

MECHANISMS OF WORK ROLLS DEGRADATION IN HSM ¹

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ABSTRACT

In the framework of the increasingly more stringent surface quality requirement for the hot rolled strip, the work roll surface quality and its evolution during a campaign play a major role. This paper deals with laboratory studies devoted to a better understanding of degradation mechanism and their respective interactions. The attention is focused on thermal fatigue and oxidation. Several laboratory trials (three discs machine, oxidation tests, corrosion tests,...) have been performed in order to point out the influence of process parameters (rolling parameters, water cooling,..) on roll surface degradation. A specific attention is paid to the influence of roll cooling water composition on oxidation. Various examinations of scrapped work roll surface have been carried out to define the typical degradation occurring in a HSM and validate the laboratory data.

Key words: Work roll; Oxidation; Fatigue; HSM.

MECANISMO DE DEGRADAÇÃO DE CILINDROS DE TRABALHO EM HSM

Resumo

No crescente quadro de exigência de uma qualidade superficial mais limitada para a laminação de tiras a quente, qualidade superficial do cilindro de trabalho durante sua campanha tem cada vez o papel mais importante. Este papel lida com estudos em laboratório com o objetivo de entender melhor o mecanismo de degradação e suas respectivas interações. A atenção é voltada para fadiga térmica e oxidação. Vários testes de laboratório (três discos usinados, teste de oxidação, teste de corrosão...) têm sido realizados com o objetivo de mostrar a influencia dos parâmetros do processo. (parâmetros de laminação, resfriamento com água...) na degradação superficial do cilindro. Atenção especial é dada à influência da composição da água de resfriamento do cilindro na oxidação. Vários ensaios na superfície de cilindros sucitados foram realizados para definir a degradação típica que ocorre em um HSM e validam os dados do laboratório.

Palavras-chave: Cilindro de trabalho; Oxidação; Fadiga;, HSM.

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INTRODUCTION

In the last few years, the surface quality requirement for the hot rolled strip have been increasingly more stringent together with similar demands on the Hot Strip Mill productivity. The work roll surface quality and its evolution during a campaign play a major role in this framework together with technology development like roll gap lubrication, strip skin cooling and roll cooling which affect significantly this evolution. The work roll surface degradation in the HSM, in standard rolling conditions i.e. without incidents, proceed by three distinct but concomitant and inter related mechanisms, namely:

- Thermal fatigue and contact fatigue
- Oxidation
- Wear.

These three mechanisms will induce on the roll surface an increased roughness, peeling, banding. Each mechanism occurrence and relative importance compared to the others is dependent of the rolling conditions on one side and on the roll material on the other side. Thermal fatigue depends on the roll material, i.e. of its thermal expansion coefficient, thermal conductivity, hot yield strength and LCF fatigue at low temperature. From the mill side, rolling conditions influences thermal fatigue through the strip temperature, contact time, strip oxide thickness and roll cooling. Roll oxidation is related to the roll material composition and heat treatment. It is also sensitive to the rolling parameters i.e. strip and roll temperature, atmosphere and water cooling (composition, temperature).^[1-3] Wear is influenced by different parameters compared to the two first mechanisms; it depends from the friction coefficient, slip, rolling pressure while the wear resistance of the roll material needs to be taken into account.

A laboratory study has been carried out to better define the role of the first two mechanisms together with examinations of industrial worn work roll.

THERMAL FATIGUE

Thermal fatigue as revealed on Figure 1 induces the formation of cracks perpendicular to the roll surface. The thermal fatigue cracks at the end of a campaign can vary largely (80-350 μm) depending on the mill, the type of rolling campaign, the roll material. and the stand. They are more frequent in stands F1 and F2. In some case, contact fatigue cracks, parallel to the roll surface occur simultaneously and interact with them (Figure 2). Contact fatigue result from the high-pressure contact with the back-up roll. They occurs mainly in the last stands but sometimes they are observed in stands F1, F2, F3

Thermal fatigue cracks results from stresses developed during the cyclic heating and cooling of a very thin outer layer of the roll when heated by contact with the strip. During rolling in the first finishing stands, the strip enters the roll bite with an average temperature of 970°C. Within the bite, heat is transferred to the roll surface with a high heat transfer coefficient due to the high pressure between strip and roll. The intensity of the heat transfer is also dependent of the thickness of the strip oxide layer, which acts as a thermal insulation. This contact results in a lowering of the strip surface temperature and an increase of the roll surface temperature. The heat generated by friction and by deformation is shared between the roll and the strip.

