METALLURGICAL APPLICATION TO WORK AND BACK UP ROLLS FOR HOT & COLD ROLLING OF FLAT PRODUCTS.

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Rolling mills are increasingly demanding rolls capable to maintain the shape and profile much longer with the aim to extend the length of campaigns.
The state of the surface is one of the criteria determining the roll change.
With the aim to satisfy the mill requirements it is necessary to pay attention to the Kinetic of oxidation, hot hardness increase in the matrix and the morphology of the different type of carbides.

Key words: Hot rolling, Cold Rolling, Kinetic of Oxidation, Hot Hardness, morphology of carbides.

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1. PREFACE:

Both for cold and hot rolling numerous studies are being carried out and starting up new forms of measurement such as:

- Increase of the quality level,
- Improve of productivity,
- Reduce the production costs by means of reliable equipment.

Rolling mills value the rolls by the cost of uses and the excellent quality of the obtained surface on the rolled product; the present exposition has various objectives:

- Rolling mills expectations,
- rappel of stresses experienced by rolls
- rappel of different degradations,
- balance of used qualities,
- new metallurgical and technological directions in the manufacturing of rolls: in this exposition it is possible to see how the rolls display an extremely high level in alloy elements: this leads to a new beginning of the rolls metallurgy, where the quality essentially depends on the relations between the different parameters of manufacturing and the structural characteristics related to germination:
    - solidification texture,
    - distribution of primary carbides morphology
    - distribution and shape of graphite at the last finishing stands

Requirements of Rolling Mills should be considered:

Rolls cost:

It represents the 5% of the direct cost of a strip sheet rolling mill and 10% including the operation of the roll workshop.

Cost of no-quality:

The inlaid calamine because of the roll represents 150 000 € up to 450 000 € /year depending on the type of Hot Strip Rolling Mill.

Productivity**:**

Wear pressures and the aspect of the surface cause great difficulties in programming.

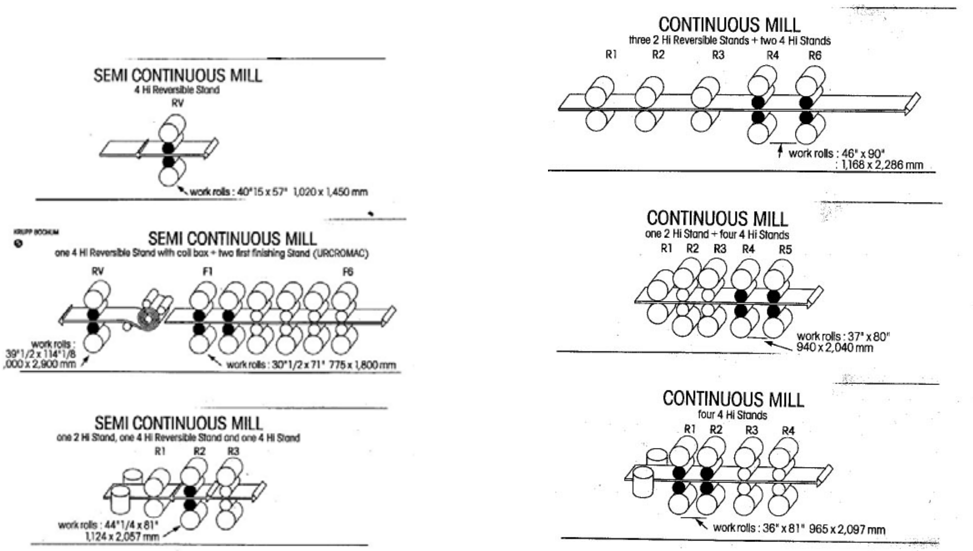
HSS and ICDP rolls give a benefit of 1%, that is from 300 € up to 900 € depending on the rolled types.

2. HOT ROLLING

Work Rolls

Roughing Rolls

Picture No. 1. Depicts the different groups of roughing rolls



Picture 1. Group of Roughers

Stresses

Thermal Fatigue

The law of the obtained experimental curves can be seen in figure No. 2:

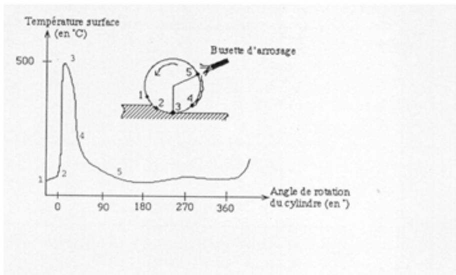


Figure 2. Experimental curve (temperature ºC, angle of rotation at º)

Influential factors

The factors influencing the thermal fatigue are :

- The amplitude of the thermal cycle followed by the surface (=difference between the maximum and minimum temperature reached by the surface).

The higher the temperature, the greatest the amplitude of the deformation cycles.

- The time of contact between the rolled product and the roll.

The greatest the reduction and the roll diameter, the worse will be the effect of the thermal fatigue on the roll.

- Coefficient of thermal conductivity

Should it be low, the maximum temperature reached by the surface will be high (local accumulation of calories)

- Coefficient of thermal expansion.

As this increases so does the plastic deformation.

- Compression yield strength.

As this decreases, the plastic deformation increases.

➢ Micrographic structure.

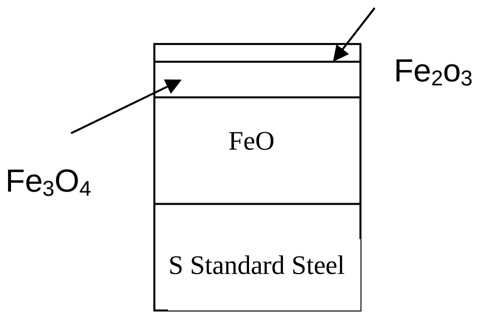
Carbides must be finely distributed and mainly they should not formed continuous networks

➢ The features (thickness, porosity, ductility, etc.) of the oxide layers which are formed in the surface of the rolls.

Hot Abrasion.

Tribologic behavior of calamine oxides.

