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# RECENT TRENDS IN HOT STRIP ROUGHING MILLS: HIGH CHROMIUM STEEL VERSUS SEMI-HSS[1]

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**Abstract**
Two alloys grades for work rolls used in the roughing stand of Hot Strip Mill (HSM) are compared. The first grade known as High Chromium Steel (HCS) is presently the most widely used alloy for such an application, while the second one known as semi-High Speed Steel (semi-HSS) is the new grade developed to improve the overall performance of the work roll in the roughing stands of the HSM. In the present paper, the new semi-HSS grade is studied starting from three chemical compositions closed one to another, the variation in the alloying elements is intended to assess, on one hand the effect of a small increase of the carbon content, and on the other hand the influence of the addition of a strong MC carbide forming element. Furthermore, corrosion behavior and performances of the work rolls in service are compared. Various techniques are used in order to characterize both grades, such as Differential Thermal Analysis (to determine phase transformations temperatures, the crystallization behavior and the interval of solidification), hardness measurements, optical microscopy, scanning electron microscopy associated with energy dispersive X ray spectroscopy (to determine the nature and the composition of phases, especially matrix and carbides). Finally micro-macro relations between the nature of the microstructure and the properties of High Chromium Steel and semi-HSS rolls grades in service conditions could be established.
**Keywords**: Hot strip mill; Roughing stands; Work rolls; High chromium steel; Semi-high speed steel.

## RECENTES TENDÊNCIAS NOS CILINDROS DESBASTADORES NOS LAMINADORES DE TIRAS A QUENTE: AÇO DE ALTO CROMO VERSUS SEMI-AÇO RÁPIDO

**Resumo**
Duas qualidades para os cilindros de trabalho usados nas cadeiras desbastadoras dos Laminadores de Tiras a Quente (LTQ) são comparadas. A primeira qualidade conhecida como o Aço de Alto Cromo (HCS) é atualmente a liga mais amplamente utilzada para esta aplicação, enquanto a segunda, conhecida como Semi-Aço Rápido (Semi-HSS), é a nova qualidade desenvolvida para aumentar o desempenho total dos cilindros de trabalho nas cadeiras desbastadoras do LTQ. Nesta apresentação, a nova qualidade Semi-HSS é estudada a partir de três composições químicas próximas umas as outras, a variação nos elementos de liga é utilizada para avaliar, por um lado o efeito de um pequeno aumento no teor de carbono e por outro lado a influência da adição de um forte elemento de formação do carboneto MC. Além disso, o comportamento da corrosão e os desempenhos dos cilindros de trabalho em operação são comparados. Várias técnicas são usadas a fim caracterizar ambas as qualidades, tais como a análise do diferencial térmico (para determinar as temperaturas das fases de transformação, o comportamento da cristalização e o intervalo de solidificação), medições de dureza, microscopia ótica, microscopia de rastreamento de elétrons associada com a espectroscopia da energia dispersiva por raio-x (para determinar a natureza e a composição das fases, especialmente da matriz e dos carbonetos). Finalmente, as relações micro e macro entre a natureza da microestrutura e as propriedades das qualidades dos cilindros Aço de Alto Cromo e Semi-HSS em condição de trabalho podem ser estabelecidas.
**Palavras-chave**: Laminador de tiras a quente; Cadeiras desbastadoras; Cilindros de trabalho; Aço de alto cromo; Semi-aço rápido.

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## 1 INTRODUCTION

In the early 80´s, the Chrome steel work roll grade was developed by European rollmakers and introduced since then in most of the existing roughing stands of hot strip mills (HSMs) as well as into the early finishing stands of compact strip mills. In 2010, the Chrome steel grade is still a standard grades in many HSMs over the world as can be derived from Figure 1.
The ever increasing requirements for roughing mills in terms of cost/performance ratio including higher throughput, improved product quality and higher safety have stimulated European rollmakers to develop in the early 90´s a new roll grade for roughing stands which is known as semi-High-Speed Steel (semi-HSS). This new grade was considered as a real revolution in terms of roll performance in nearly all aspects of required behaviour.
Semi-HSS acquired a strong position especially in Western European HSMs. However, some applications like stainless and special steel rolling have shown interest of further development to overcome some insufficiencies of semi-HSS. A special High-Speed Steel (HSS) grade for roughing mill application was developed to meet this new challenge in the late nineties – see history of work roll development in Figure 2.