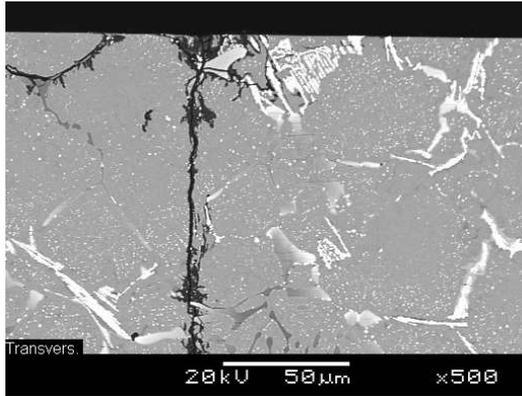


Figure 1 - Worn work roll ,fatigue cracks (F1,F2)

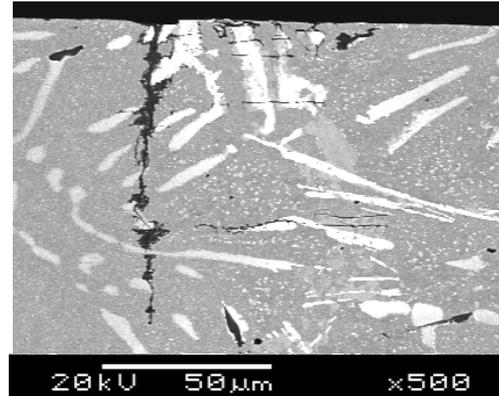


Figure 2 - Worn work roll, contact and thermal fatigue cracks

Depending on rolling conditions this temperature can be estimated between 525°C and 650°C. The peak temperature decreases rapidly due to conduction within the roll. Next, the work roll surface is rapidly cooled down by the work roll cooling sprays and reaches a temperature close to the water temperature. Slight temperature variation can still occur when in contact with the back-up roll. This cycling is repeated at each roll revolution.

Thermal fatigue is the consequence of this thermal cycling. The outer layer of the roll is submitted to compressive stress when heated by the strip due to its thermal expansion constrained by the bulk roll. If the compressive stress is higher than the roll yield strength at this temperature, plastic deformation occurs. When the surface cooled down by conduction and by roll cooling, this layer is submitted to tensile stresses. This repeated stresses cycling can induce rupture by fatigue depending on the intensity of the stresses and the mechanical properties of the roll material at room temperature and at high temperature.

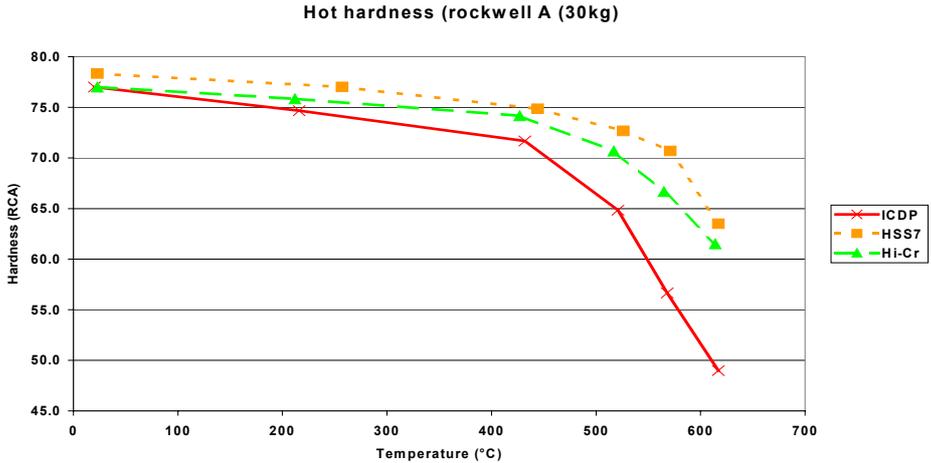
The intensity of thermal fatigue will thus depend on the strip surface temperature, the rolling conditions (friction and deformation heat), the roll material physical and mechanical properties, the roll cooling. The observed crack length and interspacing depend on the roll material, on the rolling campaign and on the HSM.

Numerical modelling allows evaluating for a typical rolling scheme, the relative influence of the rolling parameters on the roll surface temperature. Table 1 summarises these evaluations. The most influencing parameters appears to be the friction coefficient, the heat transfer coefficient (through the strip oxide thickness) and the roll material conductivity. The parameters are however the most difficult to control or to modify and even to evaluate for the first two mentioned.

Table 1 - Influence of rolling parameters variation on the roll surface temperature (numerical modelling)

Rolling parameters	Roll surface temperature (variation °C)
Rolling speed	15
Reduction	17-25
Friction coefficient	30
Heat transfer coefficient (strip oxide)	50
Strip temperature	0.5 * dT strip
Roll temperature	0.5 * dT roll
Roll thermal conductivity (Hi-Cr <->HSS)	40

The influence of the roll material properties is illustrated on Figure 3 that shows the evolution of the hot hardness of several roll materials with temperature. It is observed that the hardness of roll materials steeply decrease in the range 450-625°C, which corresponds to the roll surface temperature range in the first finishing stands. The rapid decrease of hardness within the range 500-650°C helps to explain the success of skin cooling. Indeed, even a slight reduction of the strip surface temperature decreases the roll surface temperature in the bite of roughly half this value but still drastically increases roll life by decreasing thermal fatigue.



OXIDATION

In a HSM, it is usually considered that the roll surface oxidation is formed at high temperature during the contact between the strip and the roll. The atmosphere is considered as air with a high dew point (40-65°C).^[4-6] If the oxidation time is considered as the cumulated time spent at roll surface temperature during the duration of a rolling campaign, it can reach only 2 to 12 min depending on the type of rolled strip.

