Current Developments of Alloyed Steels for Hot Strip Roughing Mills: Characterization of High-Chromium Steel and Semi-High Speed Steel

Abstract

Two alloys grades for work rolls used in the roughing stand of Hot Strip Mill — high chromium steel (HCS) and semi-high-speed steel (semi-HSS), In this paper, the new semi-high-speed steel grade is studied.

Authors

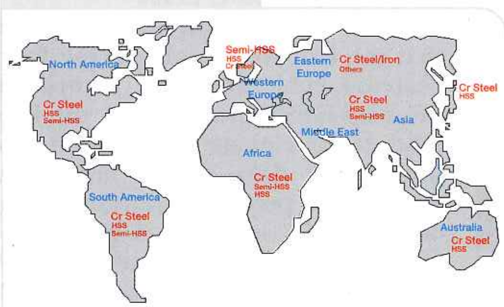
Jacqueline Lecomte-Beckers
head of metallic materials science unit, aerospace and mechanics department, University of Liège, Liège, Belgium
jacqueline.lecomte@ulg.ac.be

Mario Sinnaeve
director, R&D and quality, Marichal Ketin Belgium, Liège, Belgium
qualitycontrol@mkb.be

T. Jerome Tchuindjang
researcher, MMS unit, University of Liège, Liège, Belgium
j.tchuindjang@ulg.ac.be

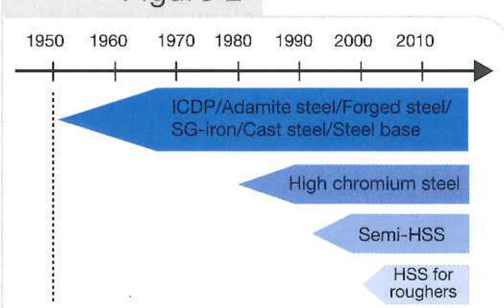
In the early 1980s, a chrome steel work roll grade was developed by European rollmakers and has, since then, been introduced in most roughing stands of hot strip mills (HSMs), as well as into the early finishing stands of compact strip mills. As of 2010, chrome steel grade was still a standard grade in many HSMs over the world, as can be seen in Figure 1.

Figure 1



Dominant roughing mill work roll grades in the world.

Figure 2



History of HSM roughing mill work roll grades from 1950 to 2010.

The ever-increasing requirements for roughing mills, in terms of cost/performance ratio, including higher throughput, improved product quality and higher safety standards, prompted European rollmakers in the early 1990s to develop a new roll grade for roughing stands, which is known as semi-high-speed steel (semi-HSS). This new grade was considered to be a real revolution in terms of roll performance in nearly all aspects of the required behavior.

Semi-HSS acquired a strong position, especially in Western European HSMs. However, some applications, like stainless and special steel rolling, have shown interest in further developments 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 1990s (see the history of work roll development in Figure 2).

Work Roll Grades for Roughing Stands

Chemical Composition — The typical chemical compositions of the main roughing roll grades used today in hot strip rolling 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.

Semi-HSS 1 and semi-HSS 2 are semi-HSS grades with different carbon contents. Both grades contain MC-carbide-forming elements, whereas 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 the 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-1980s, 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 greater 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 behavior of the different roll types.[1–5]

The present work will be focused on Cr steel and the three semi-HSS work rolls.

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 here in further detail. The microstructures of these grades are shown in Figure 3.

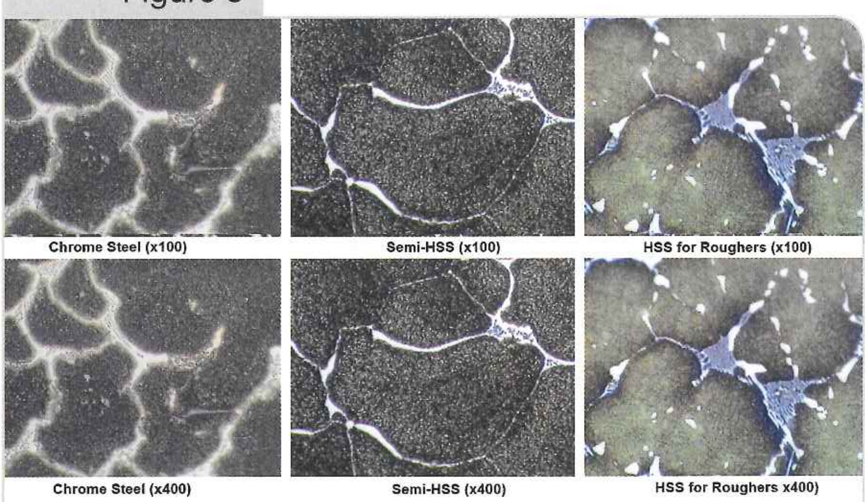
Metallurgical Characterization

Thermodynamic Simulations — Thermodynamic simulations were obtained from Thermo-Calc® software (TC). Examples of equilibrium diagrams of Cr steel and semi-HSS 3 are shown in Figures 4a–d. TC simulations assume constant equilibrium conditions, which means 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 1,500°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 assume to be of eutectoid type.