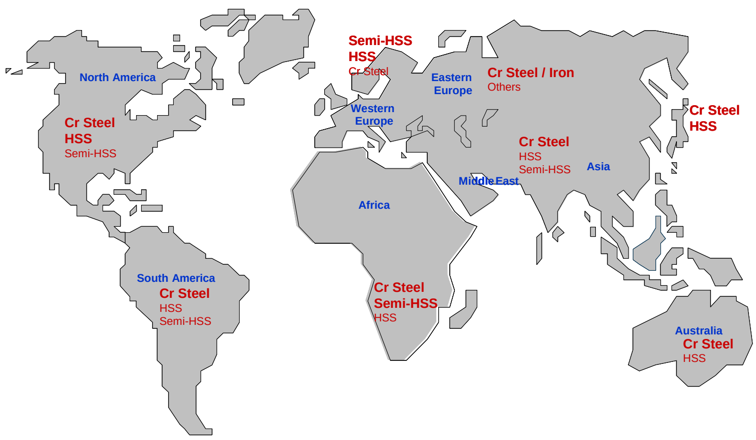


**Figure 1:** Dominant roughing mill work roll grades in the world.

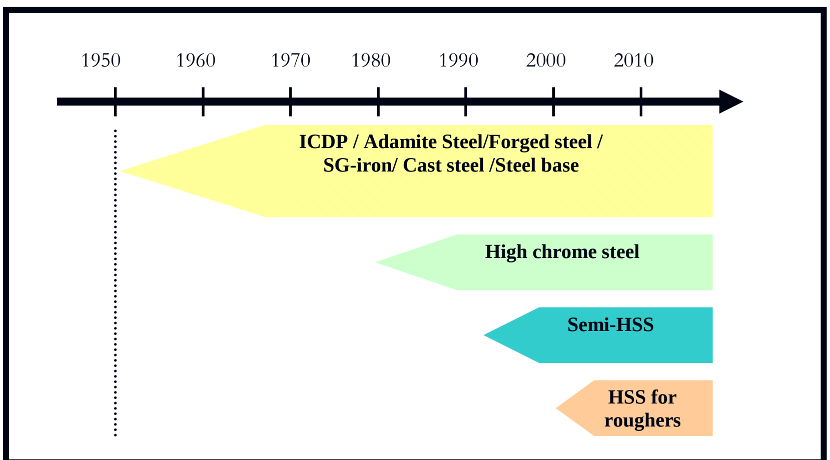


**Figure 2:** History of HSM roughing mill work roll Grades 1950-2010.

ISSN 1983-4764


# 2 WORK ROLL GRADES FOR ROUGHING STANDS

## 2.1 Chemical Composition

The typical chemical compositions of the main roughing roll grades used nowadays for hot strip rolling by Marichal Ketin are listed in Table 1. This table indicates the main elements such as Carbon, Chromium, Tungsten equivalent, MC-carbide forming elements as well as the carbide content and hardness range of the different roughing roll grades.

**Table 1:** Roughing Mill Roll Grades – Analysis, carbide content and hardness of working zone

| Roll grade | C % | Cr % | W eq. (=W+2Mo) % | MC-Carbide forming elements (%) | Carbide content % | Hardness Shore C |
|---|---|---|---|---|---|---|
| Cr-Steel | 1.3 - 1.6 | 11 - 13 | 6 – 10 | < 0.5 | 10 – 15 | 70 – 80 |
| Semi HSS 1 | 0.6 – 0.9 | 7 – 9 | 4 – 8 | 0.5 – 1.0 | < 5 | 75 - 85 |
| Semi HSS 2 | 0.8 – 1.1 | 7 – 9 | 4 – 8 | 0.5 – 1.0 | < 5 | 75 - 85 |
| Semi HSS 3 | 0.6 – 0.9 | 7 – 9 | 4 – 8 | 1.0 – 2.0 | < 5 | 75 - 85 |
| HSS (roughing) | 1.3 – 1.6 | 3 – 6 | 6 – 10 | 4 – 8 | 10 – 15 | 72 – 82 |

Semi-HSS 1 and semi-HSS 2 are respectively semi-HSS grade with different carbon content, both grades contain MC-carbides forming elements, the semi-HSS 3 shows the highest MC-carbide forming elements content (V, Ti, Nb, Ta, etc.).
The Chrome steel grade microstructure is mainly determined by a matrix of tempered martensite with eutectic carbides of the $M_7C_3$ and $M_6C$ type. The highly increased hardness of matrix and of the different carbide types other than cementite have determined a much higher wear resistance and fire crack resistance compared to former standard grades. In the mid 80´s, this roll type became a standard roughing mill work roll grade. The semi-HSS grade is characterized by a matrix of tempered martensite with a strong effect of temper hardening, where special carbides of the $M_7C_3$, $M_6C$ and MC type are embedded. This structure already offers the typical characteristics of HSS grades like high temperature strength and hot hardness. The latest developed HSS grade for roughing stands, has increased amounts of MC and $M_6C$ carbides replacing to a higher extent the $M_7C_3$ type carbides. Both semi-HSS and HSS for roughers do not present a continuous carbide network. These last two roll grades are submitted to a long sophisticated heat treatment which is responsible for the homogeneous basic structure and contributes to their high performance level.
The type, hardness and amount of these carbides have a strong influence on wear resistance, surface deterioration and oxidation behaviour of the different roll types.[1-5]
The present work will be focused on Cr-steel and the three semi-HSS work rolls.

## 2.2 Microstructures

Many different roll grades have been used in roughing stands of HSMs since the beginning of hot strip rolling.[6] Only some recent roll grades will be discussed in some more details. The microstructures of these grades are shown in Figure 3.

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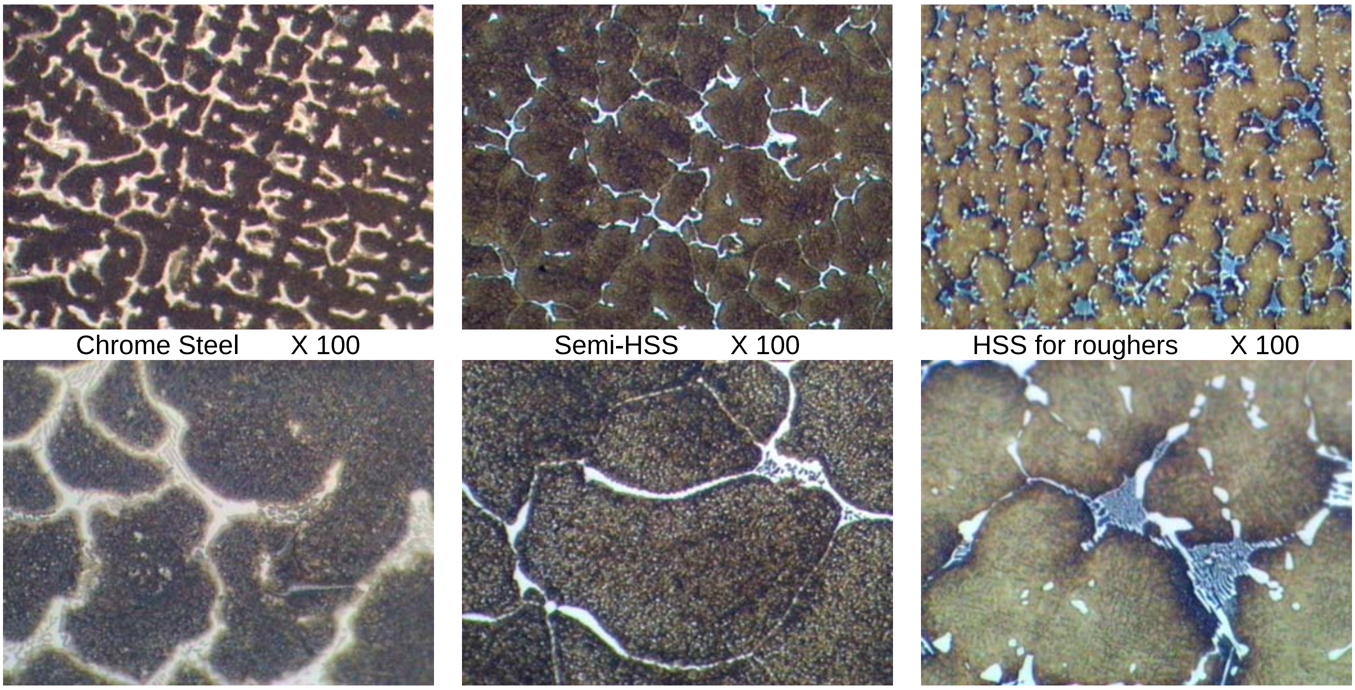