On industrial samples, a significant oxide layer is not always observed; but when present, oxide layer thickness ranging from 2 to 10 µm have been measured (Figure 4).

Several studies have been carried out in laboratory to evaluate the oxidation kinetics of roll material. These tests are usually carried out at high temperature (525-650°C).

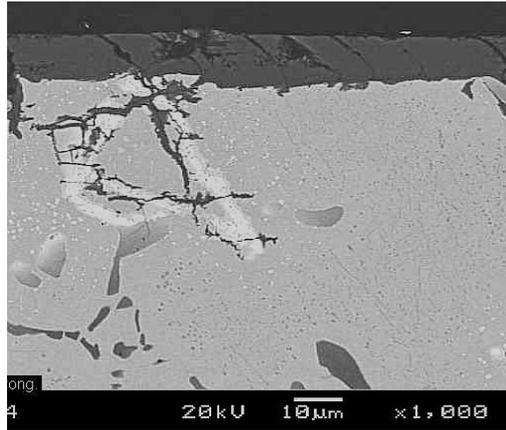
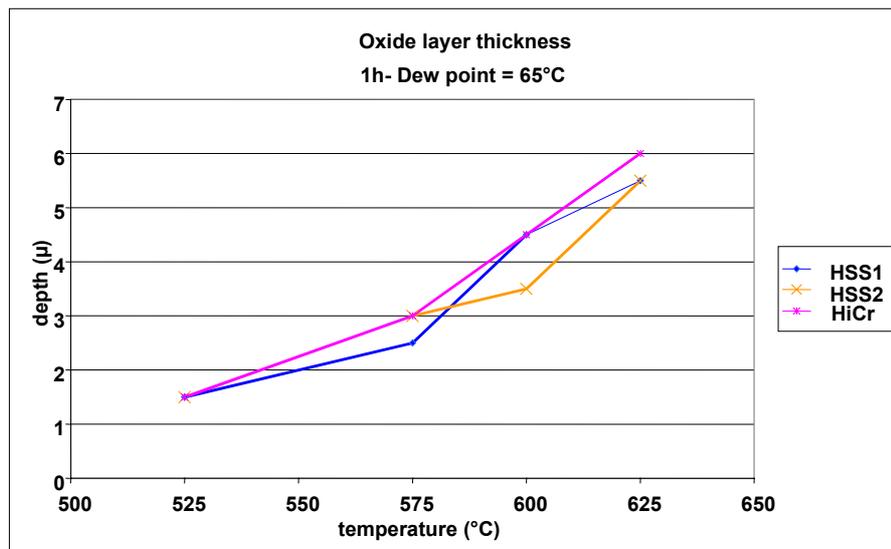


Figure 4 - Thick oxide layer on a HSS roll

In humid air to simulate the roll bite atmosphere. It however appeared that the oxide layer generated during such tests (thermo-gravimetry, static oxidation test) is thinner of at least a factor two than the oxide layer observed on some industrial rolls. Based on laboratory static oxidation test, even after an oxidation of 1h, the oxide thickness is still below 6 µm (Figure 5). Wear could explain a thinner oxide layer on industrial roll but not a thicker one.



We have excluded the possibility of this layer being an strip oxide sticking to the roll. Indeed, an analysis (by SIMS) of the in-depth oxide composition on industrial roll samples with an oxide layer have been performed. It revealed a high amount of Mo in the roll oxide. This amount is similar to the composition of a laboratory generated oxide on a HSS material .It is completely different from the Mo content of the oxide of a classical carbon steel (strip oxide) (Figure 6).

An influence of surface preparation on oxidation kinetics has also been evaluated. Specimens with different surface roughness have been oxidised but no significantly different oxide layer has been observed. It can not explain the discrepancy between laboratory and industrial oxide layer thickness.

We have investigated two remaining differences between laboratory testing and industrial oxidation conditions: i.e. thermal cycling and water cooling.

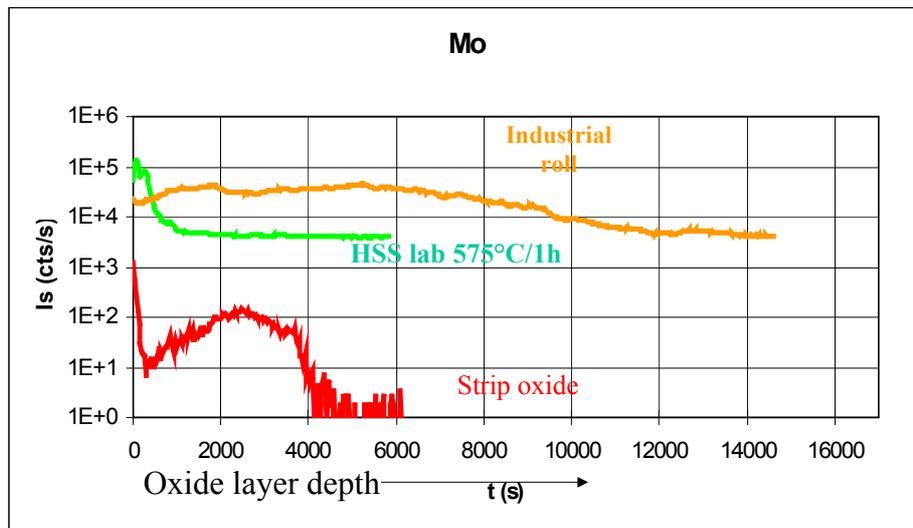


Figure 6 - Mo content of industrial roll oxide layer compared to laboratory strip oxide

