Structural Investigations of HSS Rolls for Hot Strip Mill

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ABSTRACT

High Speed Steel (HSS) cast rolls are used in front finishing stands of hot strip mills (HSM). Good wear resistance and hardness at high temperatures, are defining features of HSS.

Previous experience has shown that HSS rolls containing mainly hard MC carbides have a high friction coefficient, which is detrimental for the rolling power consumption and for the strip surface quality. On the other hand, HSS rolls containing eutectic rod shaped carbides are brittle and more susceptible to spalling. To overcome these problems, a suitable grade, called HSS7, that gives the best compromise between a low friction coefficient and a high crack propagation and wear resistance was developed. That alloy contains well-dispersed hard VC carbides improving wear, and non-interconnected eutectic carbides of the M_2C and M_7C_3 type, hindering crack propagation.

All the metallurgical factors affecting the performance and damage of under rolling condition in front finishing stands are reviewed: wear resistance, friction coefficient, resistance to rolling incident, and oxide film formation.

The effect of nature, morphology and amount was for each of the carbides studied and connected to the factor affecting the behaviour of the new grade developed.

Different techniques are used such as: differential thermal analysis, optical and electron scanning microscopy and image analysis. A correlation with mechanical properties was also performed.

Key words: carbides, microscopic identification, HSS.

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1. INTRODUCTION.

In order to adapt to severe hot rolling conditions of a Hot Strip Mill, a rolling mill roll with much higher resistance to wear and surface roughening has always been searched. In the beginning of the 1990's a challenge was launched to rollmakers to develop a product capable of better satisfying the ever-increasing requirements for rolling mills with regards to better strip's surface quality and for higher productivity of the rolling mills.

A compound roll with the outer layer made of high alloyed steel corresponding to the family of alloys used for cutting tools, which is called HSS rolls was developed and introduced into hot strip mills in Japan in the early nineties. This new roll has spread all over the mills in Japan quite quickly, even over many mills such in Europe and USA, to replace the Hi-Cr rolls used in the first Finishing Stands.

Unfortunately, problems were encountered with the use of HSS rolls initially. Peeling led to rolled-in scale on the strip and higher rolling forces were often noticed. The spalling resistance was at times very poor compared to High Chromium (Hi-Cr) iron rolls (1). In Front Stands, a 20-30 % higher rolling force comparing with conventional Hi-Cr iron rolls was observed, which is due to higher friction between rolls and strip. This gives rise to large consumption of electricity, strip scale defects, and even in case of thins gauge or hard materials, lack of mill motor power.

The challenge was both to develop a higher wear-resistant roll that could also face the problems described and could be manufactured by the centrifugal casting process. Metallurgical studies were carried on the relations between alloying elements, casting conditions, microstructure and wear conditions, when using high-alloyed steels such as High Speed Steels.

2. DEVELOPMENT OF HSS ROLLS.

High Speed Steels are ferrous-based alloys of the Fe-C-X multicomponent system where X represents a group of alloying elements including mainly Cr, W, Mo, V. These steels are mainly used for cutting tools, since they are characterised by their capacity to retain a high level of hardness while cutting metals at high speed. The as-cast microstructure of High Speed Steels consists of dendrites surrounded by a more or less continuous interdendritic network of eutectic carbides. The main features of the cast microstructure are the distribution and morphology of eutectic carbides, owing to their direct influence on mechanical properties, and on the service performance of High Speed Steels.

The idea of using these alloys for the manufacture of work rolls for Hot Strip Mills resulted from an insight into the requirements involved in this type of application: fundamentally, the capacity to retain a high level of hardness even when submitted to high temperatures, and also wear resistance. Classical High Speed Steels fulfil both.

The composition of the alloy is an important parameter as the most significant change lays on the type, morphology, and volume fraction of the eutectics carbides. The amount and morphology of these carbides is a factor of important concern as it influences deeply the wear resistance of the roll.

In the HSS quality based on high carbon, medium chromium content and addition of strong carbides forming elements like Mo, W, V, different types of carbides can be founded: MC, M_2C, M_6C, M_7C_3..The hardness of those carbides is in the 1600/2800 HV range, compared to a hardness of 1100 HV for the cementite (M_3C) Good wear resistance must be achieved with an adequate combination of them.

