LEADING EDGE METHODOLOGY FOR A BETTER UNDERSTANDING OF WORK ROLL DEGRADATION IN HSM AND FOR THE DESIGN OF NEW ROLL GRADES[1]

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Abstract

CRM is well equipped with a series of laboratory scale and on-site methods for evaluating the surface degradation behavior of work roll material in Hot Strip Mills. These methods are used for developing new work roll materials in direct relation with one of its long term industrial partner as well as for evaluating and solving unexpected degradation behavior on industrial site. These methods include classical mechanical testing (tensile and compression testing, hot hardness measurement) and specifically developed evaluation test and procedure at the level of the laboratory experimentation (three discs wear machine), of the continuous pilot mill trials (work roll with inserts) and on site (rollscope sensor, portable microscopy). This paper describes some examples of application of these techniques and the role they have played in a better understanding of the work roll surface degradation mechanisms and in the development, or optimization, of new roll grades.

Keywords*:* Degradation; Hot rolling; Work rolls; Grade.

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1 INTRODUCTION

A little more than 30 years ago, Marichal Ketin has initiated with CRM (Centre for Research in Metallurgy) a long term partnership in order to support the Belgian roll foundry in all the future material developments. Several new work roll materials were investigated and developed during this last decades based on this cooperation. Most of these grades are still standard grades in many Hot Strip Mills in the world nowadays.

Some outstanding results need to be mentioned in this frame of new work rolls grade development:

- The chrome steel grade, introduced in many roughing mills in the early 80s was one the first grades to be investigated with CRM[(1,2)]
- In the early 90s, based on their success in Japan, a huge research work started for the development of High speed steel work roll grades for the finishing stands. These developments helped MK to become one of the leading HSS work roll suppliers in the world[(3,4)]
- Microalloyed ICDP followed as a research topic in the early 2000s until 2005, a period during which many hot strip mills switched from the conventional ICDP grade to the so-called enhanced type.

The work roll surface quality and its evolution during a campaign play an increasing role on the strip surface quality and some defects are even not detected on the hot strip and appear only after galvanizing. Controlling, understanding and improving the work roll surface degradation is thus gaining increasing importance. Several research projects, from 2003 to 2009, were thus initiated for filling the lack of knowledge in the field of work roll degradation in Hot Strip Mills. The results of this work were an important milestone in the understanding of roll behaviour and served as an input for new work roll developments as well as for the improvement of the rolling process. More recently, overcoming the limits of traditional centrifugal casting and chemistries has become the subject of an on-going development project with CRM.

This paper will describe how CRM and MK carry out jointly their research activities in the field of work roll materials for hot rolling together with the techniques used and specific application cases.

2 DEVELOPEMENT OF NEW WORK ROLL GRADES

New work roll grades development is based on a specifically defined methodology (Figure 1). As MK work roll grades are cast materials, this development requires casting laboratory samples while ensuring a microstructure similar to an industrial roll shell. Based on numerical modelling, a dedicated mould and casting procedure have been designed in order to achieve a cooling rate close to the cooling rate of a bi-metallic roll shell.

The cooling rate after casting and solidification is also controlled for simulating the industrial roll cooling conditions. A laboratory induction furnace enables alloying efficiently various compositions using industrial ferro-alloys. Heat treatments are carried out either in laboratory or more preferably in the industrial furnace together with rolls. Various evaluation laboratory methods are then used for characterizing the newly developed grades including chemical analysis, metallography, mechanical testing, dilatometry. Specifically developed techniques for the evaluation of the work roll materials are also frequently used like a hot rolling simulator, hot oxidation tests and pilot mill trials.

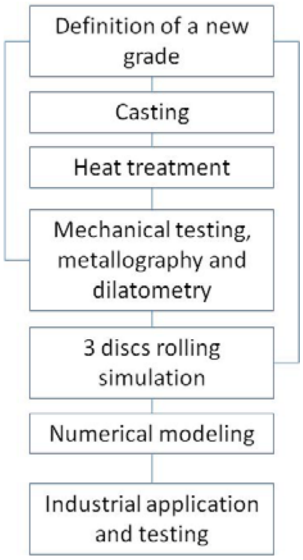


Figure 1. Methodology for the new work roll grade development**.**

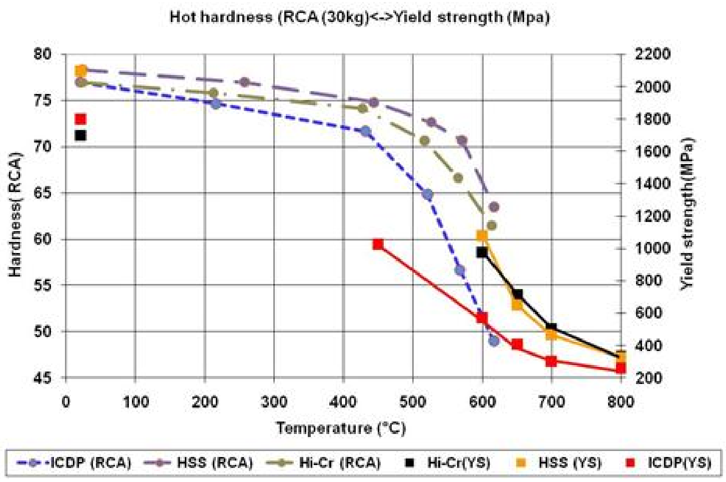


Figure 1. Hot hardness and hot compression properties of work roll materials.