**Figure 3:** Overview of work rolls microstructures for roughing stands.

## 3 METALLURGICAL CHARACTERIZATION

### 3.1 Thermodynamical Simulations

Thermodynamical simulations were obtained from Thermo-Calc ® software (TC). Example of equilibrium diagrams of Cr-Steel and semi-HSS 1, 2 & 3 are given at figures 4a to 4d. TC simulations assume constant equilibrium conditions which mean a very low cooling rate where ideal diffusion is allowed for all the alloying elements either in the liquid or in the solid state. These figures show the phase volume fraction of stable phases in the studied alloys between 500 and 1500°C with a 10°C step

From TC simulations, it appears that the first solid is almost the face centered cubic austenite except for the semi-HSS 3 grade where the first solid to precipitate is the bold-centered cubic delta ferrite. From this statement a peritectic transformation occurs in the semi-HSS 3 grade during the solidification process (Figure 4d). This peritectic transformation is known to promote a new austenite phase from the decomposition of the previous delta ferrite phase.

As $M_7C_3$ carbides in both Cr-Steel and semi-HSS grades 1 and 2 seem to start their precipitation close to or below the solidus temperature, with an increase of their amount with decreasing temperature, these carbides could be assumed to be of the eutectoid type. Only MC carbides found in semi-HSS 3 through the equilibrium diagram could be considered like real eutectic as they precipitated from the liquid.

Thus in equilibrium conditions, semi-HSS grades 1 and 2 did not exhibit eutectic carbides, as $M_7C_3$ and latter $M_6C$ precipitate in the solid state.

Furthermore, in equilibrium conditions all the primary carbides (MC, $M_7$C3 and $M_6C$) transform themselves close to the A1 point (see Figure 3a to 3d), in a partial or complete reaction that leads to other types of carbides known as fine secondary carbides, such as $M_{23}C_6$, $M_2C$ and MC, when the temperature decreases.

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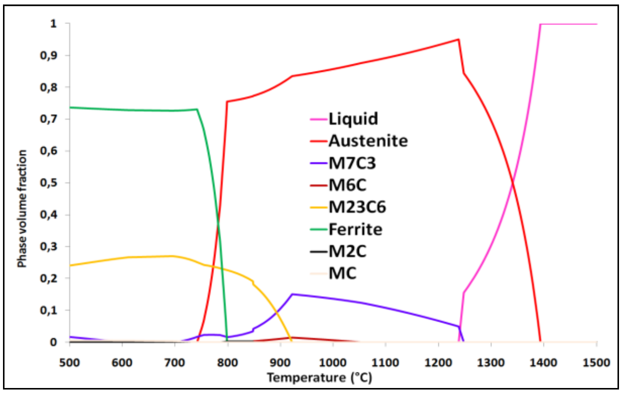


**Figure 4a**: Phase volume fraction evolution on Hi-Cr Steel - Equilibrium conditions

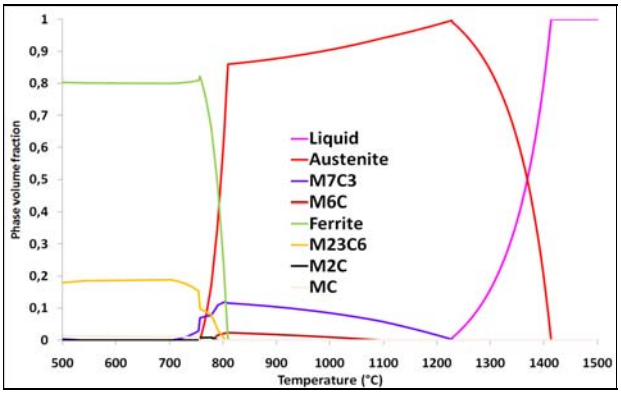


**Figure 4b:** Phase volume fractions on semi-HSS 1 - Equilibrium conditions

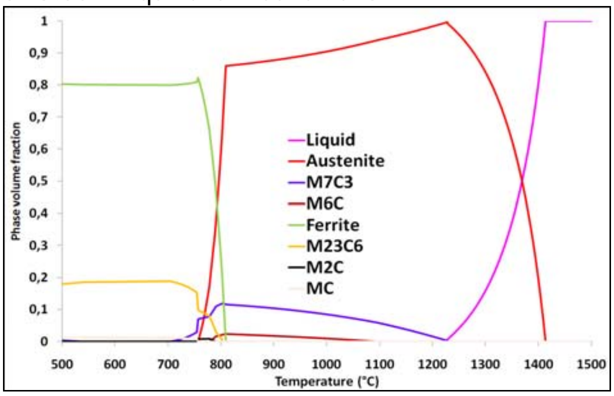


**Figure 4c**: Phase volume fractions on semi-HSS 2 - Equilibrium conditions

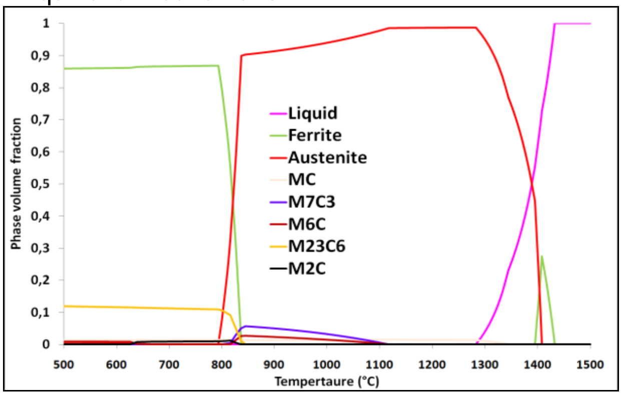


**Figure 4d:** Phase volume fraction evolution on semi-HSS 3 - Equilibrium conditions

## 3.2 Solidification Paths

Solidification paths were obtained from Differential Thermal Analysis tests. From this technique, a difference in energy is measured between the material to be tested and an inert reference material as a function of temperature while both samples are submitted to a controlled temperature program. A phase transformation occurring in the studied material appears as an endothermic or an exothermic peak when the DTA cycle goes on Lecomte-Beckers et al.[7]

Figure 5 illustrates the results of DTA tests on the four grades during the cooling cycle which starts from the melt down to room temperature at 5°C/min.