OXIDATION CORROSION

Cooling water in HSM, like most industrial water, contains variable amounts of NaCl depending mostly on their location (coastal, semi-coastal, or continental) and of the water treatment applied. It ranges from 300 ppm Cl⁻ to 3000 ppm. The chloride amount can vary along the year depending on the weather. Moreover, in some HSM, where water recycling includes cooling tower, local regulations may impose the addition of bactericide to prevent bacteria formation (like legionellae). The most common bactericide is sodium hypochloride.

Static corrosion tests have been performed on roll material at 60°C during 4h (mean campaign duration) by dipping in water, saturated in oxygen (like agitated water) and containing various amount of chloride. They have shown that these materials are corroded by industrial water. On the material surface, corrosion occurs as pitting on Mo-rich carbides in HSS or on Cr-rich carbides in Hi-Cr (Figure 7). Within the material, internal oxidation of the matrix surrounding these carbides is observed even without any cracks. Both HSS and HiCr are identically affected. The corrosion kinetics increases with the chloride content.

Initiation of corrosion is very fast as 10 sec are sufficient to induce pitting on carbide area. It means corrosion occurs as soon as water cooling is flowing on the roll surface even before any strip has entered the roll bite.

In chloride free water or in oxygen free water, no pitting is observed. These two elements play thus a major role in the corrosion phenomenon.

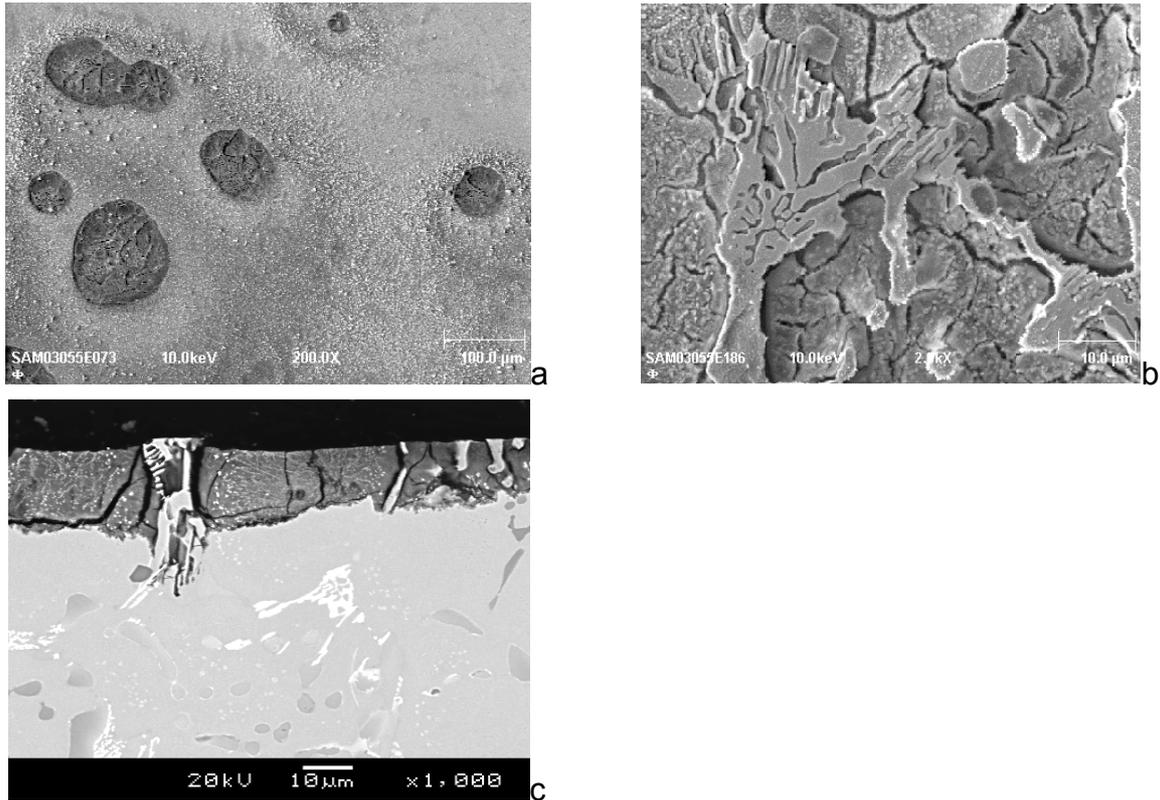
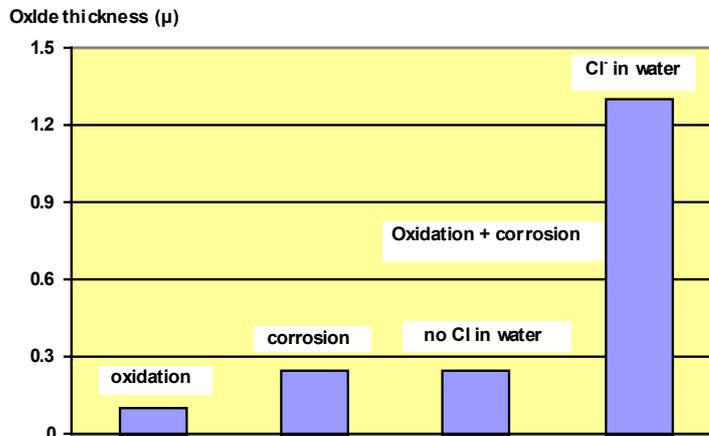