Figure 3



Overview of work roll microstructures for roughing stands.

Table 1

Roughing Mill Roll Grades — Analysis, Carbide Content and Hardness of Working Zone

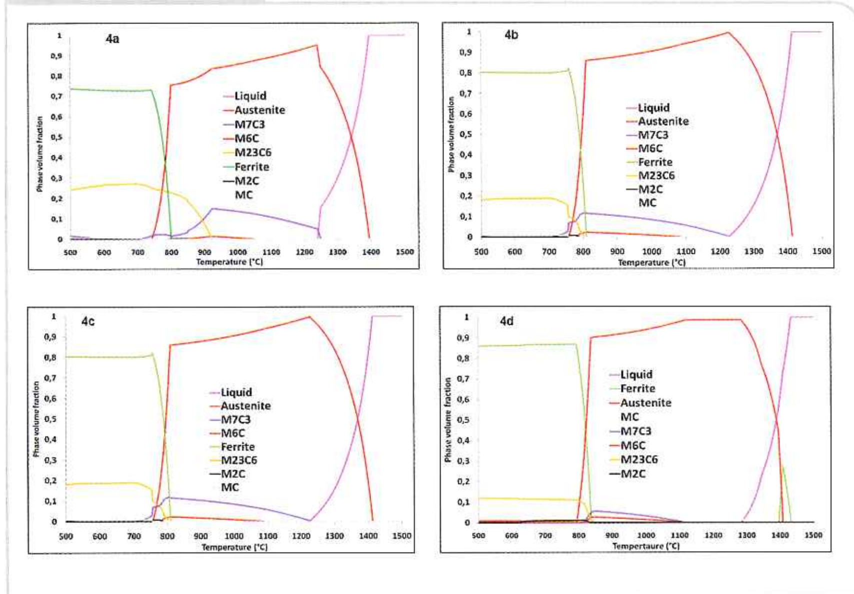
Roll grade	C, wt. %	Cr, wt. %	W eq. (=W+2Mo) wt. %	MC-carbide-forming elements (wt. %)	Carbide content (wt. %)	Hardness (Shore C)
Cr steel	1.3–1.6	11–13	6–10	< 0.5	10–15	70–80
Semi-HSS 1	0.6–0.9	7–9	4–8	0.5–1.0	< 5	75–85
Semi-HSS 2	0.8–1.1	7–9	4–8	0.5–1.0	< 5	75–85
Semi-HSS 3	0.6–0.9	7–9	4–8	1.0–2.0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

Only MC carbides found in semi-HSS 3 through the equilibrium diagram could be considered as truly 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 the latter M_6C precipitated in the solid state.

Furthermore, when the temperature decreases in equilibrium conditions, all of the primary carbides (MC, M_7C_3 and M_6C) transform themselves close to the A1 point (Figures 4a–4d) in a partial or complete reaction, which leads to other types of carbides known as fine secondary carbides, such as $M_{23}C_6$, M_2C and MC.