The solidification range was obtained while considering the liquidus and the solidus temperatures on the four studied grades. Table 2 gives the results obtained from the comparison between equilibrium (from TC) and non-equilibrium (from DTA) conditions.

SEM-EDS analyses (Figures 6a and 6b) performed after DTA tests allow the identification of the phases present at room temperature, like all the eutectics carbides and the matrix (mixture of martensite and retained austenite). Such a DTA solidification sequence had already been enhanced in previous work.[8-10]

Only the starting points of $M_7C_3$ and $M_6C$ which are considered as eutectoid carbides in the equilibrium conditions are illustrated in Table 2. It was observed that phase transformation range is shorter in the non-equilibrium conditions than that of the equilibrium conditions.

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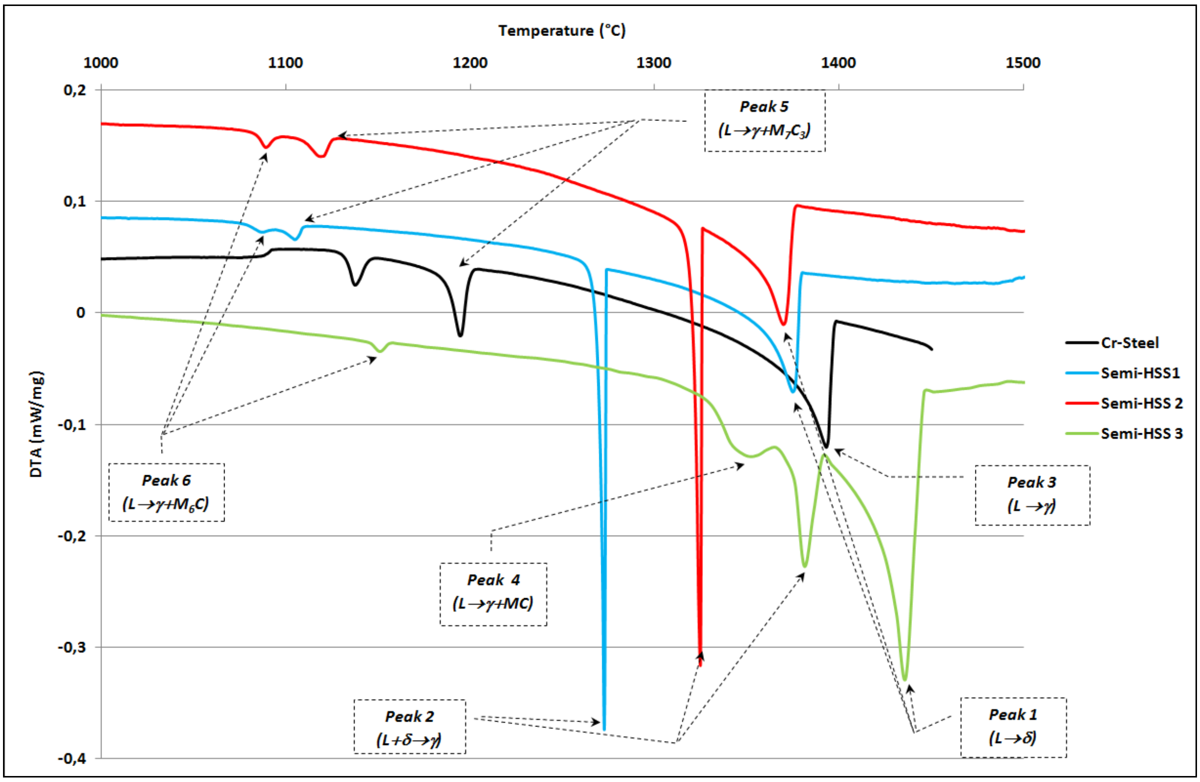


**Figure 5:** Solidification sequences on the four studied alloys during DTA cooling stage at 5°C/min.

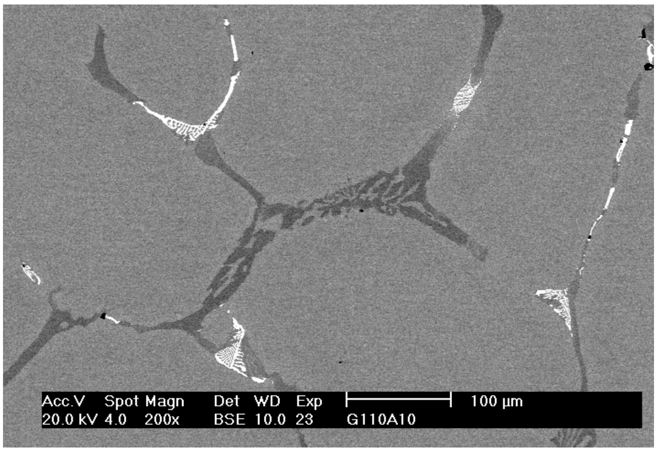


**Figure 6a**: Eutectic carbides network on Cr-Steel after DTA test – Fishbone-like M7C3 (grey) and fine-lamellar M6C (light)