This microstructure optimisation was focused on the main requirements for developing a new grade:

- High wear resistance
- Low friction coefficient
- Good resistance to rolling incidents
- Good oxidation and thermal behaviour.

For HSS development, the main purpose is to optimise the amount of very hard MC carbides, M_7C_3 and M_2C, which can be refined and dispersed. Precipitation of the low hardness and brittle M_3C carbides is avoided. To obtain the desired amount and morphology of those carbides, Marichal Ketin uses Vanadium, Tungsten and Molybdenum (7).

A. <u>Metallurgical factors determining wear resistance</u>

When using those rolls, it was found that the wear resistance of the roll for hot rolling was significantly improved by the VC type fine granular carbides, which dispersed uniformly in the matrix while the other metallurgical factors had little effect (3).

Unfortunately, consideration of the solidification process in centrifugally cast roll indicates that in the case of the centrifugal cast roll, VC carbides with a small specific gravity segregate in the inner surface side of the equiaxed grain region owing to the centrifugal force. This phenomenon can be explained in terms of the difference in specific gravity between the primary crystal and the residual molten steel (3). To prevent this carbide segregation, it is necessary to decrease this difference by adjusting the composition.

The MC precipitation temperature rises with increasing vanadium content but the eutectic temperature is practically constant (4). As the vanadium content is decreased, that ΔT decreases and moreover the MC carbides becomes correspondingly finer (4). A lower Vanadium content will give finer carbides arising at lower temperature and leading to smaller segregation.

B. <u>Metallurgical factors determining friction coefficient</u>

Experimental results show that the friction coefficient of the first delivered HSS rolls was above 0.5, which is twice the friction coefficient of Hi-Cr iron rolls (1).

These HSS rolls of the first type contained large amount of primary VC carbides embedded in a tempered martensitic matrix. These VC carbides have a high hardness (3000 HV) so they induce good wear resistance. Unfortunately, the surrounding matrix hardness is between 500 and 1000 HV, and its wear resistance is weak compared to that of VC carbides. The matrix is worn and the hard carbides project the roll surface, where they act as "spikes" making scratches on the roll matrix. A higher friction coefficient was then observed (1).

In order to suppress the micro-sized scratches, the amount of VC carbides must be limited. The use of softer carbides like M_2C and M_7C_3 can decrease the friction coefficient, especially the M_2C that can keep high wear resistance due to its high hardness necessary to compensate the decrease of the amount of VC carbides (5).

C. Metallurgical factors determining the good resistance to rolling incident.

Moreover, in order to make the roll surface smooth during hot rolling, an increasing number of eutectic carbides M_2C and M_7C_3 hard but not so hard as MC is needed. It was proved that the addition of suitable amounts of Cr and Mo improve the toughness of M_7C_3 carbides (3). Rolls having such tough carbides combined with suitable amounts of Cr and Mo are expected to provide higher wear resistance than ordinary HSS rolls.

On the other hand, the amount of M_2C carbides need to be limited to prevent the forming of networks of brittle particles which could increase sensitivity to crack propagation and reduce spalling resistance in case of rolling mill incidents (6).

It has been shown that the centifugaly cast HSS rolls containing high amount of Mo and W have a poorer spalling resistance than Hi-Cr iron rolls. The study of cracks formation in these rolls shows that the cracks follow the eutectic M_2C carbides. These hexagonal rods like carbides are too brittle, so they are easily split by the crack (1). This observation led to the reduction in the amount of eutectic M_2C carbides in the structure by a reduction in the Molybdenum and Tungsten content.

D. Metallurgical factors determining oxide film formation

Kinetics of the oxide film formation and its adherence to the roll surface differed greatly between the HSS and Hi-Cr roll grades (7).

A trial with three different grades of HSS rolls in the 2050 mm HSM of Iscor showed that the chromium content is an important factor as concern the speed of formation, adherence and thickness of the roll oxide film

3. OPTIMISATION OF HSS ROLLS.

The poor reaction to incidents of the HSS rolls has been an important obstacle to a more intensive use. The roll maker has had to optimise more the structure of the metal according to the great influence of carbides morphology, the cohesion between the matrix and carbides and the types of carbides found in the spreading of cracks. Even here, the chemical composition and the choice of a more appropriate heat treatment will contribute to a reduction of these risks.