Figure 4



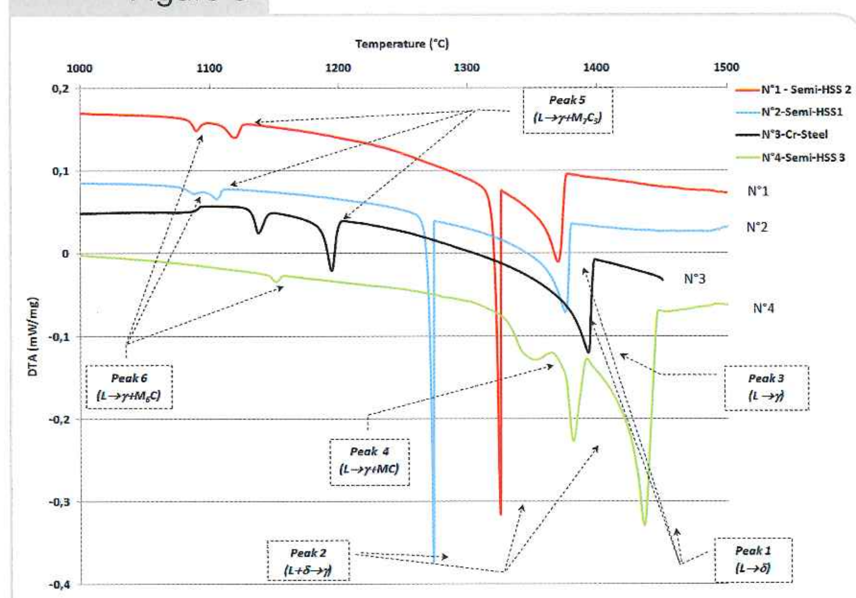
Phase volume fractions with temperature in equilibrium conditions on high-Cr steel (4a) and on semi-HSS 1 (4b). Phase volume fractions with temperature in equilibrium conditions on semi-HSS2 (4c) and on semi-HSS 3 (4d).

Solidification Paths — Solidification paths were obtained from differential thermal analysis (DTA) 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.[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/minute.

The solidification range was obtained while considering the liquidus and the solidus temperatures on the four studied grades. Table 3 gives the results obtained from the comparison between equilibrium (from TC) and non-equilibrium (from DTA) conditions.

Figure 5



Solidification sequences on the four studied alloys during DTA cooling stage at 5°C/minute.

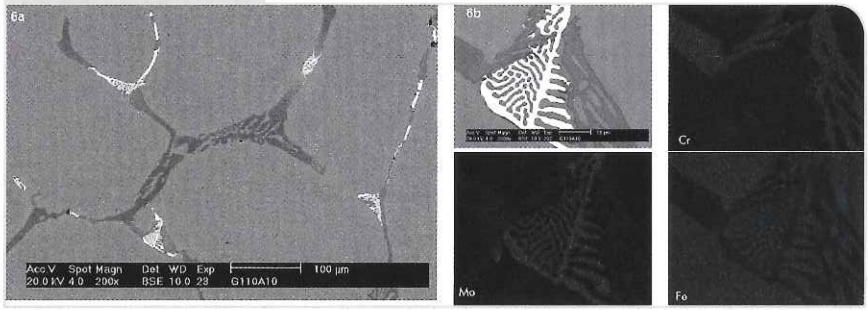
SEM-EDS analyses (Figures 6a and b) performed after the DTA tests allow for the identification of the phases present at room temperature, such as the eutectic carbides and the matrix (mixture of martensite and retained austenite). Such a DTA solidification sequence had already been enhanced in previous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

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

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 that of the Cr steel, no matter what the conditions are from equilibrium or non-equilibrium.
- The semi-HSS 3 exhibits the higher liquidus temperature in the non-equilibrium conditions (1,428°C).
- The semi-HSS 3 grade contains MC eutectic carbides which precipitate at high temperature (1,353°C); as a consequence, no M_7C_3 are found

Figure 6



Eutectic carbides network on Cr steel after DTA test: fishbone-like M_7C_3 (grey) and fine-lamellar M_6C (light) (6a); and complex M_7C_3/M_6C eutectic carbide in a Cr steel and related EDS mapping showing major elements of each phase (Cr-rich M_7C_3 and Mo-rich M_6C) (6b).

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/minute)	Temperature from TC (equilibrium conditions)
L → δ (start) Peak 1	Semi-HSS 1	1,430°C (Liquidus)	—
	Semi-HSS 2	1,430°C (Liquidus)	—
	Semi-HSS 3	1,443°C (Liquidus)	1,428°C (Liquidus)
L + δ → γ (start) Peak 2	Semi-HSS 1	1,337°C	—
	Semi-HSS 2	1,399°C	—
	Semi-HSS 3	1,389°C	1,405°C
L + δ → γ (end)	Semi-HSS 1	1,422°C	—
	Semi-HSS 2	1,419°C	—
	Semi-HSS 3	1,384°C	1,395°C
L → γ (start) Peak 3	Chromium steel	1,394°C (Liquidus)	1,388°C (Liquidus)
	Semi-HSS 1	—	1,429°C (Liquidus)
	Semi-HSS 2	—	1,409°C (Liquidus)
	Semi-HSS 3	—	1,395°C
L → γ + MC (start) Peak 4	Semi-HSS 3	1,364°C	1,343°C
L → γ (end)	Chromium steel		1,238°C (Solidus)
	Semi-HSS 1		1,279°C (Solidus)
	Semi-HSS 2		1,228°C (Solidus)
	Semi-HSS 3	1,389°C	1,293°C (Solidus)
L → γ + MC (end)	Semi-HSS 3	1,353°C	1,117°C
L → γ + M7C3 (start) Peak 5	Chromium steel	1,201°C	1,238°C
	Semi-HSS 1	1,168°C	1,165°C
	Semi-HSS 2	1,176°C	1,228°C
	Semi-HSS 3	—	1,115°C
L → γ + M6C (start) Peak 6	Chromium steel	1,143°C (Solidus at 1,135°C)*	1,052°C
	Semi-HSS 1	1,145°C (Solidus at 1,144°C)*	1,084°C
	Semi-HSS 2	1,150°C (Solidus at 1,147°C)*	1,089°C
	Semi-HSS 3	1,158°C (Solidus at 1,153°C)*	1,117°C