2.1 Materials Characterization

Several chemical analysis equipment's are available in CRM for the chemical analysis of roll materials. Optical spectrometry is currently used by MK for evaluating the chemical composition of the alloy but XRF (X-rays fluorescence) analysis is also frequently carried out for detecting and quantifying a possible pollution of the alloy by less common elements like Zn, Pb, Sn, Sb, As.
Metallography by both optical microscopy and SEM (Scanning Electron Microscopy) are basic tools of evaluation when developing a new roll grade. Indeed, the

distribution of the various carbides as well as their shape and size influence significantly the materials properties like toughness and thermal fatigue resistance.

2.2 Mechanical Testing

Mechanical tests for roll materials characterization includes tensile and compression testing, hot compression testing, fatigue and impact tests. Mechanical testing and also hardness test (from room temperature up to 625°C) are mainly used to characterize newly developed roll grades. It is indeed a characteristic of work roll materials that their high temperature mechanical properties exhibit a sharp variation within the temperature range at which the roll surface is heated during the contact with the hot strip (Figure 2).

2.3 Discs Rolling Simulator

Laboratory tests combining the effects of fatigue, oxidation and wear are important for validating a roll material or for comparing various grades. For this purpose, CRM has developed a 3-disks wear test machine simulating hot rolling of stands F1-F3 (Figure 3). The Hot Rolling Simulator is constituted of three disks where a small disk (30 mm in diameter) is rotating in between two larger disks. The smallest disk simulates the work roll while the upper larger disk simulates the hot strip and the lower the back-up roll. The upper disc is heated by an induction coil enabling to preheat its surface up to 1100°C, Two motors control the rotation of the “work roll “ disk and “strip” disk while the “back-up roll ” disk is rotating by contact with the small disk.. A nozzle enables the cooling of the “work roll” disk. The composition, temperature and flow rate of the cooling water can be modified can be adjusted in order to simulate at best industrial conditions. The load between the discs can be applied independently
The degradation evaluation is carried out by:

- roughness and profile measurement,
- GDOES (Glow Discharge Optical Emission Spectroscopy) measurements,
- optical microscopy (surface and cross section),
- scanning electron microscopy.

Figure 3. The Hot Rolling Simulator (3 discs configuration).

2.4 Pilot Trials

In order to assess roll material performance, a real hot rolling process can also be performed on the continuous hot rolling pilot line at CRM Ghent. The hot rolling pilot line enables the continuous rolling of “baby-coils” (max diameter 1700 mm, max width 200 mm, thickness 2 - 4 mm) preheated in a protective atmosphere.(5) Figure 4 shows a photograph and the layout of the continuous hot rolling pilot line.

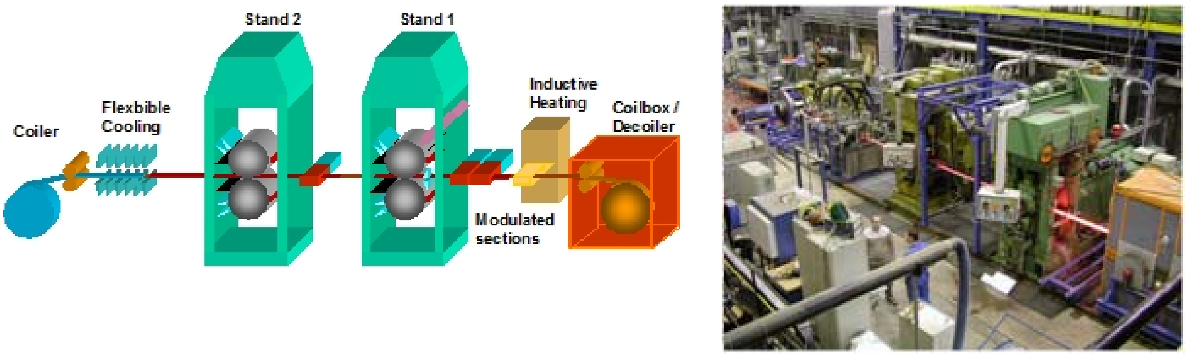


Figure 4: Continuous hot rolling pilot line – photo, layout and work roll with inserts.