Figure 7 - HSS corroded by chloride containing water (60°C, 400ppm, 4h); a) pitted surface b) Mo₂C carbide within a pit; c) cross section of a pit, internal oxidation

CYCLIC OXIDATION CORROSION

Oxidation-corrosion tests have been carried out which simulate 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 have been tested (with and without chloride). Two distinct behaviours are observed: pitting of the carbide area and covering of the matrix by an iron oxide layer with a limited amount of Cr – oxide. These simulations have shown a cumulative effect of oxidation at high temperature and corrosion in water on the oxide layer thickness as illustrated on Fig.8 for only 20 thermo-chemical cycles. Moreover, if chloride is added in water, the oxidation kinetics, in terms of oxide thickness, is still enhanced.



EXAMINATION OF SCRAPPED WORK ROLL

Degradations observed on some industrial samples are better explained with the help of this oxidation-corrosion phenomenon.

On the edge of a roll barrel where no contact with a strip has ever occurred Mo-rich carbides have been observed, like etched. It appears that their surrounding matrix has been pitted by water. Their appearance is very similar to the carbides image within corrosion pits (Figures 9 and 7).

On Figure 10 is illustrated internal oxidation of thermal cracks. It becomes clear that this internal oxidation is in fact internal corrosion induced by cooling water penetrating inside the thermal cracks and oxidising the surrounding matrix. These two combined mechanisms, thermal fatigue cracks and corrosion by cooling water facilitates and enhances the interconnection of lateral cracks, embrittles the matrix and accelerates the removal of pieces of roll material.

Frequently, thermal fatigue, contact fatigue and corrosion-oxidation are observed simultaneously and clearly interact in the mechanisms of surface degradation (Figure 11).

Non destructive examination of work roll surface as can be done currently gives only a partial view of the surface degradation and prevents often a correlation with the degradation mechanisms. Examinations of specimens sampled from scrapped work rolls have allowed establishing some of these correlation's between surface appearances, in depth degradation and mechanisms.

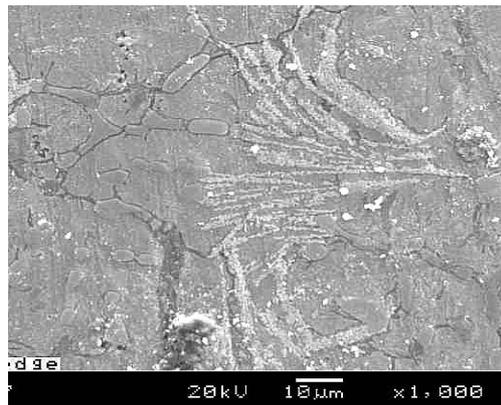


Figure 9 - Etched carbides on the edge of a roll barrel.

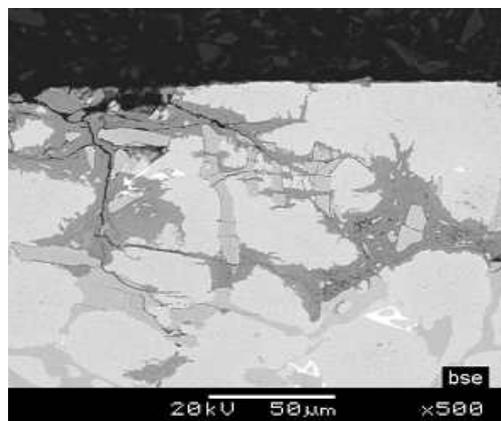


Figure 10 - Corrosion-internal oxidation along fatigue cracks

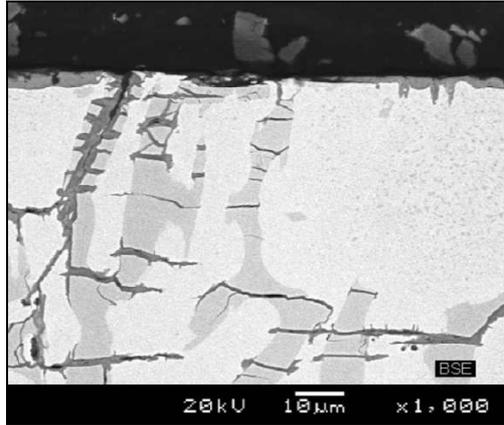


Figure 11 - Combined thermal fatigue, contact fatigue, surface oxidation and corrosion, internal oxidation-corrosion

