to zero for stands 5, 6 and 7. The wear speed \( V^* \) increases in roughing and finishing mills and is higher in continuous roughing mills than in 3/4 or semi-continuous mills - where there is a tendency for slippage. Figures 5 and 6 show that the rolling conditions are characterized as:

- passes 2-5: low \( p \), high \( W \), low \( V^* \)
- passes 6-10: low \( p \), lower \( W \), higher \( V^* \)
- pass F1: low \( p \), lower \( W \), higher \( V^* \)
- passes F2-F3: higher \( p \), even lower \( W \), higher \( V^* \)
- passes F4-7: very high \( p \), \( W = \) Zero, highest \( V^* \).

The heat penetration \( W \) is dominant in the first passes of a roughing mill but progressively decreases in the finishing mill down to the last stand. Specific load increases slowly but continuously. There is no significant difference in any of the roll condition variables between the last roughing passes and the 1st finishing stand. However, the rolling conditions of the last stands of finishing mills are totally different from the early stands. With standard cooling conditions in hot strip mills the firecrack pattern can be related directly to the heat penetration \( W \), figure 6, however this is only valid for the top rolls. It appears that the pattern on the bottom rolls is influenced by other variables. It might be that the cooling conditions vary widely, not only for the cooling conditions of the rolls, but also for the strip. The mechanical rolling conditions are the same for top and bottom work rolls in the same stand, but the metallurgical conditions are definitely not the same.

**Actual metallurgical rolling conditions.** Some aspects of this Chapter are related to D. Blazevic'). To describe the metallurgical rolling conditions is more complicated than the mechanical rolling conditions and almost impossible. We can therefore only make general statements, even though the metallurgical conditions are at least of the same importance as the mechanical. The problem is that the strip temperature is influencing all metallurgical variables and strip temperature itself cannot be measured. As soon as the slab has left the furnace, strip temperature is out of control and time and water from descaling and roll cooling systems work on the strip surface. Almost everything varies in the mill besides the descaling and cooling system and the computer follows the strip temperature somehow with "speed ups" and/or "lamellar cooling systems" and finally the right coiling temperature is reached and controlled. But all the way down through the whole mill between furnace and coiler there is actually no temperature control. And it is well known that the strip temperature varies from head to tail. from the middle to the edges, from top to bottom side (the upper side of strip 20-40 mm thick may be up to 100 C cooler than the bottom side).

![Figure 8](image1.png)

**Figure 8.** The size of firecrack pattern increases with coefficient of heat penetration \( W \)

Strip temperature and strip quality determine plasticity and the type (and with additional influence of time the thickness) of scale on the strip. Different temperatures of the strip consequently create different specific loads on the work rolls and different wear etc. The type of scale which grows on the strip depends on strip surface temperature. Figure 9. High temperature scale \( \text{Fe}_2\text{O}_3 \), is the hardest. low temperature scale \( \text{FeO} \) is the softest and the transition from one to the other is in the temperature range between 900 and 1 100 °C, which is the main range of temperature for rolling in hot strip mills. Additionally, the time between the stands of the finishing mill is inverse to rolling speed. Scale on the strip should he always removed because it could increase roll wear and influence strip quality. Anyway, scale on the strip is always found on work roll surfaces as a complete layer and this helps to protect the roll surface against wear and reduces heat transfer from strip to roll. However, up to now research did not thoroughly investigate the adhesive strength of scale on the strip and roll or the growth of thickness of scale on the roll during a rolling period or the influence of roll temperature and firecrack pattern on the adhesive strength or the influence of change of scale type on the oxide layer on the roll. Answers to these questions would help to understand the metallurgical conditions in the gap much better.

Descaling and cooling systems in all hot strip mills are often subject to trials and change with the aim of achieving a better solution. But once the system is modified, all cooling

![Figure 9](image2.png)

**Figure 9.** Oxide growth rate versus temperature

\[^2\]
parameters usually remain fixed and actual temperature distribution on the Strip surface is not uniform and constant as it should be. The primary aim of roll cooling systems is cooling the work rolls - however, this may create problems on strip temperature distribution which vice versa influences the work roll surface.

**Rolling conditions and requirements on roll surface.** In hot mills, under normal rolling conditions, we very often find the following problems:
- wear in roughing mills.
- surface breakdown in early finishing stands.
  especially in F2 bottom roll: scale rolled in the strip, bruises in the very last finishing stands,
  strip surface particles sticking to the roll and hack to strip again. This phenomenon is observed in the last finishing Stand, for special strip grades (ferritic stainless steel) in all finishing stands.

Roll wear is a function of
- wear speed (figure 5),
- specific load (figures 2, 6).
- sliding length,
- roll-, strip surface (oxide layer!),
- roll cooling water.

In roughing stands, scale (high temperature. low speed etc.) causes most of the roll wear and a high coefficient of heat transfer creates firecracks and a high roughness.

Sometimes, however, excessive wear is also related to slippage in the mill. Slippage is a result of too low friction. mainly depending on the wear speed a, the specific load a, and the roll surface roughness.