In order to investigate in details the complex interactions in the roll gap, the stands are equipped with work roll cooling, skin cooling, lubrication and additional measuring systems (i.e. laser speed, roll and strip surface inspection systems). To study different work roll grades, rolls are prepared with inserts of different roll materials. Each work roll contains five inserts. The dimensions of an insert are 175 x 75 x 30 mm, while the work roll diameter is 400 mm and the table width 350 mm. This approach gives a direct comparison during the complete hot rolling operation for the different grades because each insert is submitted to identical rolling conditions. When the procedure is used to simulate the rolling conditions in a specific stand, it is advised to have at least one insert with a grade that is well-known for that specific stand.

To obtain an accurate assessment of roll material performance, a wide range of measurements is performed, each with a specific objective. The different types of measurements can be divided into three groups:

- On-line measurements taken during the trial:

- rolling data (e.g. force, temperature, speed, motor current)
- work roll surface state with a “Rollscope” (monitoring of the top roll surface)
- product surface quality with a stroboscopic on-line strip surface inspection system
- exit strip speed measured by a Laser Speed Measurement Device
- spindle torque measured with strain gauges (monitoring of the symmetric/asymmetric rolling behaviour in roll gap)

- Measurements taken during a stop, between two trials or at the end of the procedure:

- Photographic images
- Roughness measurement
- Profile measurement
- Microscopic analysis with the portable optical microscope

- Destructive measurements performed after the removal of the inserts.
- Optical microscopy
- Scanning electron microscopy

Using work rolls prepared with different inserts in the continuous hot rolling pilot line offers the opportunity to compare different grades directly and under equal industrial conditions. All the measurements give a complete scope of the advantages that one grade may have compared to another. It can be concluded that this procedure opens a lot of possibilities towards a better understanding of work roll behaviour and the introduction of new work roll grades in lines.(6)

2.5 Hot Oxidation Tests

Oxidation during hot-rolling has a noticeable effect on the roll performance and the product surface quality. A classical approach to oxidation consists in performing hot oxidation tests in humid atmosphere. The temperature range corresponding to the surface contact temperature of the roll (525-700°C) is usually investigated with dew point from 40 to 90°C simulating the humid air at the exit of the roll gap and duration from 1 to 100h.

Oxidation kinetics as a function of the material composition and heat treatment can thus be evaluated. However, comparison with the oxide thickness observed on industrial roll samples has indicated that this method of static oxidation test tends to underestimate the oxidation kinetics (Figure 5).

It has led to the development of a combined oxidation-corrosion test which simulates the thermo-chemical cycle of a roll surface Specimens are heated at 600°C/2 sec in a vertical furnace and cooled down by dipping in water. Different water compositions can be tested. These simulations have shown a cumulative effect of oxidation at high temperature and corrosion in water on the oxide layer thickness as well as the influence of the cooling water composition on roll materials oxidation and degradation.(7)

2.6 Numerical Modelling and Dilatometry

When a new work roll grade has been developed, thermo-mechanical modelling by FEM is used for defining the heat treatment parameters in terms of heating and cooling rate in order to achieve the satisfactory stresses state both in the shell and at the core-shell bonding zone. Physical and mechanical properties of the new grades are required for this modelling together with dilatometric curves.

Dilatometric measurements are also frequently used for defining the specific phase transformation temperature for each grade.

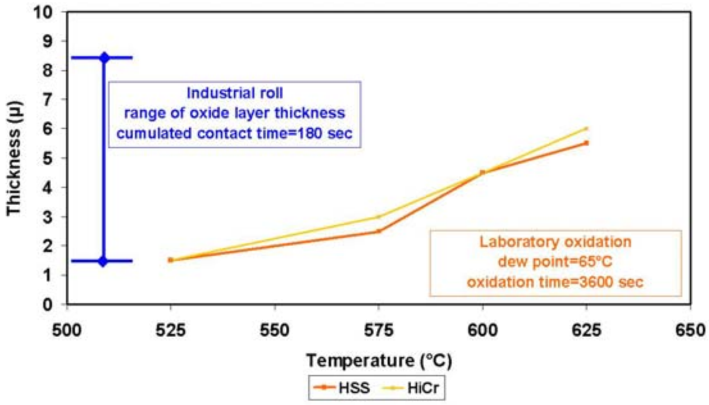


Figure 5. Oxidation kinetics in static hot oxidation test versus industrial oxide thickness.

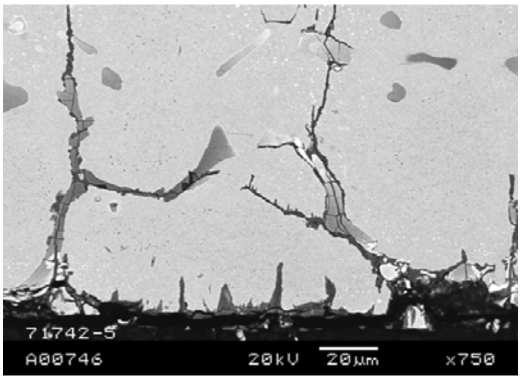


Figure 6. SEM cross section of a roll sample.