*End of the eutectic reaction from DTA tests in this alloy, and M_6C precipitated earlier (1,158°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 achieved precipitation at higher and more distinguishable temperatures in Cr steel than their equivalents 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:

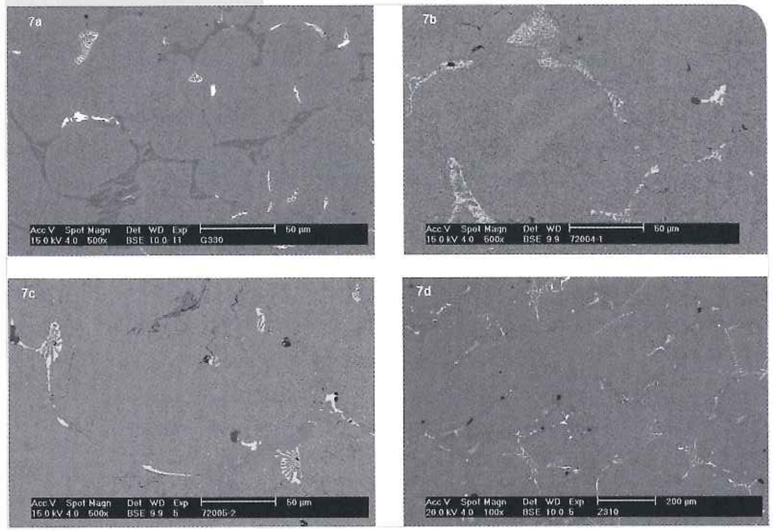
- Liquidus temperature obtained by DTA is always above that which was obtained from TC simulation.
- The first solid to precipitate in the non-equilibrium conditions is not correctly found by TC simulation, as it was the case of the three semi-HSS grades in which delta-ferrite precipitated first, instead of austenite.
- Eutectic carbides found in non-equilibrium conditions appear only in solid-state transformations in the equilibrium conditions; thus, they must be considered as 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 the continuous cooling of the melt are still present at room temperature, unlike the corresponding carbides found in the equilibrium conditions, as the latter disappear with solid-state transformation. In fact, M_7C_3 and M_6C transform themselves respectively into $M_{23}C_6$ and M_2C in the TC simulation.

The differences observed between non-equilibrium and equilibrium simulations could be explained in several ways.

Delta ferrite that appears in the semi-HSS grades during non-equilibrium DTA tests could probably arise from inclusions (sulfides or oxides), as they are known to be delta-ferrite germs and they can promote non-heterogeneous nucleation.[9]

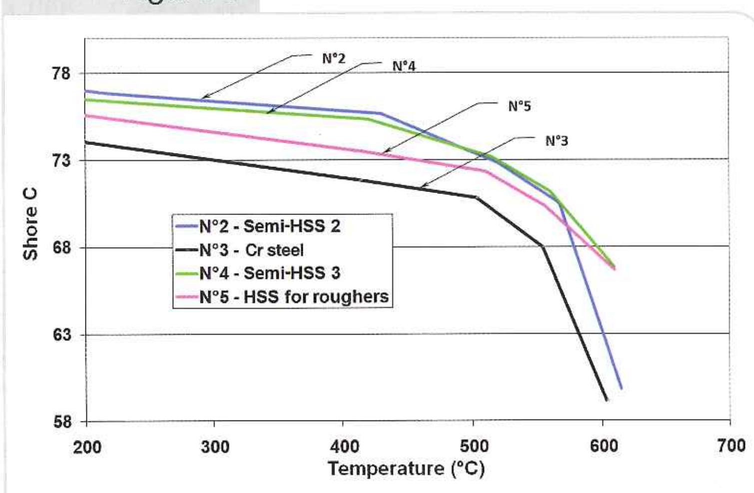
While equilibrium conditions assume a full diffusion of all the alloying elements, there is a segregation phenomenon in the non-equilibrium conditions, especially within the interdendritic space where strong carbide-forming elements, such as Nb, Mo, Cr that are gamma-incompatible, are rejected when the growing dendrite is of the austenite type.