Hence Marichal Ketin developed a suitable grade, called HSS7, that gives the best compromise between a low friction coefficient and a high crack propagation and wear resistance. The choice of the composition is based on the considerations developed in the previous chapter.

The microstructure of this HSS grade is based on hard well dispersed primary and eutectic carbides embedded in a tough tempered martensitic matrix. It achieved to give promising results in several hot strip mills.

4. ROLL CHARACTERISATION.

The composition is shown in table 1. In addition to classical alloying elements (C, Cr, Mn, Si, Ni), it contains Vanadium, Molybdenum and Tungsten.

C	Cr	Mo	V	W
1.5-2.0	5.0-7.0	3.0-4.0	4.0-5.0	1.5-2.5

Table 1: Composition of HSS7

The samples analysed correspond to industrial conditions. The rolls were manufactured by centrifugal vertical spin casting process. Pieces were then cut off from the roll to obtain samples corresponding to different depths in the working layer. They were used for microstructure characterisation and mechanical testing.

The characterisation of the microstructure was done using various techniques:

- Differential thermal analysis for solidification sequence
-Optical and electron scanning microscopy to determine the analysis of carbides
-Image analysis to quantify the volume fraction of carbides and the grain size

5. SOLIDIFICATION SEQUENCE OF HSS7.

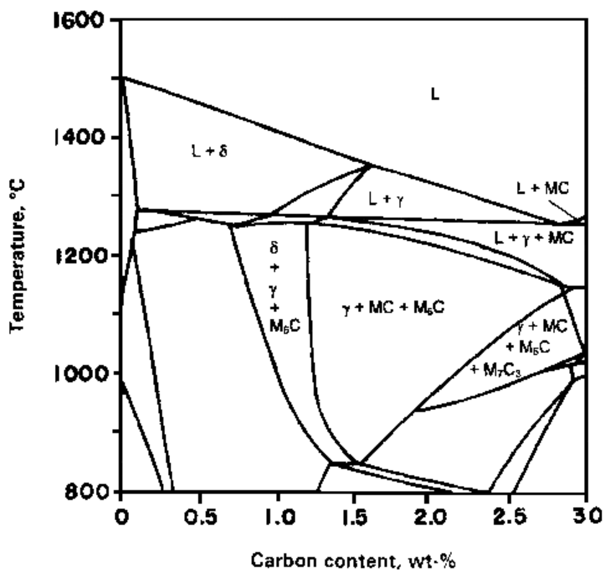

Figure 1: Isopleth Fe-5Cr-5W-5Mo-5V-C (wt-%) calculated using Thermocalc (1)

The alloy design of High Speed Steels for rolls is based on the composition of the M2 steel, the main changes being the higher carbon and vanadium contents. Thus, though the roll makers have developed alloys specifically designed to the operational conditions of each hot strip mill plant, their chemical compositions often fall into the following ranges: 1.5-2.0 %C; up to 5 %W; up to 5 %Mo; 3-7 %Cr, and 4-8 %V which is the case for the alloy studied here. Figure 1 shows the calculated isopleths Fe-5Cr-5W-5Mo-5V-C (wt-%), a typical diagram for this composition. It shows that the solidification sequence is rather complex and needs some investigations.

The differential thermal analysis technique (DTA) was used to investigate the solidification sequence and especially the carbides precipitation. Differential thermal analysis (DTA) is a technique in which the sample is heated (or cooled) following a temperature schedule and which can detect any endothermic or exothermic type transformation. Any phase change leads to variations in the sample temperature. The difference in temperature between the sample and the programmed temperature is monitored against time. With the DTA method, any transformation even the small one, can be detected (fusion, solidification, decomposition...).