The calamine formed during the rolling process at a high temperature (> 800ºC), for a standard type of steel, is constituted by a superposition, from the surface towards the substratum, of layers of hematite Fe_3O_4 and iron protoxide FeO, with proportional thicknesses respectively of 1 up to 4 and 95% of the thickness of the layer (figure No. 3) These elements have in hot conditions a viscoplastic behaviour.



Fe_2O_3: hematite

Fe_3O_4: magnetite

FeO: wusitite or iron protoxide.

Figure 3: Forms of steel. oxidation

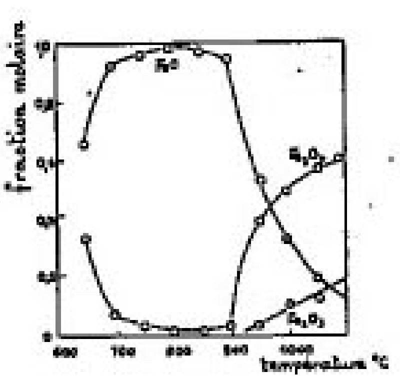


Figure 4: Evaluation of the proportion of magnetite & westite based on the temperature

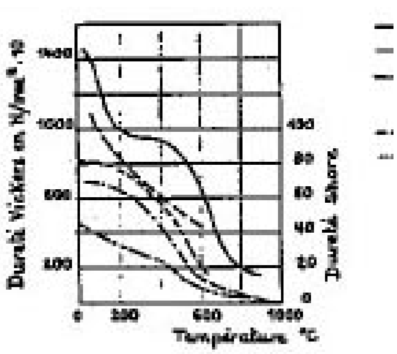


Figure 5: Hardness variation of the roll calamine based on the temperature.

_______ Fe_3 O_4 on calamine
__ __ Fe_3C on the roll
-------- FeO on calamine.

Material of the roll
--------   Hardness Shore
___ _ __ Hardness Vikers (Calculated by conversion)

Table 1. displays the hardness classification, at ambient temperature, of the main iron oxides of work rolls :

Material	Hardness in Vikers (Hv a temp amb)	Hardness Shore (ShC a temp amb)
Oxide		
Fe O	270 to 350	40 to 051
Fe_2O_3	1030	>97
Fe_3O_4	420 to 450	60 to 064
Rolls for long products		
Cast Rolls :		
Indefinite Chill	450 to 680	60 to 80
Clear Chill	450 to 680	60 to 80
Pearlitic Nodular Cast	320 to 480	45 to 64
Acicular Nodular Cast	480 to 580	64 to 76
High Chromium	570 to 652	70 to 80
Steel Rolls		
Eutectic Steel Cr, Mo alloyed Rolls.	270 to 380	40 to 55
Graphitic Steel.	285 to 499	42 to 67
Hypereutectic Steel Cr, Mo alloyed Rolls.	295 to 490	43 to 65
Rolls for Hot Flat products		
Cast Rolls :		
Indefinite Chill	550 to 740	70 to 85
High Chromium Cast Iron	450 to 740	60 to 85
Steel Rolls		
Eutectic Steel Cr, Mo alloyed Rolls.	320 to 550	45 to 70
Graphitic Steel.	370 to 490	50 to 65
Hypereutectic Steel Cr, Mo alloyed Rolls.	370 to 550	51 to 70
High Chromium Steel.	360 to 740	50 to 85

FeO appears under the shape of a soft and porous layer.
FeO can be expected to play the roll of a lubricant between the contact surfaces, while Fe_2O_3 and Fe_3O_4 cause higher frictions and put the rolls under a severe abrasion.

Friction

The metal preservation gives us the following relation:

v_E Strip . e_E Strip = v_S Strip. e_S Strip

e_E Strip: thickness of the strip at the entrance
e_S Strip: thickness of the strip at the exit.

The sliding down river can be defined as:

$$G_{down\ river} = \frac{V_{s\ strip} - V_{roll}}{V_{roll}} \cdot V$$

Let's note that for reductions over 10% the formula will be :

$$g_{down\ river} = \frac{Reduction}{4}$$

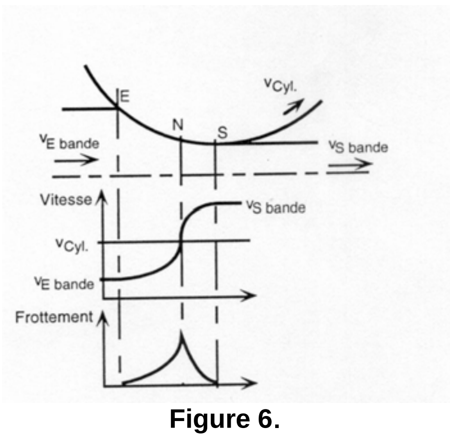


Figure 6.

The energy dissipated by the friction among rolls corresponds to the surface under the friction curve. It can be observed that it dissipates by thermal conduction in the plate and the work roll.

The space between rolls is the point where the speed of the strip equals the peripheral speed of the work roll, and is known as neutral point (figure 6 letter N).

On the left of the neutral point, towards the entrance of the rolls (figure 6 letter E), the strip moves at a lower speed of the roll periphery .The friction caused by the engine has tendency to drag the metal between the rolls. When the traction exerted on the strip at the exit of the stand increases, the neutral point moves towards the exit: the friction mainly comes from the engine, this leads to the plate slipping between rolls.

On the right of the neutral point, at the rolls exit (figure 6 S), the plate is accelerated by the reduction of the thickness, it has a higher speed than the peripheral speed of the roll.

- A given rolling process needs a minimum level of friction. Without friction the rolling process will not be possible. It is advisable to maintain, just from the entrance of the rolls at the neutral point, a sufficient friction of the engine, but without getting to the threshold, since this would cause the seizure between roll and plate. The ideal would be, from the neutral point at the exit of the rolls, to diminish the friction.

- The minimum friction required increases with the imposed reduction.

For such a reason the roll rugosity is so often increased. The drag condition (or non-slipping) in permanent regime is less draconian but it still implies a minimum level of friction.