3 DEGRADATION MECHANISMS

The degradation mechanism of work rolls in HSM is a combination of three concomitant and interrelated mechanisms(7):

- thermal fatigue and contact fatigue
- oxidation-corrosion
- wear

By the combination of these three mechanisms, roughness increase, peeling and banding can occur. These degradation mechanisms are dependent of the roll material (its thermal expansion coefficient, thermal conductivity, hot yield strength and LCF fatigue at low temperature, roll composition, heat treatment) but also on the rolling parameters (strip and roll temperature, reduction ratio, contact time, strip oxide thickness and roll cooling).

In order to have a better understanding of work roll degradation mechanisms and to improve work roll resistance towards degradation, CRM with MK is using several in-lab evaluation methods and also on-site techniques including portable optical microscopy, portable Vickers Hardness tester, rollscope).

3.1 Microscopy and Hardness

Metallographic examinations of roll surface on samples from rolls at the end of their life or after an incident leading to a roll breakage are of prime importance for understanding the degradation mechanisms of a work roll surface. Fig. 6 illustrates an example of metallographic examinations of roll samples in cross sections enabling the identification of the degradation mechanisms.
On-site hardness measurements are also possible. MK is equipped with a portable Vickers hardness tester able to do 30kg and 50kg Vickers hardness tests on-site.
Surface analyses techniques like GDOES and ToF-SIMS help often for complementing the metallographic examinations. GDOES enables an in-depth profiling of the various elements constituting the roll material together with the elements from the cooling water incorporated in the oxide layer. ToF-SIMS (Time-of-Flight Secondary Ion Mass Spectrometry) is used for detailing the information obtained by GDOES as it enables a more local in-depth profiling and an identification of the ions and their molecular form (oxide, nitride, ...)
CRM has developed on-site metallography (NDT) for observing roll surfaces with a portable optical microscope without sampling the roll. It enables examination of the roll surface between two rolling campaigns. The microscope is installed on a specifically designed holding system depending on the size of the roll. Most often the two rolls are dismantled and the microscope is placed upon them (Figure 7 a), but occasionally, when the examination needs to be carried out during a campaign without dismantling the pair of rolls, the microscope is fixed vertically (Figure 7 b). The examinations are usually carried out in the roll shop. The microscope is equipped with a digital camera and software enabling to compute a clearly focussed image using a series of images of a surface at varying levels of focus. This feature is of particular interest for examining the rough surface of a degraded work roll at the end of a campaign.

Figure 7. On-site microscopy with a portable microscope a) microscope on the roll; b) microscope fixed vertically.

A complete set of metallographic preparation equipment's has also been adapted to industrial conditions. CRM is now able to do a complete on-site metallographic examination. It includes the direct surface analysis with the portable optical microscope, but polishing and etching before examinations is also feasible.

3.2 Rollscope

To visualize and analyse the degradation of rolls inside roughing and finishing mills, the RollScope sensor has been developed by CRM. This industrial sensor grabs images of the surface on line and in real time in the range of 6mm field of view width.
To work in the harsh environment of roughing and finishing mills, the developed principle consists in the creation of a column of water between the lens and the surface using a moving nozzle (Figure 8). This column of water acts as an optical fibre and mainly as a protection of the window against dust and vapour. The result is a high quality image of the surface.

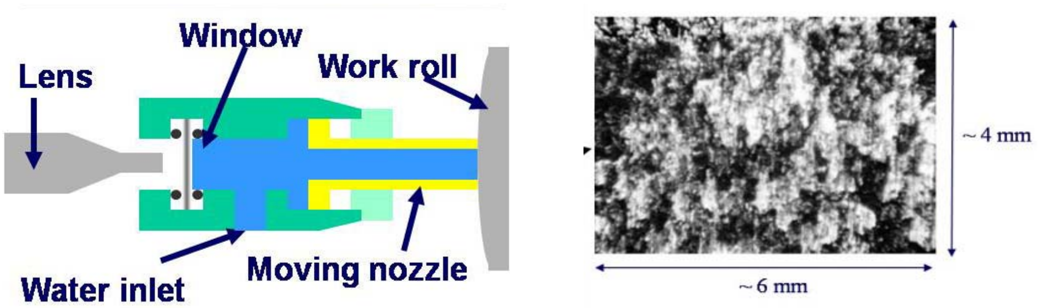


Figure 8. Rollscope principle and image grabbed by the Rollscope

The sensor synchronization enables to grab images random, incremental or fixed position of the roll. This enables to follow the surface evolution of a fixed position and also to realize a complete map of the roll when coupled with a translation system.
The Rollscope is used to monitor the work roll surface evolution, to analyse the roll degradation kinetics and to evaluate work roll performance. The monitoring of the roll surface aspect is essential for

- roll makers in order to optimize their roll grades
- HSM plants in order to
- increase the lifetime of their rolls;
- prevent rolling problems and surface defects on the product directly linked to the roll surface characteristics.