The figure 2 and 3 illustrate the curve obtained during heating and cooling modes. For carbon between 1.7 and 2.0 %, the solidification sequence can be described by the following reactions:

1) Primary crystallisation of austenite
2) Eutectic decomposition of the residual interdendritic liquid: liquid $\rightarrow$austenite + carbides; this reaction moves down a eutectic trough with continuously changing phase compositions, so as to form different eutectic carbides according to the decreasing temperature.

The residual interdendritic liquid decomposes through different eutectic reactions as it moves down a eutectic trough, leading to the formation of up to three eutectics: γ + MC, γ + M_6C or γ + M_2C and γ + M_7C_3. Although the isopleths in Fig. 1 predicts the formation of the γ + M_6C eutectic, this eutectic seldom forms since the solidification normally occurs under non-equilibrium conditions and the formation of the metastable γ + M_2C eutectic is favoured. The γ + MC eutectic always precipitates first, owing to the high vanadium content of these alloys. The sequence by which γ + M_2C and γ + M_7C_3 precipitate depends on the overall chemical composition, the former being favoured by high W, Mo or V contents and the latter by high Cr or C contents.

The experimental conditions were: heating from room temperature up to 1500°C with a 10°C/min rate, and cooling from 1500°C down to room temperature at 10°C/min.

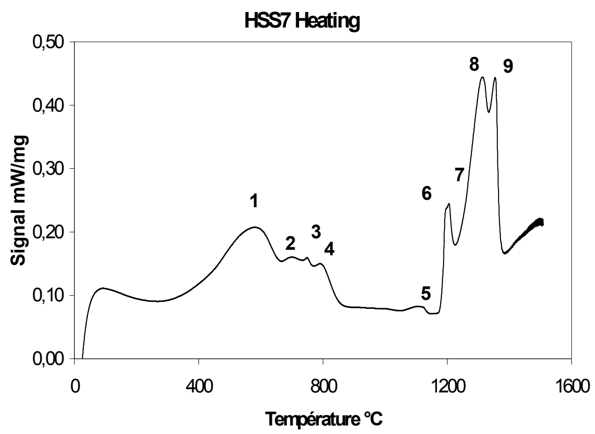

Figure 2: DTA curve during heating

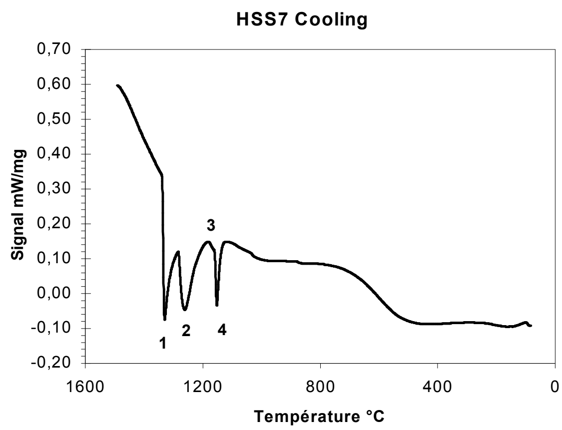

Figure 3: DTA curve during cooling

During heating, we have the reverse austenitic transformation (peaks 1,2,3,4), the dissolution of the carbides $M_{23}C_6$ formed in the tempered matrix (peak 5), the dissolution of the eutectics carbides (peaks 6,7,8) and fusion of austenitic matrix (peak 9). During cooling, due to cooling rate, we observed only the solidification peak

of the austenite (peak 1) and the peaks corresponding to eutectic reactions (peaks 2,3,4).
The eutectic reaction with MC (peak 8 on heating and peak 2 on cooling) is well defined. The two peaks corresponding to $\gamma + M_2C$ and $\gamma + M_7C_3$ are overlapping: it is difficult to separate them. But due to the fact that the volume fraction of M_2C is lower than that of M_7C_3 as it will be shown latter, we can assume that peak 7 on heating and related peak 3 on cooling correspond to the transformation of eutectic $\gamma + M_2C$; the peak 6 on heating and related peak 4 on cooling correspond to the transformation of eutectic $\gamma + M_7C_3$.

6. CARBIDES IN HSS7

The HSS7 microstructure contains a matrix with the products of austenite decomposition (tempered martensite): globular secondary carbides precipitated in the matrix and eutectic carbides distributed in both in interdendritic and intercellular region.