FEATURES OF ROUGHING ROLLS

Main features:

- High resistance to hot cracking (mainly on first stands).
- Resistance to mesh loosening.
- Thermo-mechanic impact resistance (mainly on first stands).
- Bending strength (duo stands)
- Limit to slipping risk
- Good surface conditions (mainly on first stands).

Metallurgical and mechanical parameters

- Total absence of massive carbide
- The highest hot hardness in spite of carbide absence
- Protective oxidation.
- A very adherent oxide film
- Very high thermal conductivity (to diminish the thermal gradient during the peripheral heating).
- A core with high yield strength and high elastic module (rigidity of the stand)

Centrifuged qualities

In the 80's the metallurgical bases of HCRS were characterized by the total absence of carbides M_7C_3: %k=12.33%C+0.55%Cr-15.2

- To determine the Cr content: %Cr=8.75%C+3.5

The problems encountered were:

→a very slow kinetic of oxidation (diminishing of irrigation)
→profile loss (adhesive wear: micro porosities)
→surface degradation (very low hot hardness -matrix-)

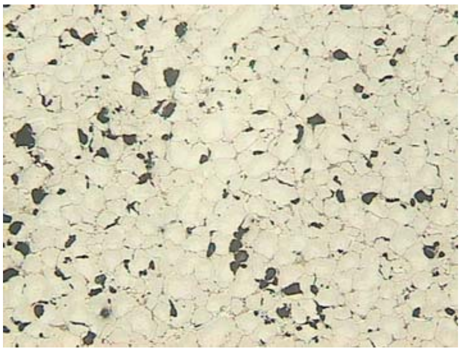
%C=0.70	Cr/C=14
%Cr=9.00	%Cr matrix=25

The Chemical Analysis should be optimized to:

1- Avoid fragile eutectic carbides.

2- Increase the kinetic of oxidation and modify the oxide chemistry

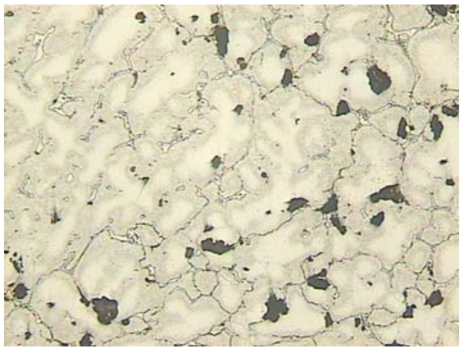
- ❖ Add V+Nb+Co



Micro1. ↓ ACRA

3- Increase Hot Hardness.

- ❖ Increase the carbon percentage in the austenite
- ❖ add V+W+Nb+Co
- ❖ Low down the Ni+Si content



Micro2. ↓ ½ HSS

4- Measure up the germination of MC carbides

- ❖ solidification of granular texture
- ❖ Put in massive carbides in the liquid

5- Increase the adherence of the oxide film

- ❖ Measure up the thickness of the oxide layer

- Influence of Cr+Co

Micro3. HSS

- Actions on chemical phenomena.
    - Influence of Nb+Co

6- Increase the secondary hardening

- To endow the matrix.
- diminish the state of residual stresses

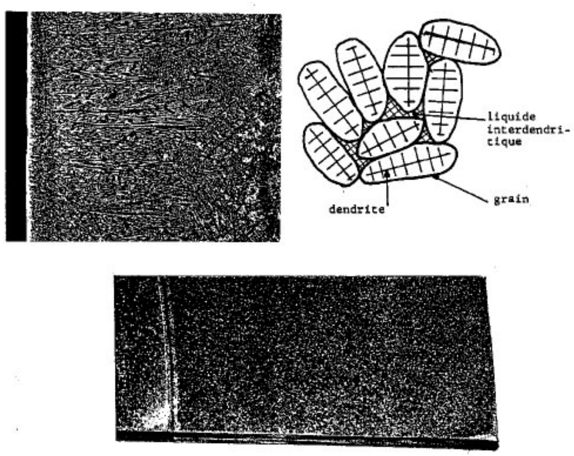
7. Improve the solidification structure (picture 1)

a) Basaltic or columnar zone
   Grains grow in extended shape following a direction

- Overheating increases this area.
- The cooling speed accentuates it.

b) Equal-axis Area
   Free crystals move in the liquid metal and prevent the basaltic growth. In fact, the thermal gradient is disturbed → dendrites are oriented in a random way.

c) Granular Area
   The mixture breaks the secondary branches of the dendrites and this leads to a coalescence and a growth in the shape of fine grains.



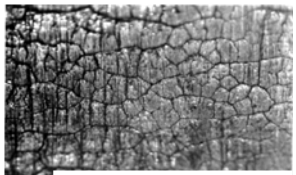
Picture 1. Solidification structure

Finishing Rolls (First Stands):

Stresses - Degradation methods

Thermal Fatigue

The metallurgical factors acting on the thermal fatigue are (picture 2):



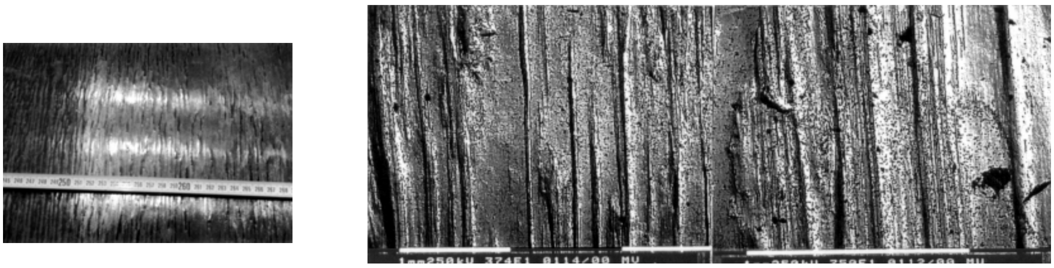
Picture 2.
Thermal Fatigue

- Nature, quantity and shape of primary carbides
- The stability of the expansion coefficient (destabilization of residual austenite)
- Hot hardness of the matrix (compressing strength)
- The kinetic of oxidation, that is to say, the oxide film creates a heat shield and the oxidation of the cracks edges accelerates its progression.