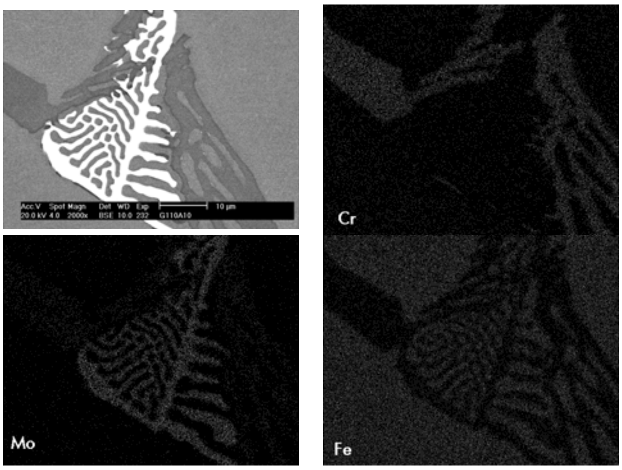


**Figure 6b**: Complex M7C3/M6C eutectic carbide in a Cr-Steel and related EDS mapping showing major elements of each phase (Cr-rich M7C3 and Mo-rich M6C)

ISSN 1983-4764


**Table 2 :** Comparison of phase transformations between equilibrium and non-equilibrium conditions

| **Phase transformation obtained from the solidification sequence (*Peak number)*** | **Grades** | **Temperature range from DTA (non-equilibrium conditions; cooling at 5°C/min)** | **Temperature from TC (equilibrium conditions)** |
|---|---|---|---|
| $L \rightarrow \delta$ (start)<br>*Peak 1* | Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | **1430°C (Liquidus)**<br>**1430°C (Liquidus)**<br>**1443°C (Liquidus)** | -<br>-<br>**1428°C (Liquidus)** |
| $L + \delta \rightarrow \gamma$ (start)<br>*Peak 2* | Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | 1337°C<br>1399°C<br>1389°C | -<br>-<br>1405°C |
| $L + \delta \rightarrow \gamma\,(end)$ | Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | 1422°C<br>1419°C<br>1384°C | -<br>-<br>1395°C |
| $L \rightarrow \gamma$ (start)<br>*Peak 3* | Chromium Steel<br>Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | **1394°C (Liquidus)**<br>-<br>-<br>- | **1388°C (Liquidus)**<br>**1429°C (Liquidus)**<br>**1409°C (Liquidus)**<br>1395°C |
| $L \rightarrow \gamma + MC$ (start)<br>*Peak 4* | Semi-HSS 3 | 1364°C | 1343°C |
| $L \rightarrow \gamma\,(end)$ | Chromium Steel<br>Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | 1389°C | **1238°C (Solidus)**<br>**1279°C (Solidus)**<br>**1228°C (Solidus)**<br>**1293°C (Solidus)** |
| $L \rightarrow \gamma + MC\,(end)$ | Semi-HSS 3 | 1353°C | 1117°C |
| $L \rightarrow \gamma + M_7C_3$ (start)<br>*Peak 5* | Chromium Steel<br>Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | 1201°C<br>1168°C<br>1176°C<br>- | 1238°C<br>1165°C<br>1228°C<br>1115°C |
| $L \rightarrow \gamma + M_6C$ (start)<br>*Peak 6* | Chromium Steel<br>Semi-HSS 1<br>Semi-HSS 2<br>Semi-HSS 3 | **1143°C (Solidus at 1135°C)***<br>**1145°C (Solidus at 1144°C)***<br>**1150°C (Solidus at 1147°C)***<br>**1158°C (Solidus at 1153°C)*** | 1052°C<br>1084°C<br>1089°C<br>1117°C |

**End of the eutectic reaction from DTA tests*

From the comparison between Cr-Steel and semi-HSS grades, the following observations arise:

- The liquidus temperature of semi-HSS grades is always higher than the Cr-Steel one whatever the conditions are from equilibrium or non-equilibrium;
- The semi-HSS 3 exhibits the higher liquidus temperature in the non-equilibrium conditions (1428°C);
- The semi-HSS 3 grade contains MC eutectic carbides which precipitate at high temperature (1353°C); as a consequence, no $M_7C_3$ are found in this alloy and

ISSN 1983-4764


$M_6C$ precipitated earlier (1158°C) when compared to the related eutectic transformations on Cr-Steel, semi-HSS 1 and semi-HSS 2 grades;
- Eutectic $M_7C_3$ and $M_6C$ carbides have got their precipitation temperature higher and more distinguishable in Cr-Steel than the equivalent ones in semi-HSS grades 1 and 2 in the DTA solidification sequence;

From the comparison between equilibrium and non equilibrium conditions, the following observations are made:
- Liquidus temperature obtained by DTA is always above the one obtained from TC simulation;
- The first solid to precipitate in the non equilibrium conditions is not correctly found by TC simulation, as it was the case for the three semi-HSS grades where delta-ferrite precipitate first instead of austenite;
- Eutectic carbides found in non equilibrium conditions appear only in solid-state transformations in the equilibrium conditions and so they must be considered like eutectoid carbides;
- The solidification range is always larger in the non equilibrium conditions than that found in TC simulation, even if the first solid to form is the same in both conditions (see the case of Chromium steel);
- Eutectic carbides obtained from continuous cooling of the melt are still present at room temperature, unlike the corresponding ones found in the equilibrium conditions, as the latter disappear with solid-state transformation; in fact $M_7C_3$ and $M_6C$ transform themselves respectively in $M_{23}C_6$ and $M_2C$ in the TC simulation.

The differences observed between non equilibrium and equilibrium simulations could be explained on several ways.
Delta ferrite that appears in the semi-HSS grades during non equilibrium DTA tests could probably arise from inclusions (sulphides or oxides) as they are known to be delta-ferrite germs and they can promote non heterogeneous nucleation.[9]
While equilibrium conditions assume a full diffusion of all the alloying elements, there is a segregation phenomenon in the non equilibrium conditions, especially within the interdendritic space where strong carbides forming elements such as Nb, Mo, Cr that are gamma-incompatible, are rejected when the growing dendrite is of the austenite type.