The nature and morphology of the carbides are influenced by chemical composition. In conventional High Speed Steels, MC carbide dissolves mainly Vanadium. M_2C carbides are rich in Molybdenum and Tungsten and can dissolve Chromium, M_7C_3 are rich in Chromium.

The characterisation of carbides that precipitated in the HSS7 indicates the presence of MC, M_6C, M_2C and M_7C_3. The identification of carbides was made using optical microscopy with selective etching and electron microscopy (SEM) with EDAX microanalyses.

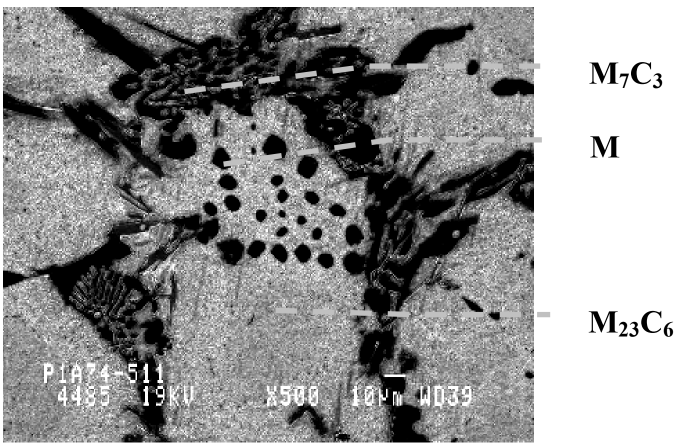

Figure 4: Cluster of M_7C3, M_2C and MC

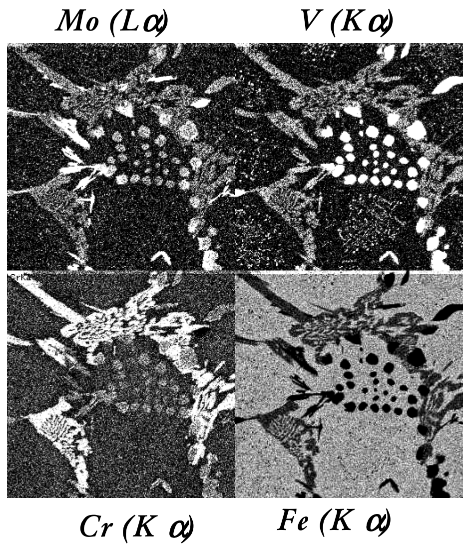

Figure 5: EDX on figure 5

Five types of carbides were founded after SEM/EDX analyses: MC, M_2C, M_7C_3, M_6C, and $M_{23}C_6$. MC, M_2C, M_7C_3, M_6C as eutectic carbides, which means that they precipitate from the liquid. MC is V-rich and its morphology is often globular. M_2C is Mo/W-rich, with an acicular shape (Cluster of rod-like particles). M_7C_3 are Cr-rich, and they are located at grains boundaries and distributed as a continuous network.