Hot plastic deformation: grooves:

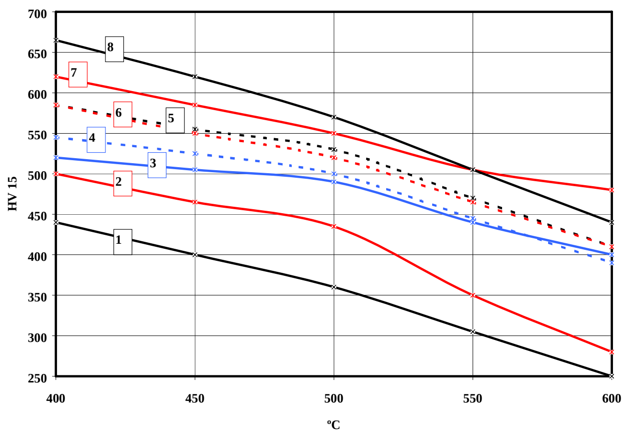
Hot resistance of the matrix is an essential criterion. Qualities where the secondary hardening is obtained by the secondary carbide precipitation allow to obtain a high hot hardness in the domain of temperature ranging from 450º up to 675º, the C,Mo,W,Co elements are the most influential.

Picture 3. Plastic Deformation



HOT HARDNESS

Graph 1 shows the variation of hardness with the temperature of the different families (board 2)
The Carbon component monitors the hot hardness (secondary hardening of the matrix)
The cobalt increases hot hardness at a high temperature.



Graph 1. Hot hardness profile.

	C	Si	Mn	Ni	Cr	Mo	V	W	Nb	Co
1	**High Chromium**									
2	**1750**	**200**	**1000**	**/**	**6000**	**3500**	**4400**	**2000**	**/**	**/**
3	**1700**	**400**	**1000**	**1000**	**4500**	**5000**	**5250**	**6400**	**/**	**/**
4	**1625**	**675**	**600**	**600**	**5500**	**3500**	**5000**	**/**	**/**	**/**
5	**2000**	**600**	**600**	**/**	**4000**	**3000**	**6000**	**400**	**1000**	
6	**1900**	**600**	**600**	**/**	**5000**	**5100**	**4600**	**5000**	**/**	**/**
7	**2450**	**1000**	**750**	**600**	**6000**	**1750**	**4600**	**5000**	**/**	**5000**
8	**2450**	**1000**	**1000**	**600**	**6000**	**1750**	**4600**	**5800**	**/**	**/**

Board 2. Grades

Eutectic carbides break down; decohesion of grains:

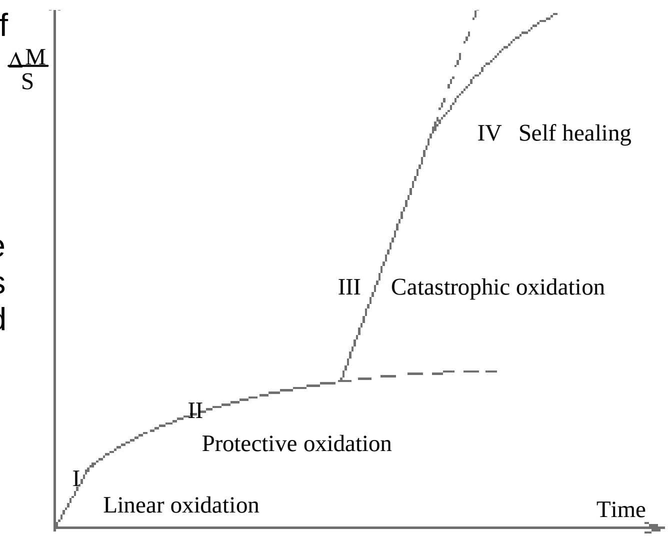
The break down of fragile γ/M7C3 y γ/Mo2C carbides (micro 4) causes a considerable wearing in the matrix (wearing summit). The interdendritic carbides net favors the decohesion of the grains in the cells

Micro4. Carbides break-down

Oxidation:

The knowledge of mechanisms of formation of the oxidation layer based on the oxidation parameters (temperature and the atmosphere atomization point) allows to improve the performance of new rolls in terms of surface quality.

Figure 7 represents the general law of the oxidation kinetic in the grades containing Cr.



Periods I & II: make up of a protective layer rich in Cr. This oxidation follows in the beginning a linear law followed by a parabolic law based on time

Period III: when the oxidation conditions become severe, the speed of oxidation increases in an accentuated way; it is in this state when the oxide film loses its protective properties. The kinetic becomes linear and leads to a catastrophic state.

Period IV: the speed of oxidation slows down and two situations may take place: oxidation can always be catastrophic or the oxide film always regenerates.

The oxidation kinetic of roll grades is always characterized by the following two definitions:

- **Protective oxidation corresponding to stages I and II**
- **Catastrophic oxidation corresponding to stages III and IV**

The different studied grades are reflected in table 3:

Grade	C	Cr	V	W	Nb	Mo
URFAC	2.2/2.8	16/20	0.3	-	-	1.5/3.0
HSS-A	2,00	5,00	4,50	-	-	5,00
HSS-B	2,00	4,00	6,00	5,00	-	3.00
HSS-C	2,00	5,00	4,50	5,00	-	5,00
HSS-D	2,00	4,00	6,00	-	1,0 0	3,00

Board 3. Different grades

Figure 8 depicts a first linear stage and a second parabolic stage which characterize the protective oxidation:

Later on there is a transition in the curve.