*Banding* is a never ending story. Some papers are published about this subject and some people believe in patents hat this problem is not solved at all. All twill people have their own experience but right now, the problem is not even described completely: sometimes it really snakes problems - sometimes it does not. There are some observations which seem to be valid for most mills:
- banding does not occur directly after work roll change.
- but more commonly in the second half of a standard rolling program.
  - special roll grade, heat-treatment of the rolls, roll microstructure or other roll property.

It seems this problem cannot he solved by any special roll grade but only by research on rolling conditions.

Bruises are often caused by hard, cold strip tails with high speed impact on roll surface. High roll hardness may reduce bruises. But hardness is only one point - sticking is the other. It seems today evident that the microstructure of the roll is the main factor to avoid sticking in the later finishing stands. I he stainless steel strip problem in the early finishing stands can be solved by different materials, that of the last stand up to now only by one single grade.

**Qualities for work rolls in hot strip mills.** The variety of roll grades used for work rolls in hot strip mills is considerable and almost confusing. In addition, it is now necessary and state of the art to have compound rolls, which increases the number of roll grades even more.

High wear resistant materials used for the working layers are unable to withstand the thermal stress, torque and bending loads at the necks. The material of the Core and necks of compound work rolls is normally grey or nodular cast iron, or steel. The materials used for the working layers of work rolls for hot strip mills are given in table 1.

Table I includes some characteristic properties like hardness, microstructure etc. The variety of grades can be in-
creased by varying the heat treatments within these roll grades. Figure 10 shows typical microstructures of materials from table 1.

Table 2 shows typical applications of these roll grades (table 1) and state of the art. Some grades are used successfully while others are not. Using performance figures and rolling conditions it is easy to compare different stands and different mills and to improve total roll performance under normal rolling conditions.

Table 2. Application of different roll grades in hot strip mills

<table>
<thead>
<tr>
<th>Roll grade</th>
<th>Roughing mill</th>
<th>Finishing mill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Semi-continuous mill</td>
<td>1/4 continuous mill</td>
</tr>
<tr>
<td></td>
<td>Rev-stand</td>
<td>Cont-stands</td>
</tr>
<tr>
<td>1 hypoeutectoid steel</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>2 hyper eutectoid steel</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>2 graphite steel</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3 high chrome iron</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>4.2 ICP</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.6 nodular iron</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

?, impossible; 0 possible, resp. no longer state of the art; + State-of-the-art. + Y for rolling stainless steels

Figure 10. Microstructures of typical roll grades for hot strip mill work roll
Rolling conditions in F1 are similar to the last passes of the roughing mills. High chrome iron is doing very well in this location. However, high chrome steel or graphitic cast steel should also work well.

In finishing stands 2-4 of many hot strip mills high chronic iron is now standard. Qualities for rolling special strip grades such as austenitic or ferritic steels are available. Previously it was common to use ICDP rolls but the high chronic iron has been a great improvement performance-wise. In some mills Adamite steel rolls were (arc still) being used in these stands with good results. Under high loads these grades tend to shatter and show surface fatigue problems in the mill.

In the last stand of the finishing mills where there are the highest loads \( p \) and speeds \( v \), the roll surface also has to withstand rolling impacts. A roll of high hardness as well as "sticker resistance" is required. The only roll quality successfully used and available for many years has been the Indefinitely Chill Double Poured Roll (ICDP). Higher wear resistance is required without losing the other properties. Heat resistance is no problem (very low \( W' \)). All roll makers are developing and trying new qualities but so far without success. Attempts to use high chronic iron have not been successful, even with very high hardness. Hardness cannot solve the sticking and surface problems.

To obtain good performance figures under normal rolling conditions the parameters given in sections 3 and 4 should be the normal rolling conditions. Frequently, so-called abnormal rolling conditions are normal, see section 7 and these abnormalities have to be eliminated.

However there are special circumstances concerning abnormal rolling conditions:
- Damage due to stickers, cobbler, mill stops with strip in the gap, etc. (i.e., \( W < 10^7 \)) is less severe when the surface of a roll is softer.
- The firecrack pattern becomes finer (smaller) when the strength (hardness) of roll material is lower.
- Crack propagation can be reduced or stopped by having high residual compression stress in the rolls.
- Thermal breakage of rolls can be reduced by having higher strength and by lower residual tensile stresses in the core material.
- Core fatigue cracks are prevented the same way.

Always the best solution is to reduce or eliminate the abnormal rolling conditions.

**Conclusions.** Rolling conditions can be determined in a good, informative way from rolling schedules, rather than from the mills layout. The rolling conditions should be studied for all rolling schedules of a rolling program to detect possible critical conditions concerning specific pressure, coefficient of heat transfer or strip temperature. There are, for example, correlations between rolling conditions, roll quality and firecrack pattern. There is also abundant information available to compare the rolling conditions of various passes in different mills: therefore it is relatively easy to make decisions on the optimum roll grade based on these analog examples.

Abnormal rolling conditions may require different roll grades for different applications, however, this is beyond the normal rolling mill experience.

A special roll grade property, the immunity to mill accidents’, is required, and this "property" is dependant on the individual mill's abnormality or accident standard.

Using the mechanical variables of the 2nd and 3rd category, it is possible to give precise information on rolling conditions and to use the experiences of other mills with different roll grades as long as "normal rolling" conditions are normal.

**References**