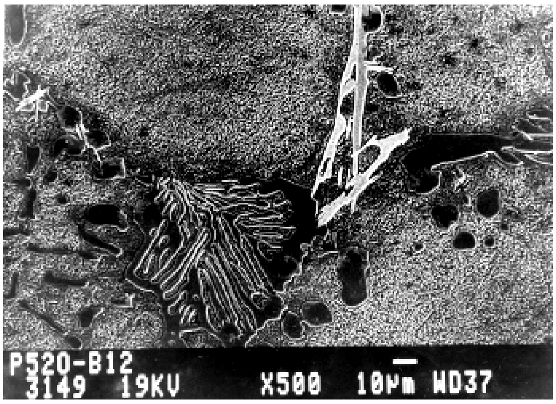

Fig. 6: Clusters of MC, M_2C and M_7C_3

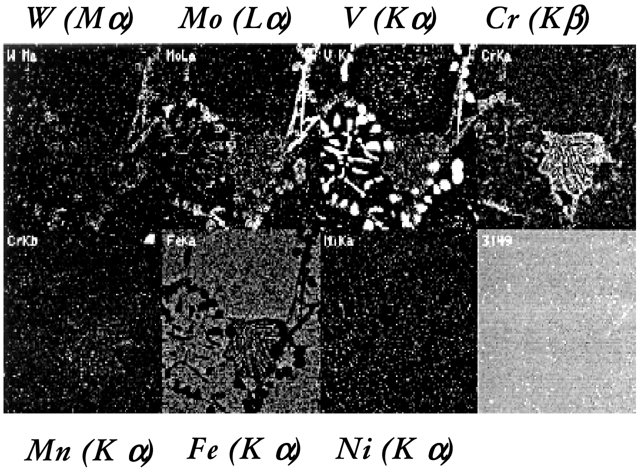

Figure 7: EDX on figure 7

M_6C are Fe/Mo-rich, and they appear to be located only on the first five millimetres of the shell (higher cooling rates), whereas others carbides types are present on the full shell thickness. $M_{23}C_6$ are Cr-rich fine secondary carbides fully dispersed within the matrix. Hence, $M_{23}C_6$ appear during tempering.

We found both divorced and complex regular MC carbides. Figures 4 and 6 illustrate the microstructure. MC carbides are present in the full shell thickness of the roll. Their shape is globular; they form clusters inside the matrix, or they are associated to M_7C_3 carbides in the interdendritic region. These MC carbides are rich in vanadium but dissolve Cr, Mo, a little W and very few Fe elements as shown in the EDAX mapping of Figure 5.

M_7C_3 carbides are also present in the full shell thickness of the roll. They possess a complex fan-shaped morphology. M_7C_3 are rich in Cr but dissolve also Mo, V, a little Fe and very few W as shown in the EDAX mapping of Figure 7.

Most of M_2C carbides possess an acicular form as shown in Figure 7 where they appear light grey. They are generally associated to M_7C_3 and MC. M_2C carbides are rich in Mo and dissolve W and V but very few Fe as shown in the EDAX mapping of Figure 7.

7. DENSITY OF CARBIDES

The total volume fraction of eutectic carbides and the volume fraction of each eutectic carbide depend mainly on the chemical composition, the effect of the cooling rate being less significant (8). The total volume fraction of eutectic carbides in High Speed Steels for Rolling mill rolls ranges from 9% to more than 15%, which is one of their main characteristics (8).

Table 2 gives the volume fraction of the MC, M_7C_3 and M_2C eutectic carbides in HSS7 as obtained in our image analysis study compared to other High Speed Steels rolls (8). The total volume fraction of HSS7 carbides equals to 15%.

Chemical composition (Main elements), wt-%	Volume fraction, %			**Total**
	MC	M_7C_3	M_2C	
1.95C-5.1V-1.6W-1.7Mo-5.5Cr	4.4	4.7	---	**9.1**
2C-6.1V-1.8W-1.1Mo-5.6Cr	8.2	3.2	---	**11.4**
2C-4V-1.8W-2.5Mo-5.5Cr	4.4	6.9	---	**11.3**
2C-4.3V-6.5W-4.1Mo-5.6Cr	4.9	---	10.6	**15.5**
HSS7	6.0	7.5	2.0	**15.2**

Table 2: Volume fractions of carbides in High Speed Steels for rolling mill rolls

8. DENDRITE SPACING

The as-cast dendrite microstructure is defined in a quantitative basis by the primary and secondary dendrite spacing, the latter being more widely used as a parameter for correlating process variables and microstructure, since the primary dendrite spacing intervenes only in the case of directional solidification. The effects of the liquid phase thermal gradient, dendrite growth rate, and coarsening/coalescence phenomena on the secondary dendrite arm spacing (simply designated hereafter as the dendrite arm spacing, DAS) have been well characterised experimentally (8).

It is generally admitted that the effects of the liquid phase thermal gradient G and dendrite growth rate V (which are independently controlled in directional solidification experiments) on the DAS are related by an empirical relationship where both variables are lumped into one single parameter, namely the cooling rate, as dT/dt = GV

$$DAS = A(dT/dt)^{-b}$$

where A and b are material-specific parameters. Figure 10 shows experimental curves, DAS versus DT/dt for M2 (8). In the MK Spin Casting Process, a cooling rate ranging from 5 and 10°C/min is observed, leading to an average DAS around 23 to 35 µm.