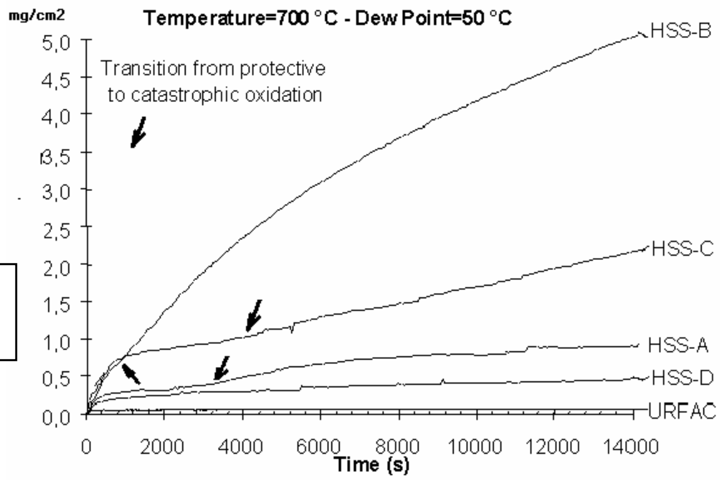
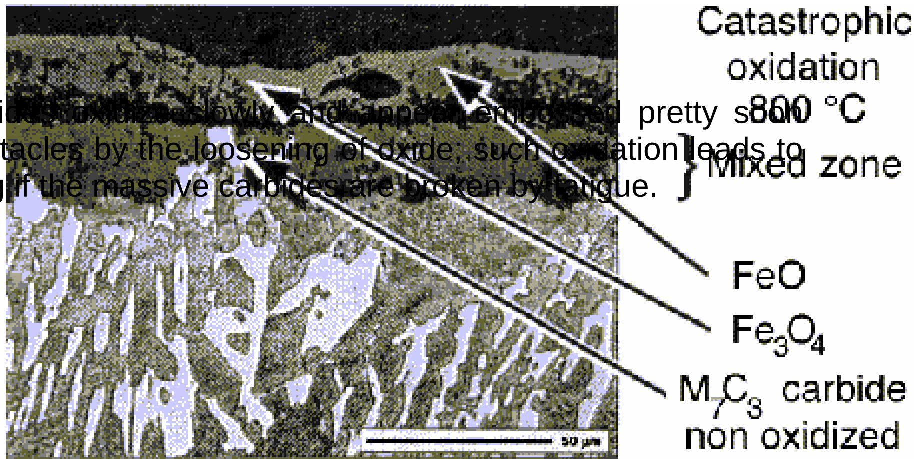


Figure 8. Lineal stage.

Grade D shows a quite interesting kinetic of oxidation in comparison with that of High Chromium Iron.

As for grade B, the catastrophic way appears quickly since the matrix presents a rather high V content, which oxidizes more quickly than carbides.

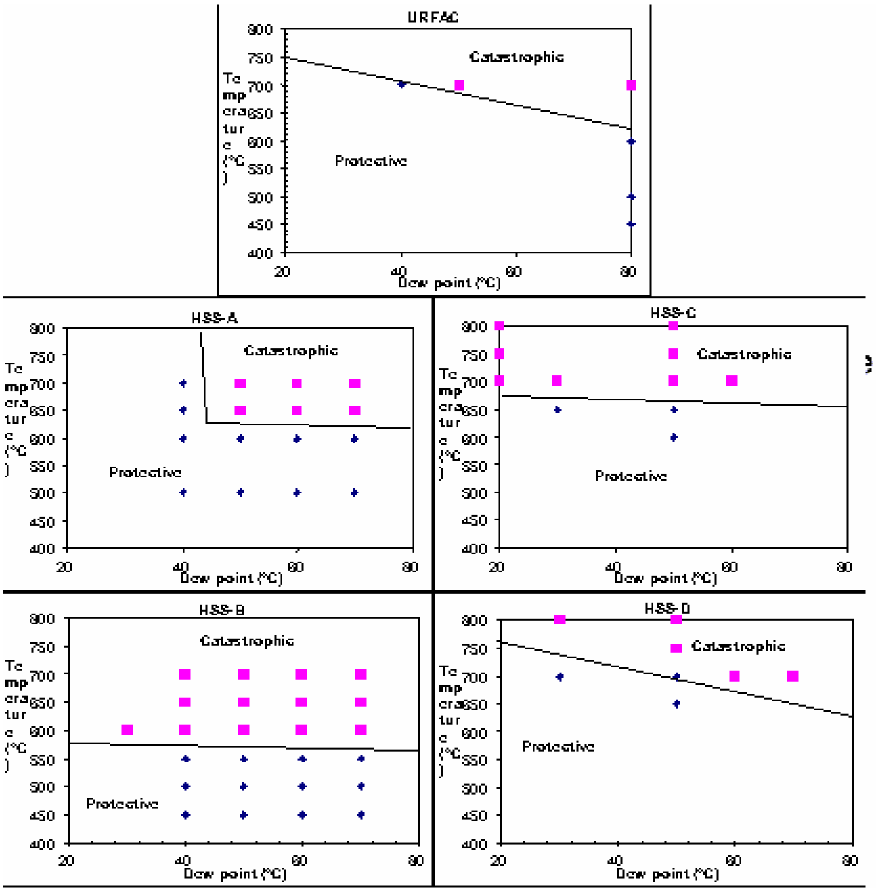
Micro 5 shows how M7C3 carbides oxidize slowly and appear embossed pretty soon transforming themselves into obstacles by the loosening of oxide; such oxidation leads to the initiation of peeling or banding if the massive carbides are broken by fatigue.



Micro 5. Oxidation layers.

From the results obtained by the isothermal test of oxidation, it is possible to determine the used zones of the studied grades and to establish maps of oxidation based on the oxidation temperature and on the dew point.

<u>The following example illustrates the results of the studied qualities (Graph 2)</u>



Graph 2. Study of the oxidation behavior on different grades.