Figure 7



High-Cr steel (near the surface of the shell): network of eutectic M_7C_3 (fishbone-like, grey) and M_6C (light) carbides at grain boundaries, in a tempered martensitic matrix (7a). Semi-HSS 1 (close to the scrap diameter): network of eutectic M_7C_3 (grey) and M_6C (light) carbides at grain boundaries, in a tempered martensitic matrix (7b). Semi-HSS 2 (close to the scrap diameter): network of eutectic M_7C_3 (bulk, grey) and M_6C (light) at grain boundaries, in a tempered martensitic matrix (7c). Semi-HSS 3 (near the surface of the shell): network of eutectic MC (Chinese script, light) and M_6C (rod-like, light) carbides at grain boundaries, in a tempered martensitic matrix (7d).

Figure 8



Hot hardness (Shore C) on Semi-HSS grades 2 and 3, Cr steel, and HSS for roughers (as a reference).

Microstructures Through SEM Analysis — Typical microstructures of studied rolls are shown in Figures 7a–d as obtained from a 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]

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 behavior of three studied grades and HSS rougher.

Both semi-HSS grades 2 and 3 seem to have similar and flat hot hardness behaviors, except for temperature above 570°C, where hot hardness of semi-HSS grade 3 decreases slowly when that of semi-HSS grade 2 collapses. Such a leveling 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.

Corrosion Behavior — Some static corrosion tests were performed in a liquid medium on Cr steel and semi-HSS 3 in a laboratory with the following conditions: 60°C; holding time from 4 to 27 hours; $[Cl^-]$ from 350 to 1,000 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.

Roll Behavior in Service

Layouts of Hot Strip Roughing Mills — In order to obtain a better understanding of the behavior aspects of roughing mill work roll grades, a short description of the different layouts found worldwide will be helpful for the reader (Figure 10).

Many different kinds of roughing mills have been designed over the last 60 years. There are fully continuous HSMs with five to seven roughing stands and additional edgers. This concept was born in the 1960s and was phased out after the first oil crisis of the early 1970s. In this layout, there is only a 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.

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 when 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 HSMs 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 2-high or 4-high mills, one-way, reversing, single or tandem configuration.

Situation in European Roughing Mills — A survey made in 25 western European HSMs clearly highlights the dominant position of semi-HSS or HSS roughing mill grades in all types of roughing mills in Europe (Figure 11).

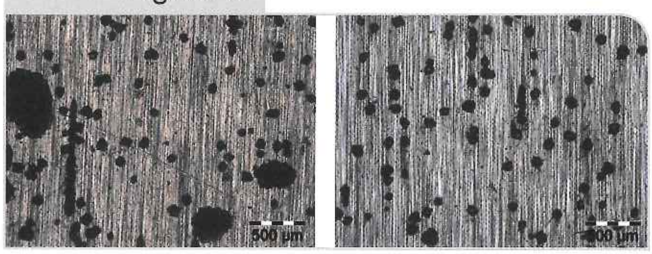
Mill Demands With Respect to Work Roll Properties for Roughing Stands — The interpretation of mill demands, with respect to work roll properties for roughing stands, may be summarized as follows:

- 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 means no peeling, no banding and no microspalling during one campaign.
- 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 are compared in Table 3 referring to these aspects.