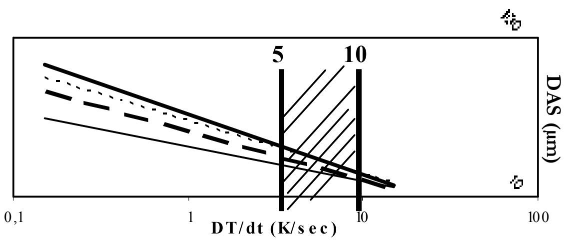

Figure 8: Dendrite Arm Spacing (DAS) versus dT/dt

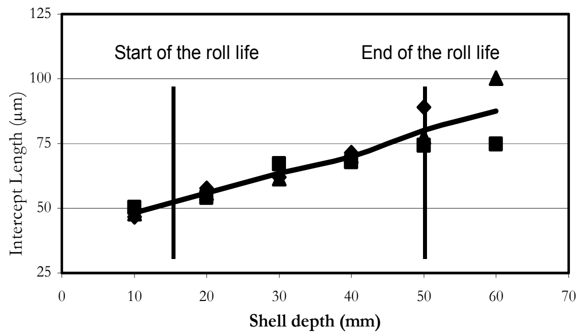

Figure 9: Grain Size in depth

Solidification is equiaxed from the surface to a depth of 10mm of the shell. Then the solidification becomes columnar till the bonding zone between shell and core. Nevertheless one can observed, near that bonding zone, areas where columnar zone are mixed to equiaxed zone grain size measurement is obtained from Image Analysis. The M_7C_3 carbides network outlines grains boundaries. As a result, we found that there is an increase of the grain size from the shell (50 µm) to the core (70 to 100 µm) (Figure 9).

9. MECHANICAL PROPERTIES

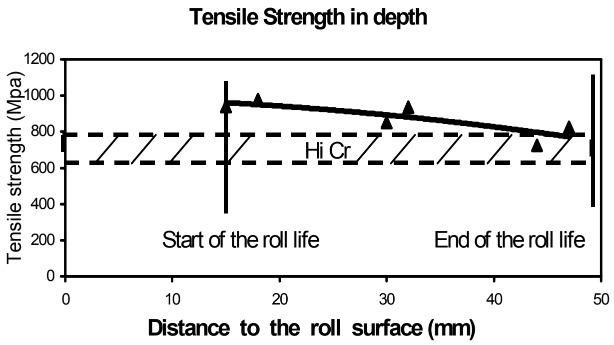

Figure 10 : Tensile Strength in depth (Hi-Cr/HSS)

Figures 10 indicates the properties of HHS compared to Hi-Cr. Mechanical properties of HHS are better than those of Hi-Cr. The decrease in tensile strength in the shell depth is to be related to the corresponding increase of the grain size. Nevertheless at the roll end of life the mechanical properties are still comparable to Hi-Cr. As concern hardness in depth, no decrease is observed, whereas HSS7 hardness is generaly above Hi-Cr one.

10. CONCLUSIONS

The HSS7 grade gives a good compromise between a low friction coefficient and high crack propagation and wear resistance. The microstructure is based on hard well dispersed primary and eutectic carbides embedded in a tough tempered martensitic matrix. This alloy contains small VC carbides and well dispersed eutectic carbides improving wear resistance,. These eutectic carbides are a mixture of M_2C and M_7C_3, hindering crack propagation.

These materials were developed with compositions near that of M2 tool steel, but with higher carbon and vanadium contents. For carbon levels between 1.7 % and 2.0 %, their solidification sequence can be described by the following reactions: (a) primary crystallisation of austenite; (b) eutectic decomposition of residual interdendritic liquid, leading to the formation of up to three eutectics: γ + MC; $\gamma + M_6C$ or $\gamma + M_2C$; and $\gamma + M_7C_3$. The total volume fraction of eutectic carbides in high speed steels designed for rolls ranges from 9 % to more than 15 %, which is one of their main characteristics. However, some Japanese publications mention carbides content higher than 20%. The volume fraction of carbides in HSS7 is around 15 %.

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