4 SPECIFIC APPLICATIONS

Table 1 summarizes the different techniques here above described and their field of application (new material development or degradation mechanism). Some techniques (e.g. metallography, wear tests, pilot mill trials) are used for both applications. We will describe some specific cases where the combination of several techniques has helped explaining materials behaviour.

Table 1. Summary of the evaluating methods and their applications

	New materials development	Degradation mechanisms
OES	■	
GDOES		■
OM, SEM, SIMS	■	■
Mechanical testing	■	
Roughness measurements		■
Dilatometry	■	
Numerical modelling	■	
3 discs rolling simulator		■
Pilot line	■	■
RollScope		■
Portable microscope		■
Portable hardness tester		■

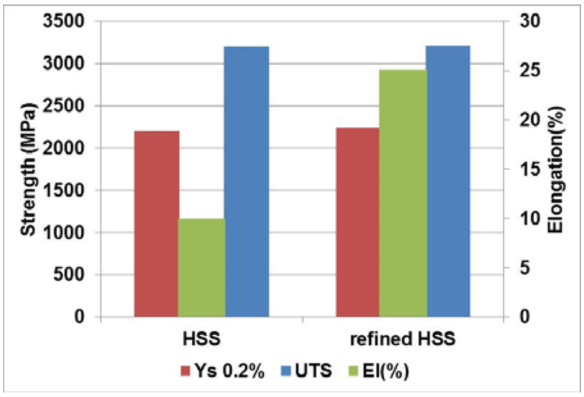
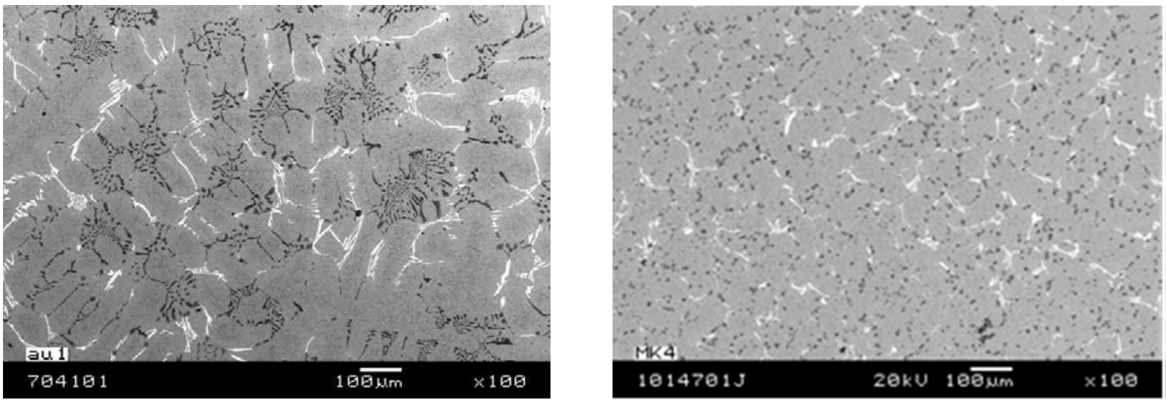


Figure 9. Influence of a nucleating agent on carbides distribution and mechanical properties of HSS

4.1 Optimisation of Carbides Distribution



a b

Figure 10. a. HSS; b. HSS with a nucleating agent.

The new grade development procedure described in Figure 1 has been applied for optimising the carbide distribution in a HSS grade. The examination by SEM shows clearly the more homogeneous and finer distribution of the different types of carbides observed in a new HSS grade when carbides nucleating elements are added (Fig.10).This type of microstructure modification enables increasing significantly the ductility of the work roll material (Fig.9).