<u>Defects on the rolled product.</u>

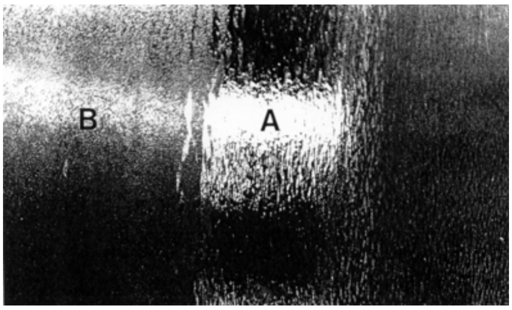
The defects on the surface of the work rolls cause not only loosening, which lead to litigation with the customers, but also cause problems in the rolling programs:

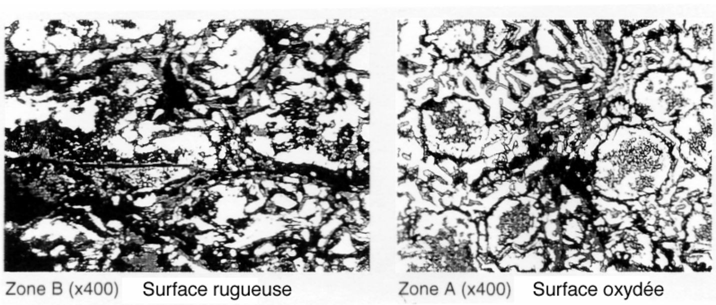
- The duration of the campaign is frequently related to the state of the roll' surface.;
- The surface degradation is directly related to the nature of the rolled product and its thickness, it is possible to regenerate this surface by varying those parameters , in the course of a campaign, and using actuators such as:
- Inter stand cooling
- Skin cooling
- Lubrication.

There are two large families of defects related to the microstructure and the phenomena of oxidation of the rolls

Peeling & Banding:

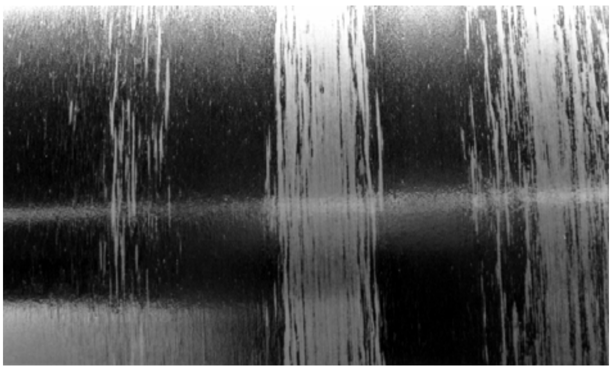
Grades with a high Chromium content (C: 2.4 to 2.9% and Cr: 16 to 16%) present γ/M_7C_3 & Mo_2C carbides and are the initiators of the oxide film break down (peel) Picture 4. This leads to a defect in the roll known as BANDING and to a defect on the rolled product named OXIDE INCLUSIONS.





Micro 6.Microestructure of areas A & B

HSS Grades (high contents in V-Mo-W-Nb) may present γ/M_7C_3 & γ/Mo_2C primary carbides in smaller amount; the break down of these carbides causes a defect on the rolls known as PEELING (Picture 5) and to a defect on the rolled product also named OXIDE INCLUSIONS.

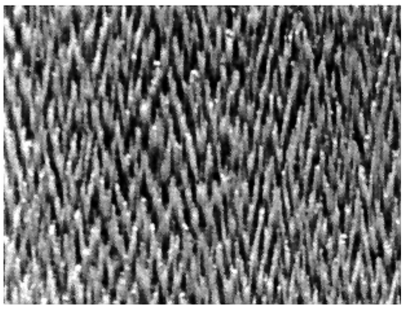


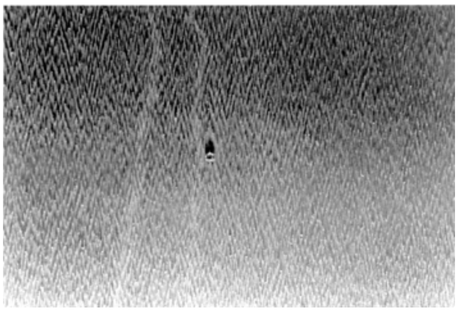
Picture 5. Peeling

Chevron Marks.

This type of defect is associated to a hot deformation of the matrix in the shape of little chevrons (Picture 6). That is the reason why hot hardness is critical and essential.

Inside the bearings with a V-shape the calamine of the rolled product is trapped to be then placed on the plate; this defect is known as CHREVRON MARKS.





Picture 6. Chevrons.

<u>Finishing Rolls (Last Stands):</u>

Over the last thirty years, only the grade named "INDEFINITE CHILL" was used in the last stands.

The frequent disassembling of rolls, where the wearing down crest is considered as a critical factor, is the reason why nowadays productivity is slowing down.

The degradation mechanisms are well known:

- Cementite oxidation,
- Cementite break down and formation of a third body.
- Hot Abrasion,
- Seizing ⇐ sticking ⇐ cracking of shearing,
- propagation of cracks known as "colliers plongeants"

The rugosity of the surface must stay at a very low level; reason why a great amount of carbides is needed (30% minimum). The initiation of the superficial cracks of thermal-mechanical origin depends on the morphology of this phase of carbides. The cementite presents characteristics non-adapted to the stresses observed in these finishing stands; this carbide oxidizes very quickly at service temperature and breaks. That is the reason why the rolled material plays such an important role; it leads to a wear summit that influences in the obtaining of the dimensional tolerances.

The development of HSS rolls and the numerous investigations made on the use of HSS led to a grade named

<u>Enhanced carbides ICDP</u>

C	Si	Mn	Cr	Ni	Mo	Ta	B	Ti	<u>Zr</u>	Nb	V

Indefinite Chill	3,1 3,5	0,5 0,9	0,4 1,0	1,6 2,0	4,2 4,6	0,2 0,4	/	/	/	/	/	/
New grade	3,1 3,5	0,5 0,9	0,4 1,0	1,6 2,0	4,2 4,6	0,2 0,4	MC Carbides					

Board 4. Analysis

The presence of graphite plays an essential role on the service behavior in these stands; the shape, distribution and the amount of graphite are being adapted for each particular Hot Strip Rolling Mill.

The purpose of the new quality is to improve the maintenance in service by means of the reduction of the cementite amount, which breaks under the combined efforts of oxidation and shear stresses due to intense sliding in these last stands.