The examinations have been carried out by SEM. Image of the surface have been done in secondary electrons thus giving a topographic image of the surface. Some of the cross section examinations are done in BSE (back scattered electron) thus giving also a chemical contrast, with the heavier elements appearing clearer than the light ones (Mo carbides in white, oxide in dark grey, etc)

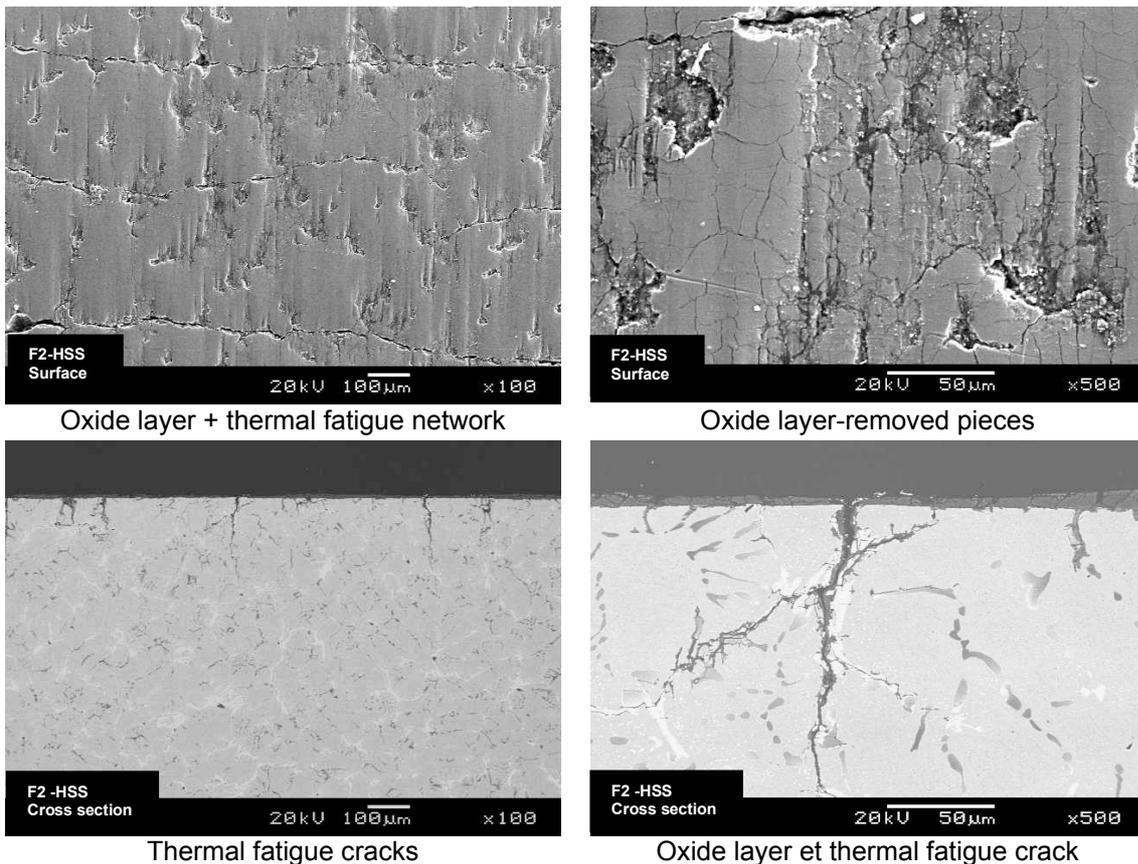
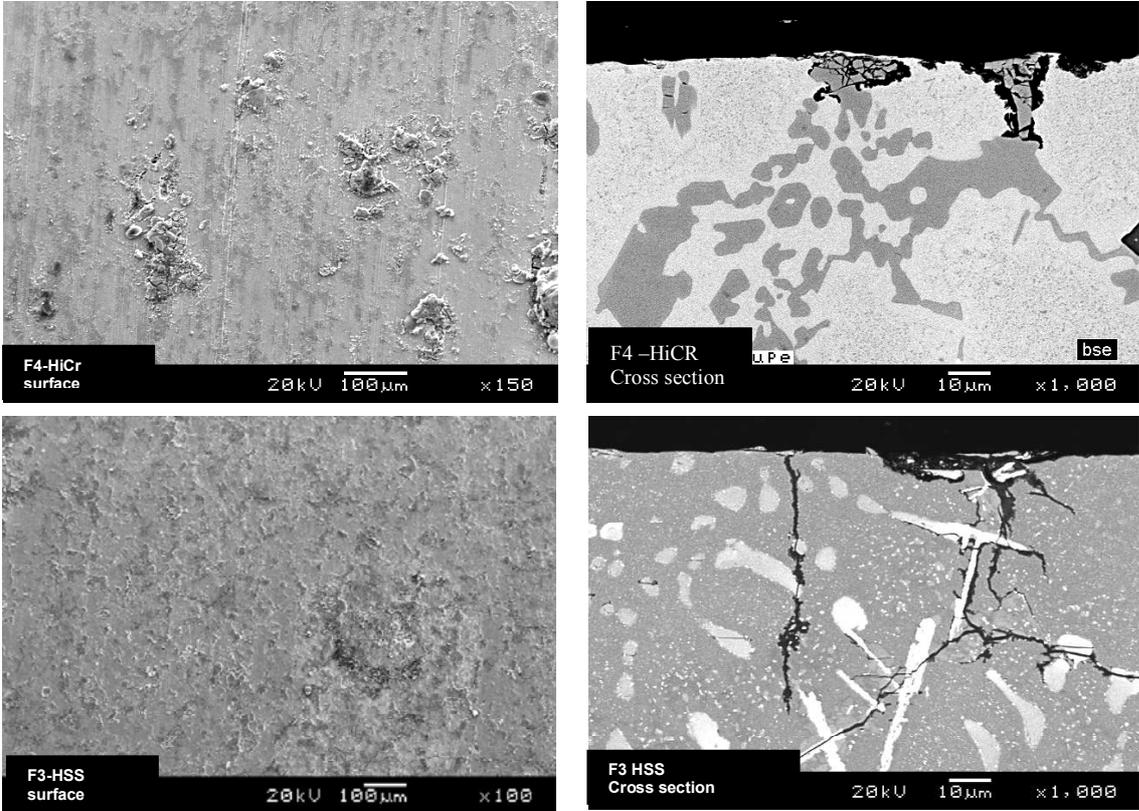