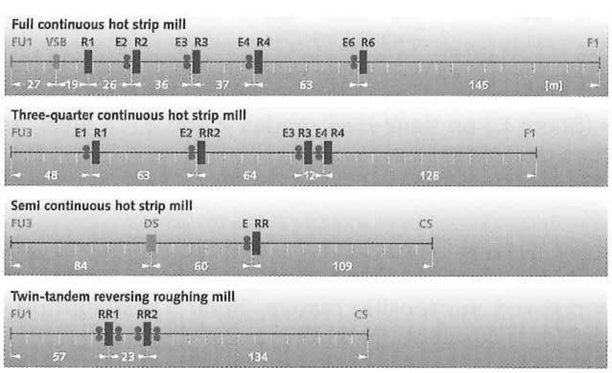
High throughput for the HSM asks for a minimum number of passes in the roughing mill, which is of particular importance for semi-continuous HSMs. This means high reduction per pass, which is possible only

Figure 9



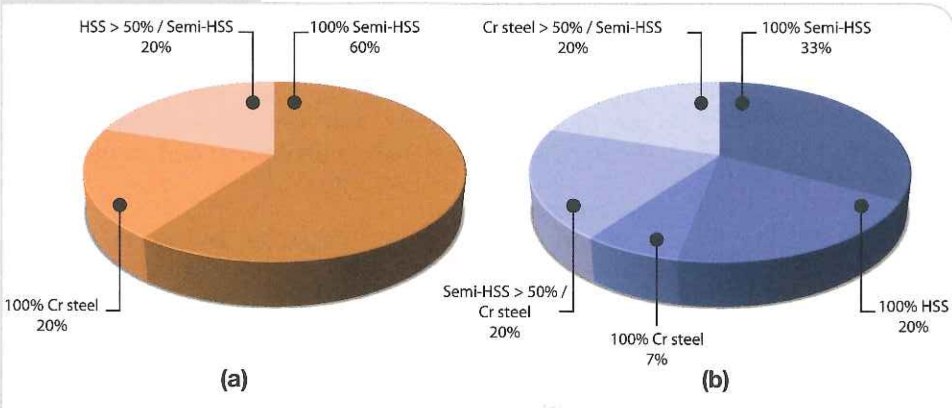
Overview of corrosion pits on Cr steel (left) and semi-HSS 3 (right) surfaces.

Figure 10



Layouts of hot strip roughing mills.

Figure 11



The 2010 situation in five full continuous HSMs in Europe (a); in 20 HSMs (1/2 – 3/4 or DSP mills) in Europe (b).

with excellent roll biting behavior. It is well known that roll bite is improved with lower carbide content and lower hardness of the working surface. 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 for how far plastic deformation can be limited in the outer layer of the roll when the surface is heated 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 of 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 favorable roll bite behavior, based on low carbon content, allows for a strongly increased hardness and wear resistance of the homogeneous matrix 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 characteristics is obtained by a sophisticated heat-treatment process, which stands for a homogeneous distribution of microcarbides and high temperature resistance. The improved mechanical properties at elevated temperatures and 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 mills. 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 bottleneck of the whole hot mill process, the 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 150–300% compared to chrome steel in either reversing or one-way roughing stands.

In many mills, 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 50,000–80,000 tons per run for reversing roughing stands and five-pass reductions. A further important behavior of this roll grade is the smooth, symmetric wear curve without any tendency for a dogbone 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 confirmed as the optimum grade based on the investigations developed in this paper, which could be confirmed by numerous laboratory and industrial results.

Table 3

Comparison of Roll Behavior 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	4	4	3	4	4	4
Semi-HSS	5	5	5	5	5	4
HSS for roughers	4	5	4	5	5	4

5=Excellent 4=Good 3=Satisfactory 2=Sufficient 1=Poor

Regarding the HSS grade for roughing stands, industrial results in European HSMs with a 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 become a standard grade for stainless and special steels rolling.

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 mills 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 conditions 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 lack of acknowledgment of segregations in the equilibrium approach, as well as the heterogeneous germination phenomenon that is promoted by inclusions (sulfides promoting delta-ferrite formation, for example).

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 behavior during the rolling process.

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Did You Know?

Engineers Week: 19–25 February 2012

Founded by the National Society of Professional Engineers (NSPE) in 1951, Engineers Week, or EWeek, is now organized by the National Engineers Week Foundation. The Foundation, a formal coalition of more than 100 professional societies, major corporations and government agencies, is dedicated to ensuring a diverse and well-educated future engineering workforce by increasing understanding of and interest in engineering and technology careers. Aimed at raising public awareness of engineers' positive contributions to quality of life, EWeek promotes recognition among parents, teachers and students of the importance of a technical education and a high level of math, science and technology literacy, and motivates youth to pursue engineering careers in order to provide a diverse and vigorous engineering workforce. EWeek includes such initiatives as "Introduce a Girl to Engineering Day," the Future City Competition and Discover E/K–12. Each year, EWeek reaches thousands of schools, businesses and community groups across the United States. For more information or to get involved, visit www.eweek.org.