The inclusion of alloyed elements such as **Ta, B, Ti, Zr, Nb, V** contributes to:

- ➔ the formation of γ/MC eutectic carbides which provide **excellent tribologic properties**.
- ➔decrease the size of eutectic cells **to restrain crack propagation.**

Results of Enhanced ICDP rolls (board 5)

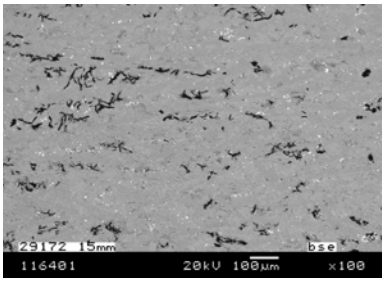
	Stands without incidents			**Stands with incidents**			**Stands % inc**		
	F5	**F6**	**F7**	**F5**	**F6**	**F7**	**F5**	**F6**	**F7**
Global 2001	3169	4188	6460	2447	2655	4659	22,8	36,6	27,9
ICDP	3268	3773	5085	2576	2218	4024	21,2	41,2	20, 8
CIL A	**3768**	**4931**	**7751**	**3692**	**4220**	**6778**	**2.00**	**14.42**	**12.55**
CIL B	**3762**	**4940**	**7547**	**3740**	**4225**	**6672**	**1.01**	**14.96**	**11.60**
Improvement in comparison with the standard ICDP	**+15%**	**+ 31%**	**+50%**	**+44%**	**+90%**	**+92%**	**///////////**	**////////////**	**//////////**

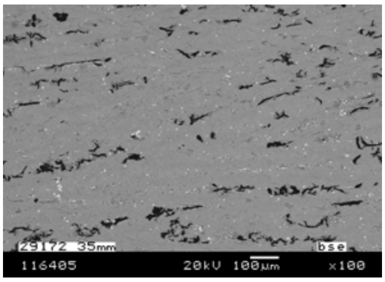
Board 5. Performances.

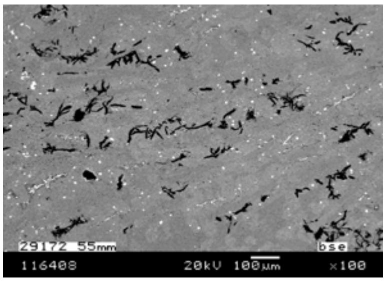
These results of rolls containing Nb-V show an improvement in Stand 5, where they finish their life. In fact, rolls with Nb have in this stand a low performance due to the low amount of NbC carbides.

Amount of Graphite

Morphology and distribution of γ/(Nb-V)C carbides. The micros below show a homogeneity in relation to the amount of graphite and carbides MC(micros 7-8-9)







3. COLD AND HOT BACK UP ROLLS.

<u>Required characteristics</u>

Terms such us "fatigue" and "surface deformation " usually represent the limit use of back up rolls.
The most common failure is the surface deformation. This includes an ample range of deformations

- Weariness because of material tearing up; this type of wearing can have an abrasive origin or be due to the formation of a micro-spalling .
- Seizing with transference material among the back up roll surface and that of the work roll and cracking due to rolling incidents
- Plastic deformation marks.

<u>Stresses</u>

<u>Fatigue</u>

The surface wear caused by fatigue does no occur instantaneously but a great number of cycles are necessary to cause it.

The theory of Herz gives an idea of the complex system of pressures exerted in the superficial layers. In the surface the fatigue damage has its origin in the application of shearing pressures; this leads to the plasticity of the tension areas in the sub-layer when the friction between both rolls (back up & work) is important.

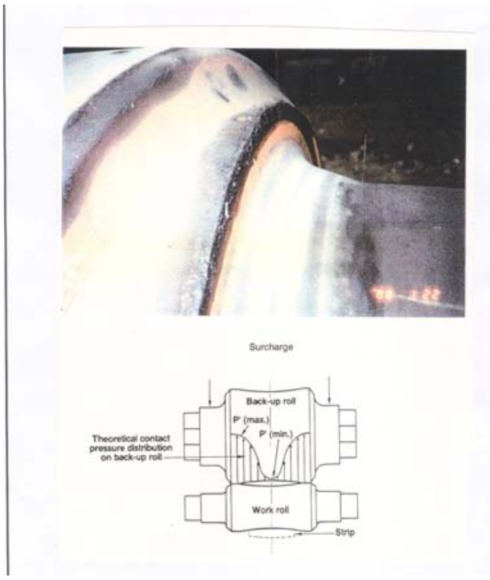
Such plasticity will favor the origin of cracks this phenomenon depends on the level of tensions induced by contact and residual stresses.

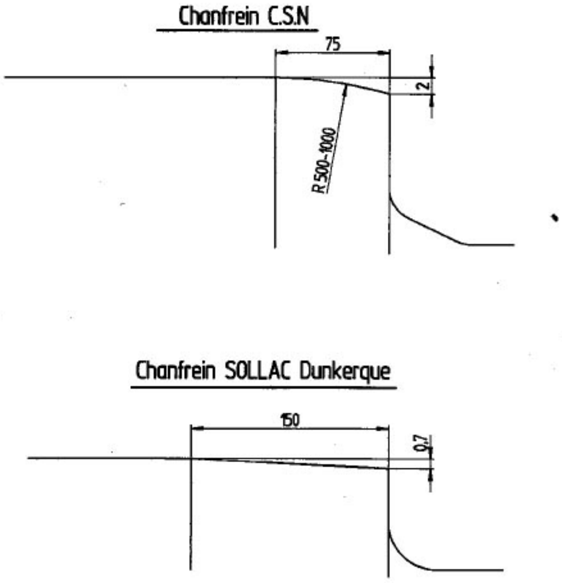
Considering the vulnerability of the nondestructive controls to measure the layer, the rolls are retouch in an experimental way considering the risks of progressive cracking

WEARING

Wearing is caused mainly by abrasion: this abrasive wearing increases with the high superficial pressures of contact as well as by the sliding speed
Such wearing can be accelerated by the presence of abrasive particles coming from the rupture of essential carbides of work rolls.

Another kind of wear is the corrosion which demands to take a particular care with regards to the surface state.
The wearing mechanisms can also generate very important local tensions of contact in relation to the wearing profile
This wearing and the increase of the local pressure explain to a large extent the breakage at the barrel edge (Picture Nr. 7).





Picture 7 .Spalling in a corner

Picture 9. Chamfers policy.