4.2 Comparison of an Industrial Roll with 3 Discs Rolling Simulator Samples

In order to verify the adequacy of the 3 disks test machine for simulating hot rolling, comparison exams have been performed on inserts after 3 discs rolling simulator trials and on industrial end-of-life rolls.
For the industrial roll, several examinations have been carried out:

- On site optical microscopy (Figure 11)
- GDOES (Figure 12)
- Scanning electron microscopy on cross section (Figure 13)

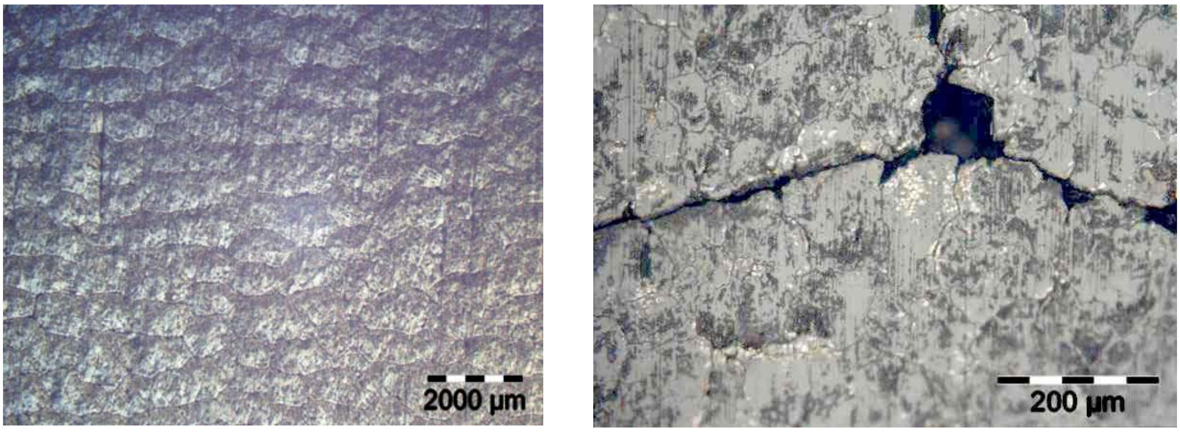


Figure 11. On-site optical microscopy on a finishing mill roll.

On-site optical microscopy is a non-destructive method enabling examination of rolls of various diameters. These exams enable the observation of the surface degradation i.e. roll oxidation, cracking pattern, carbides, defects (holes). These surface observations are of primary importance to understand the degradation mechanism.
GDOES gives information about the oxide layer formed on the roll (its thickness and its composition).
In this case (Figure 12), an oxide layer of about 7 µm is observed, constituted of iron oxide enriched with calcium originating from the cooling water.
SEM examination of a cross section shows the thermal cracks propagating preferentially along the carbide network whilst the surface and the cracks edges have been oxidised by the cooling water.
3 discs rolling simulator trials have been performed with various water compositions based on industrial data. Roughness and profile measurement are efficient methods for characterizing roll degradation. Figure 14 illustrates profile measurement on HSS inserts after 3 discs trials. It can be observed that cooling water composition influences the work roll surface degradation.

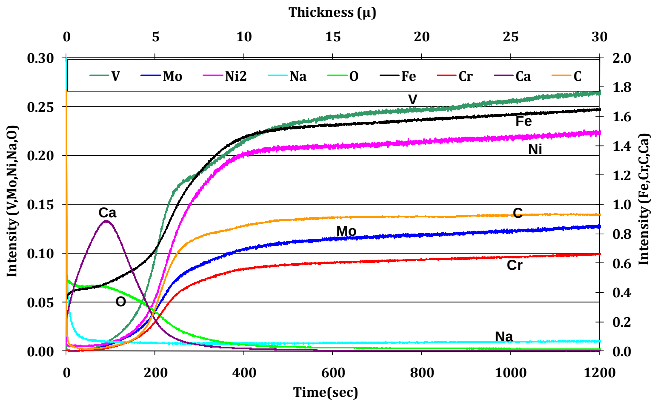


Figure 12. In-depth composition of the surface of an industrial finishing mill roll (HSS F1 bottom) by GDOES.

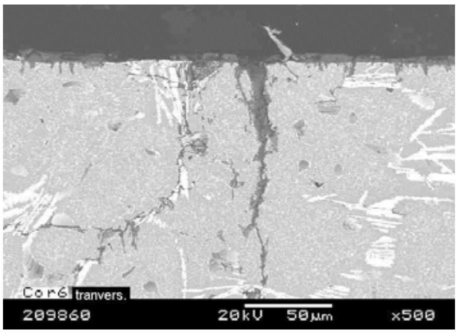


Figure 13. SEM examination of the cross section of a HSS industrial finishing mill roll (cracks and oxide layer)

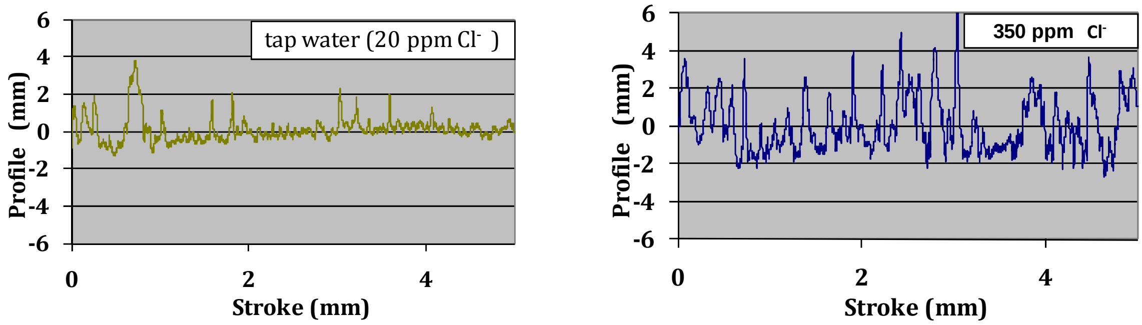


Figure 14. Influence of chloride content on roughness profile after 3 discs rolling simulation (HSS)