### 3.3 Microstructures Through SEM Analysis

Typical microstructures of studied rolls are given in Figure 7a to Figure 7d as obtained from scanning electron microscope (SEM). The microstructure of all rougher grades in the service conditions consists of a non continuous network of eutectic carbides located at grain boundaries, with a tempered martensitic matrix. Such a distribution of carbides is common for HSS grades.[8,10]

ISSN 1983-4764


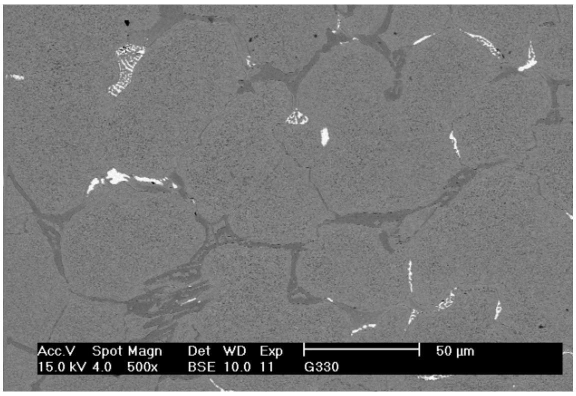


**Figure 7a**: Hi-Cr steel (near the surface of the shell). Network of eutectic M7C3(fishbone-like, grey) and M6C (light) carbides at grain boundaries, in a tempered martensitic matrix

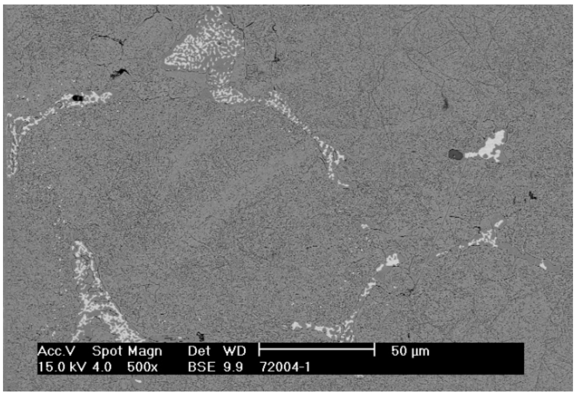


**Figure 7b**: Semi-HSS 1(close to the scrap diameter). Network of eutectic M7C3 (grey) and M6C (light) carbides at grain boundaries, in a tempered martensitic matrix

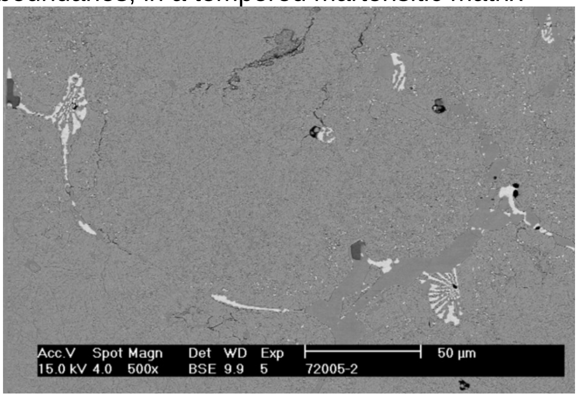


**Figure 7c**: Semi-HSS 2 (close to the scrap diameter) – Network of eutectic M7C3 (bulk, grey) and M6C (light) at grain boundaries , in a tempered martensitic matrix

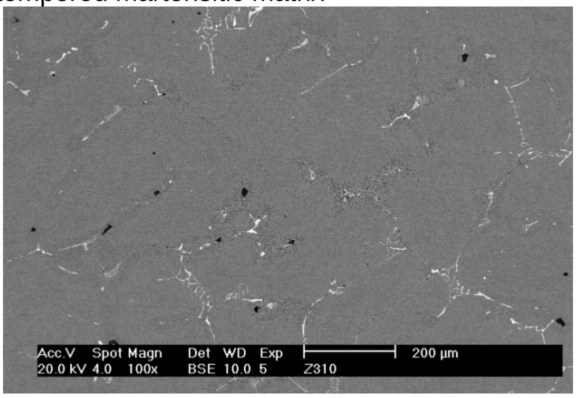


**Figure 7d**: Semi-HSS 3 (near the surface of the shell) – Network of eutectic MC (Chinese script, light) and M6C (rod-like, light) carbides at grain boundaries, in a tempered martensitic matrix

### 3.4 Hardness Features

Hot hardness had been determined on three of the four studied grades with regard to HSS for roughers as a reference.
Figure 8 gives the hot hardness behaviour of 3 studied grades and HSS rougher in addition.
Both semi-HSS grades 2 and 3 seem to have similar and flat hot hardness behaviours except for temperature above 570°C where hot hardness of semi-HSS grade 3 decreases slowly when that of semi-HSS grade 2 collapse. Such a levelling of the hot hardness above 570°C on semi-HSS 3, which is also observed on HSS for roughers, is probably due to the presence of a higher amount of MC carbides on both compared to semi-HSS grade 2 or Cr-Steel.

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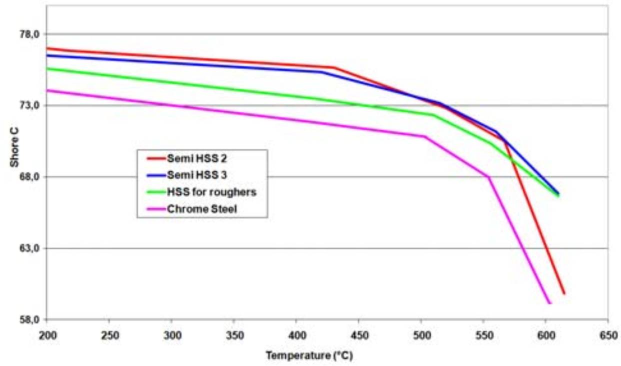


**Figure 8:** Hot Hardness (Shore C) on Semi-HSS Grades 2 and 3, Cr-Steel, and HSS for roughers (as reference).

### 3.5 Corrosion Behaviour

Some static corrosion tests were performed in a liquid medium on Cr-steel and semi-HSS 3 in laboratory with the following conditions: 60°C – holding time from 4 to 27 h – [$Cl^-$] from 350 to 1000 ppm and [$HOCl^-$] from 0 to 5 ppm. Figure 9 shows the results obtained on the surface of the samples at the end of the corrosion tests. Semi-HSS 3 appears to exhibit a less corroded surface than Cr-Steel, as pits found on the previous are smaller than those found on the latter. Further trials in this field are ongoing and their results will be dealt in a future publication.