This implies the use of chamfers at the ends of the barrel (Picture Nr. 9).

SEIZING.

Seizing with transference of material between the surfaces of back up & work rolls, leads to incidents in the course of rolling; the passage of the band with various thickness around the work rolls provokes a sharp elevation of the surface temperature of the back up rolls due to seizing under strong pressures. The consequence is:

- An increase of the tensions whose beginning may be related with a metallurgical defect, a cracking whose direction will be perpendicular to the radial plane.

- An increase of superficial shearing tensions which lead to the beginning of cracks whose direction is inclined in relation to the surface

Two types of nondestructive controls should be carried out before these sort of incidents:

- Ultrasound (longitudinal waves); detection of under-surface cracks
- Eddy Currents; detection of surface cracks.

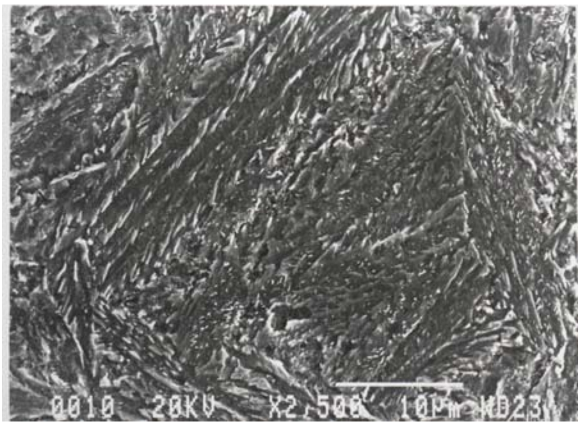
Plastic Marks and Deformations.

The marks resistance is obtained by a high elasticity module and high harnesses level.

From the analytical point of view the grades are characterized by the transition of rolls with a 3% of chromium towards rolls with a 5% Cr.

MICROSTRUCTURE

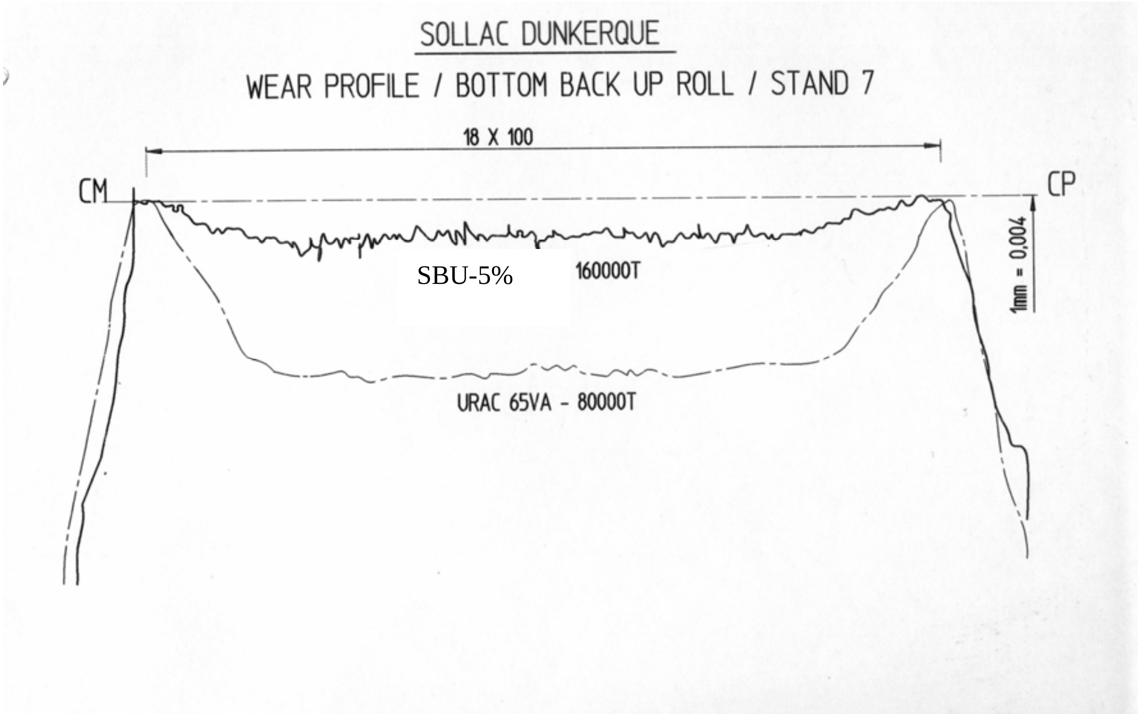
Bainitic-martensitic matrix with a fine distribution of secondary carbides (micro 10)



Micro10. Microstructure of back up rolls.

Performance of 5% Cr Rolls.

Graph nr. 3 shows the difference between the wear profile of a back up roll with a 5%Cr. and that with a 3% Cr.



4 .CONCLUSIONS :

Nowadays, the technological evolution of the vertical centrifugal casting allows to start up this new metallurgy for work rolls, which entails the measurement of:

- Granular crystallization, which allows to remove pores and micro-shrik-holes
- The interface of two materials that allows to suppress spallings after the hardening process or in service.

Each strip mill leads to particular stresses: its heating, cadence, rolling speed of the rolled products; for this reason the roll manufacturer must carefully choose the material whose properties will be optimized with the aim to respond to all the criteria that have been previously exposed.

The type of carbides morphology, the oxidation ways, the shape and amount of graphite (for the grades used in the last stands of hot rolling mills) and the hot hardness of the matrix are the essential parameters that demand a correlation between the results of the laboratory and the different industrial tests.

The perspective of these materials is very important both for productivity (time of campaigns, weak wear) as for quality (good aspect of the surface).

As for cold work rolls, just the bimetallic rolls (compounds) will allow the use of new materials; in fact the alloy elements, the heat treatment laws give the rolls manufacturer a new concept ; the centrifugal castings has already shown its advantages in other technologies.

As far as back up rolls are concerned, grades with a 5% Cr have excellent performances. There could be a competition between monobloc and bimetallic (compound) rolls. The homogeneity of the material and the level of residual stresses are preponderant factors.

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