Figure 15 illustrates a GDOES in-depth analysis on HSS insert after one of those tests. Altough the oxide layer is thinner than what is observed on an industrial roll, the composition profile is very similar between both graphs illustrated in figure 12 and 15. It was expected to form a thinner oxide layer during a 3discs rolling simulation trial compared to an industrial campaign as those laboratory trials last 2000 cycles versus 20000 cycles for an industrial roll.

Figure 16 illustrates the surface aspect and a cross section of a HSS insert after a laboratory trial. These examinations have been done by SEM. It exhibits internal oxidation-corrosion along the carbides network similar to that observed on industrial rolls.

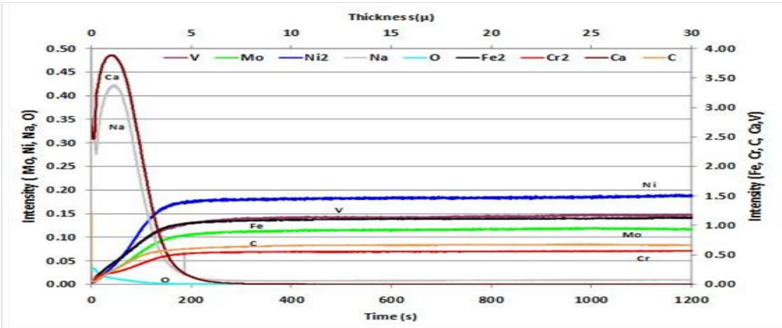


Figure 15. In-depth composition of the surface of a 3 discs rolling simulation sample (HSS)

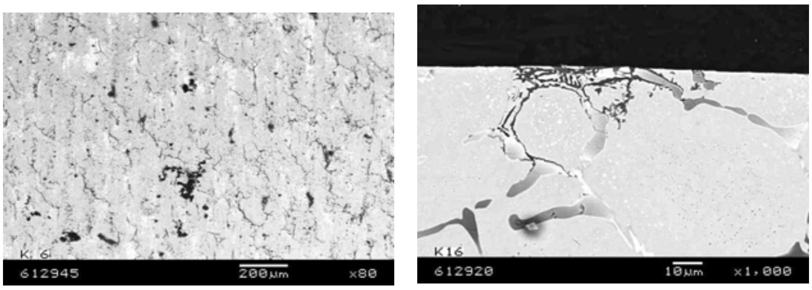


Figure 16. SEM image after 2D trial. a: surface image, b: cross section.

4.3 Identification of a Roll Oxide Layer Origin

Some industrial rolls are covered with an oxide layer (Figure 17). It is often debated if this oxide is strip oxide sticking on the roll or roll oxide. In order to clarify it, SIMS examinations have been performed on industrial roll covered with oxide and on strip oxide. These exams have excluded the possibility that the oxide could be strip oxide. The molybdenum content in the industrial roll oxide is much higher than the molybdenum content of strip oxide. Besides, a HSS sample has been oxidised in laboratory and SIMS measurements have also been done on it. The molybdenum content of the oxide layer on the oxidised laboratory sample is at the same level as the molybdenum in the industrial roll oxide.

4.4 Rollscope in a Finishing Mill

The Rollscope has been successfully used several times in finishing and in rouging mills. In the specific case illustrated here the rollscope has been implemented in a finishing mill (stand F2). Figure 18 illustrates the surface evolution of a HiCr work roll surface during a campaign. Images have been acquired at 5 positions over the width of the roll. The images presented have been taken at the beginning of the campaign, ¼ campaign, mid campaign, ¾ campaign and at the end of the campaign. Due to rolling conditions, the surface degradation can vary over the width of the roll. The

rolling conditions optimization and an accurate evaluation of the roll performance require thus a full-width inspection.
Regarding the large number of acquired images, an automatic image-processing algorithm has been integrated defining two discriminating parameters related to the work roll surface degradation.[8]