Figure 12 - Illustration of the surface and cross section appearances when an oxide layer covers the roll surface (HSS from a stand F2)

Figure 12 illustrates the appearance when an oxide layer covers the surface; bits of the oxide layer have already been removed while the thermal fatigue cracks are visible as they have crossed this layer. They are up to 150 µm deep. The oxide layer is clearly visible in cross section.

Figure 13 concerns stands F3 and F4 when thermal fatigue is a minor phenomenon but where contact fatigue is more important. The carbides present at the extreme surface are more specifically affected and are broken. Those pieces are clearly visible on the surface as no oxide covers them. Both Hi-Cr and HSS are affected.

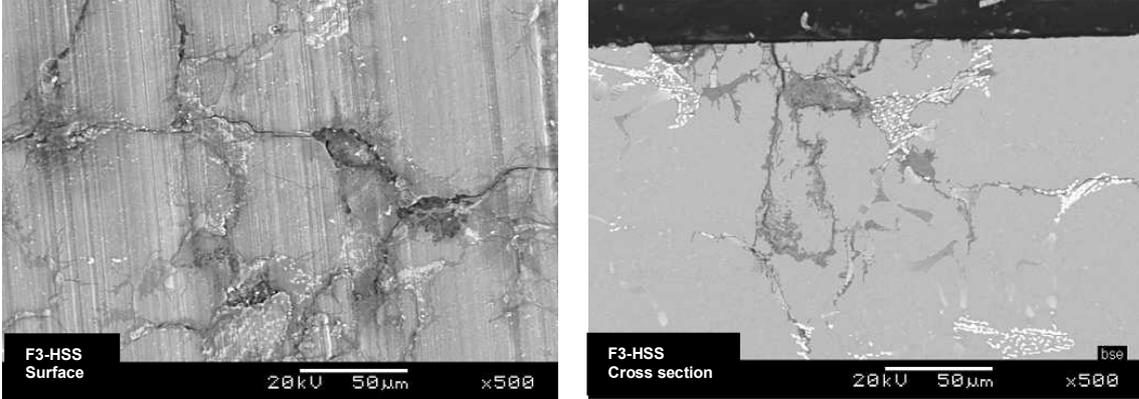


Broken carbides on the surface

Carbides broken by contact fatigue

Figure 13 - Illustration of the surface and cross section appearances of carbides broken by contact fatigue

Figure 14 shows that when no oxidation of the surface has occurred, the carbides network is clearly visible on the surface (similar observation can be made with an optical microscope). Internal oxidation-corrosion of the thermal cracks is also observed in cross section. (dark grey zones along the cracks).



Carbides network visible (surface)

No oxide layer covering the carbides

Figure 14 - Illustration of the surface and cross section appearances when no oxide layer covers the roll surface