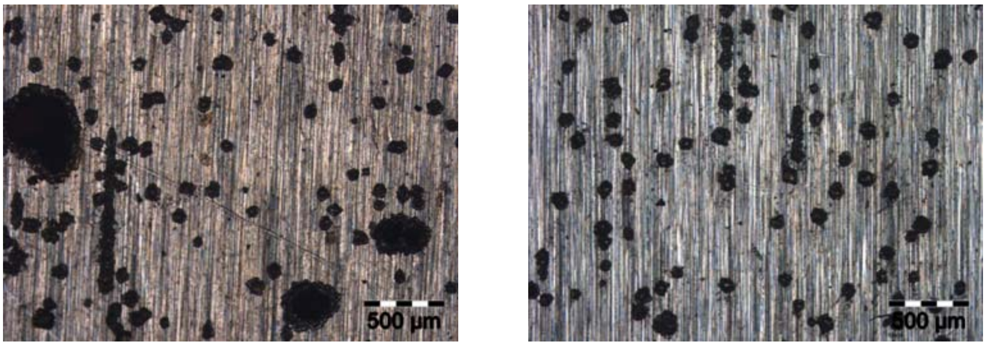


**Figure 9**: overview of corrosion pits on Cr-Steel (left) and Semi-HSS 3 (right) surfaces.

## 4 ROLL BEHAVIOUR IN SERVICE

### 4.1 Layouts of Hot Strip Roughing Mills

In order to get a better understanding of the behaviour aspects of roughing mill work roll grades, a short description of the different layouts found worldwide will be helpful for the reader (see also Figure 10).

Many different kinds of roughing mills have been designed over the last 60 years. There are fully continuous HSMs with 5 to 7 roughing stands and additional edgers, this concept was born in the 60's and died after the first oil crisis of the early 70's. In this layout, there is only one way rolling operation in the roughing mill. The distances between different roughing stands must be adapted to the length of the slab after each stand. Therefore, the whole roughing mill is considerably long.

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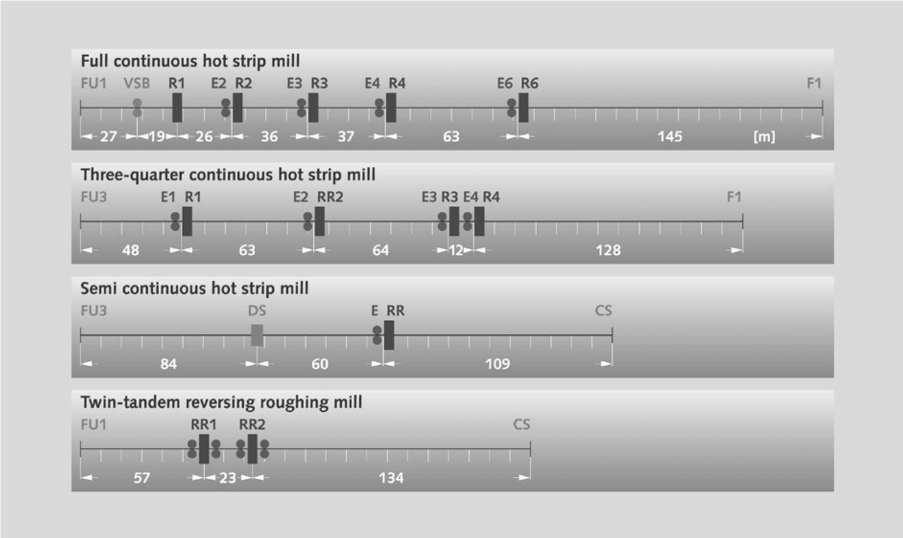


**Figure 10:** Layouts of hot strip roughing mills.

Another concept is the so called three-quarter continuous HSM, which includes at least a reversing roughing stand and one or several one-way roughing stands. The length of the roughing mill for this type is quite reduced compared to the full-continuous mill. The next type, the semi-continuous HSM, includes just one reversing roughing mill combined with a vertical edger or a sizing press. Most of the recent new HSM built since 2000 are based on this concept. A twin-tandem reversing roughing mill has been realized as well which combines the advantage of a short roughing mill and a high throughput. On the other hand, this solution asks for a more sophisticated process control. The roughing stands may be built as two-high or four-high mills, one-way, reversing, single or tandem configuration.

### 4.2 Situation in European Roughing Mills

A survey made in 25 western European HSM clearly highlights the dominant position of semi-HSS or HSS roughing mill grades in all types of roughing mills in Europe - see Figures 11a-11b:

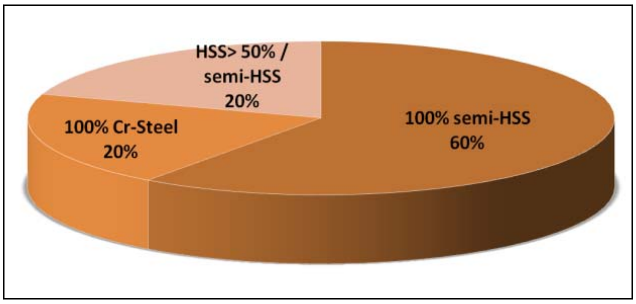


**Figure 11a** – Situation 2010 in 5 full continuous HSM in Europe

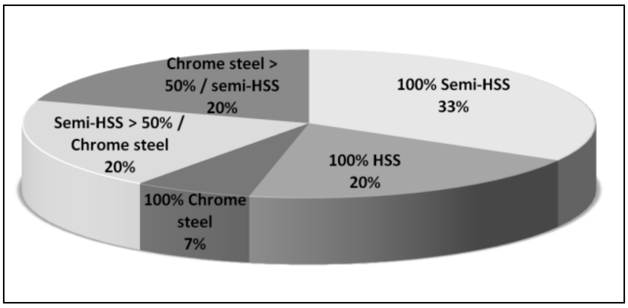


**Figure 11b** – Situation 2010 in 20 HSM (1/2 – 3/4 or DSP mills) in Europe

### 4.3 Mill Demands with Respect to Work Roll Properties for Roughing Stands

The interpretation of mill demands with respect to work roll properties for roughing stands may be summarized as follows:

ISSN 1983-4764


- high roll bite based on high friction coefficient, allowing high reductions per pass without chattering or slippage and consequently higher throughput with reduced heat loss of the product.
- high resistance of shell material against wear, thermal fatigue and oxidation/corrosion, resulting in low and homogeneous wear allowing longer rolling campaigns and reduced downtime.
- high heat and fire crack resistance which stands for a smooth tiny fire crazing network preventing high damage caused by mill stalls.
- perfect roll surface quality over long runs, which is related to no peeling, no banding, no microspalling during one campaign time.
- high safety against roll failures generated by any kind of operation conditions including mill incidents, high thermal and mechanical loads etc...