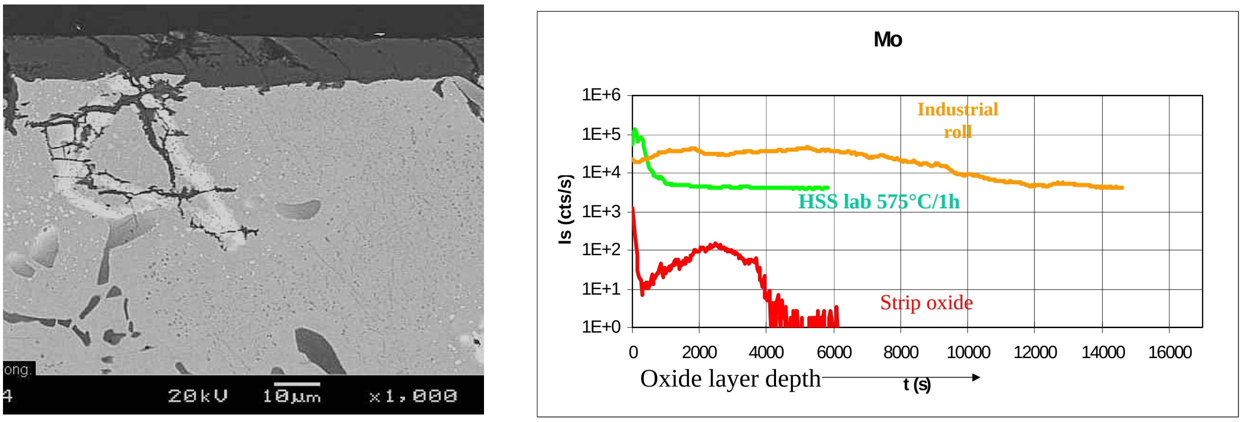


Figure 17. Oxide layer on an industrial HSS roll and its SIMS analysis

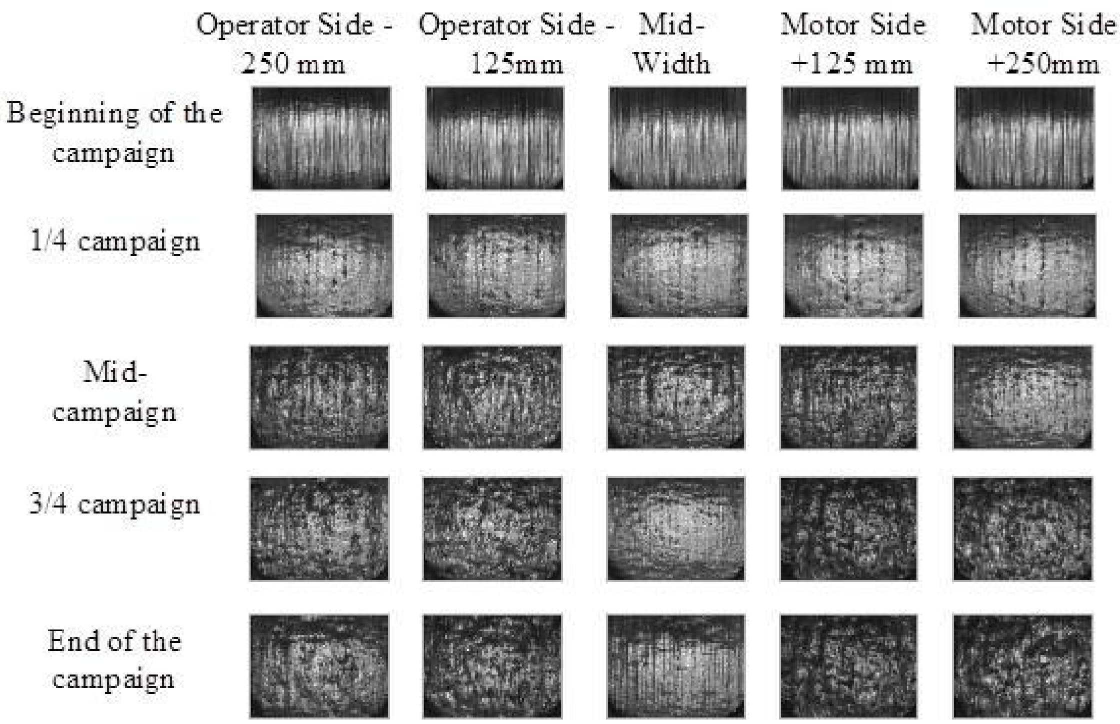


Figure 18. Evolution of the work roll surface during a campaign.[8]

5 CONCLUSIONS

MK is collaborating with CRM on a long term basis for developing new roll grades, improving the roll process manufacturing and achieving a better understanding of work roll degradation.
CRM is equipped for a detailed characterization of roll materials and roll degradation in laboratory. Techniques are continuously developed for characterizing roll degradation on site (portable optical microscope, portable Vickers hardness tester, full metallography set and portable spectrometer, rollscope).
This combination of techniques is an efficient tool for developing more performing roll grades as well as understanding work roll degradation and its relations with rolling process parameters

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