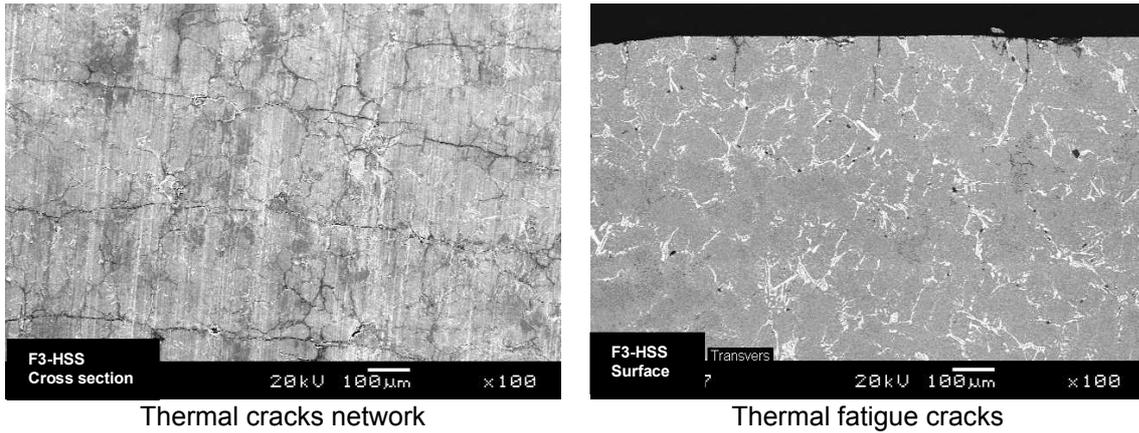
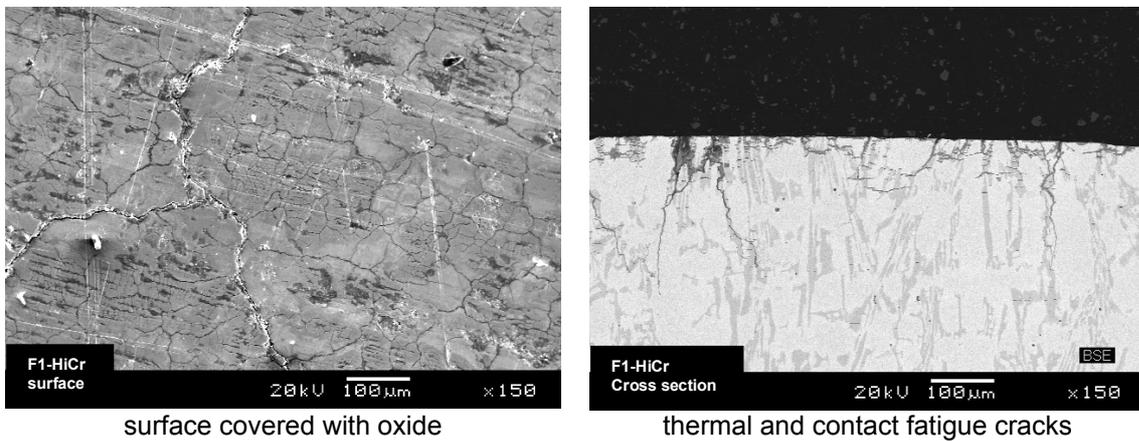


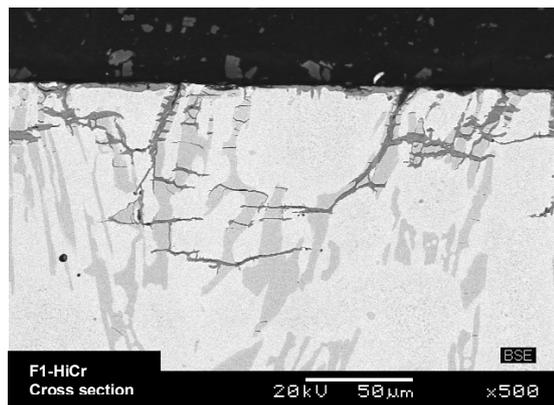
Figure 15 - Illustration of the surface and cross section appearances of the thermal fatigue network

Figure 15 illustrates the thermal fatigue cracks network with the carbides clearly visible and no oxidation of the surface



surface covered with oxide

thermal and contact fatigue cracks



internal oxidation of cracks(BSE)

Figure 16 - Illustration of the surface and cross section appearances when oxide layer , thermal and contact fatigue are combined

Figure 16 illustrates the surface degradation observed in more severe rolling conditions encountered in some stands F1 where the different mechanisms are combined. An oxide layer covers the surface, thermal cracks are up to 250 μm deep; they are interconnected with numerous contact fatigue cracks. These mechanisms will favours the removal of large pieces of material (0.1 by 0.1 mm) Internal

oxidation-corrosion of all those cracks has occurred. Pieces of oxide and of roll material have already been removed.

CONCLUSIONS

Base on laboratory test and examinations of industrial worn roll samples, work roll degradation mechanisms have been explained. The following mechanisms have been clearly identified:

- Contact fatigue cracks parallel to the roll surface and mainly located in large carbides.
- Thermal fatigue with straight cracks perpendicular to roll surface.
- Internal oxidation-corrosion oxidising the matrix along the fatigue cracks.
- Oxide layer on the roll surface induced by oxidation-corrosion.

Oxidation mechanism has been more thoroughly explained by introducing the influence of cooling water on:

- corrosion (pitting of Mo-rich carbides),
- oxide layer (cumulative effect of high temperature oxidation and oxidation in cooling water)
- internal oxidation (oxidation of matrix along fatigue cracks).

The cooling water composition (chloride amount) is a leading parameter in oxidation-corrosion of roll material in the HSM.

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