The different roll grades used in roughing mills have been compared in Table 3+
0 referring to these aspects.

**Table 3:** Comparison of roll behaviour for different work roll grades in roughing stands

| Roll grade | Bite | Wear resistance | Fire crack resistance | Surface quality | Campaign time | Safety in service |
|---|---|---|---|---|---|---|
| Chrome Steel | ↗ | ↗ | → | ↗ | ↗ | ↗ |
| Semi-HSS | ↑ | ↑ | ↑ | ↑ | ↑ | ↗ |
| HSS for roughers | ↗ | ↑ | ↗ | ↑ | ↑ | ↗ |

↑ Excellent ↗ Good → Satisfactory ↘ Sufficient ↓ Poor

High throughput for the HSM asks for a minimum number of passes in the roughing mill which is of particular importance for semi-continuous HSMs. This means high reduction per pass, which is only possible with excellent roll biting behaviour. It is well-known that roll bite is improved with lower carbide content and lower hardness of the working surface. Obviously, the semi-HSS grade and so far the new HSS grade for roughers have confirmed this basic rule.

Both semi-HSS and HSS for roughers offer improved mechanical properties at elevated temperatures compared to any other roll type so far used in roughing mills. High temperature yield strength is mainly responsible to how far plastic deformation can be limited in the outer layer of the roll when the surface is heated up to more than 600°C when it passes the roll gap in contact with the hot slab. Corresponding thermal compressive stresses are induced. The outstanding thermal resistance of these roll grades results in an extremely fine fire crazing network compared to other grades under similar conditions.

Normally, a low carbide content stands against high wear resistance. In case of the semi-HSS grade, the contradiction between low carbide content and high wear resistance has been eliminated by different factors.

The semi-HSS alloy results in a completely different microstructure containing primary and secondary carbides of MC-, $M_6C$- and some $M_7C_3$-compositions. All these carbides have a higher hardness compared to normal high Chrome iron or high Chrome steel compositions. Even the $M_7C_3$ carbide, which is a typical Chromium carbide, becomes harder whenever it contains alloying elements such as Molybdenum and Vanadium.

The very favourable roll bite behaviour based on low carbon content allows a strongly increased hardness and wear resistance of the homogeneous matrix and this for low and high temperature levels.

In addition, wear due to high temperature oxidation is minimized by a matrix composition offering high temperature corrosion resistance. The full benefit of these

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characteristics is obtained by a sophisticated heat-treatment process, which stands for a homogeneous distribution of micro-carbides and high temperature resistance. The improved mechanical properties at elevated temperatures, the absence of a closed primary carbide network guarantees a net improvement of shearing resistance and absence of micro-spallings.
The combination of better roll bite and wear resistance offers important advantages to mill people. Examples from semi-continuous HSMs have proved that the standard seven pass reversing operation in the roughing stand could be reduced to a standard five pass practice. At the same time, the heat loss of the transfer bar is accordingly reduced. If the reversing rougher is the bottle neck of the whole hot mill process, this advantage of better roll bite improves the possible throughput by more than 20% compared to Chrome steel work rolls. Pure wear performance of this new roll grade could be improved by 150 to 300 % compared to Chrome steel in either reversing or one-way roughing stands.
In many mills, the campaign times could be doubled compared to Chrome steel work rolls without exceeding the allowable tolerance of roll gap geometry. It has become standard to achieve 50,000 to 80,000 tons per run for reversing roughing stands and five pass reductions. A further important behaviour of this roll grade is the smooth symmetric wear curve without any tendency for dog-bone profile. For one-way roughing stands more than 200,000 tons per campaign could be realized even in the last roughing stand of a full continuous mill. Regarding the roll cooling practice, no major modifications were necessary to adapt both semi-HSS and HSS work roll grades for normal rolling operation.
As far as semi-HSS is concerned the semi-HSS 3 is nowadays confirmed as the optimum grade based on the investigations developed in this paper which could be confirmed by numerous laboratory and industrial results.
Regarding the HSS grade for roughing stands, industrial results in European HSM with high percentage of stainless steel rolling have shown that wear performance in terms of campaign time as well as tonnage per millimeter wear could be doubled compared to the traditional Chrome steel grade. The consistency of roll gap geometry and roll surface quality has fulfilled all requirements. This grade has established nowadays as a standard grade for stainless and special steels rolling.

## 5 CONCLUSIONS

Semi high-speed steel grades for roughing stand work rolls of HSMs have been presented in this paper. Different roll properties of particular interest for mill people have been discussed in comparison with other typical roll grades for roughing mills. The combination of equilibrium diagrams and DTA tests could be helpful for the actual solidification sequence prediction in the industrial conditions on working rolls as the as-cast microstructure strongly influences subsequent mechanical properties.
Simulations of solidification in equilibrium conditions do not seem to be in good agreement with non equilibrium ones on the one hand, and with actual industrial conditions on the other hand. Differences between the results obtained from equilibrium and non equilibrium conditions are probably due to the non recognition of segregations in the equilibrium approach as well as the heterogeneous germination phenomenon that is promoted by inclusions (sulphides promoting delta ferrite formation for example).

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In addition, comparison of different semi-HSS grades with Chromium steel done on roughing stands show that the new semi-HSS grade 3 exhibits better general behaviour during rolling process.

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