Development of Tailored Roll Grade Materials for the Early Stands of Finishing Hot Mills

Where chatter and high mill loads are a problem, alternative low-friction high-speed steel materials can be used. By manufacturing roll grades to suit a wide variety of mill conditions, each mill will be able to maximize roll performance.

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In the majority of hot steel finishing mill applications, the typical early stand work roll technology is spun-cast, duplex materials made from one of two material categories: high-chrome (HiCr) iron and high-speed steel (HSS).[1] Generally these rolls are manufactured using the same casting method of duplex spin casting, meaning that the rolls actually consist of two separate materials that are "welded" together. The spin-casting process allows for a hard, wear-resistant shell metal (typically HiCr iron or HSS) to be cast into a high-speed centrifuge and solidified first where the solidification rate can be controlled and allowed to progress in a rapid fashion. Once complete, the core metal (typically nodular cast iron) is then cast.

Over time, the shell chemistries and heat treatments have been modified based on theoretical knowledge and limited mill feedback. However, the majority of the materials in the market today are produced to satisfy every application and not optimized to ensure the best performance possible according to a specific and detailed understanding of each mill environment that is supplied.

Standard laboratory test results have little predictive value for the actual performance of a work roll in an industrial hot strip mill. Numerous examples have shown that even a successful introduction of a particular roll grade in one mill is no guarantee for a satisfactorily roll performance in another mill. The reason for this situation, as pointed out by K.H. Schröder,[2] is that:

- On the one hand, roll makers have insufficient insight into the mill-specific factors (mill layout, product mix, rolling practices, roll shop practices) that are decisive for roll performance in the industrial practice, and eventually for the question of whether a roll type is suitable for a particular mill.
- On the other hand, roll users (mills) have insufficient insight into the roll properties, and, more importantly, they do not know what roll properties are really important for their mill.

As a result, discussions are often focused on parameters that are easy to measure, like hardness and chemical composition of the roll, but only indirectly affect the issues that really matter. So the trial-and-error approach to introduce new roll types in industrial mills is the result of a knowledge gap between the roll suppliers and the roll users, i.e., the steel industry. Since mill trials with new roll grades are rather expensive, and the failure risk is high, mills are usually reluctant to start such trials, especially if the newly developed rolls have not yet been tested elsewhere. This has a retarding effect on the development of roll technologies.

The solution is to develop tests that accurately simulate the rolling environment and to test new shell grades by producing small-scale test blocks that provide material comparable to that from a full-size roll.

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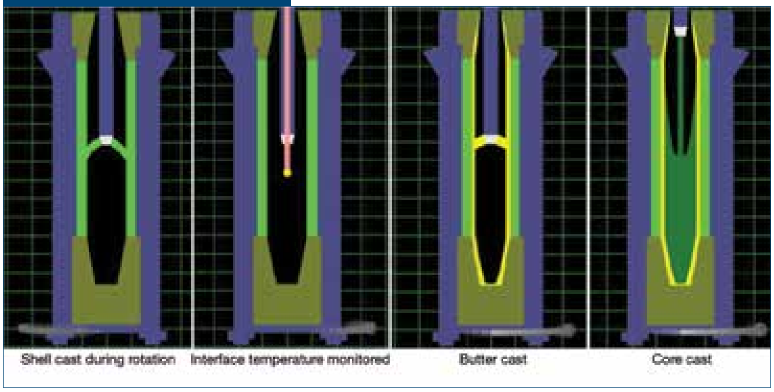
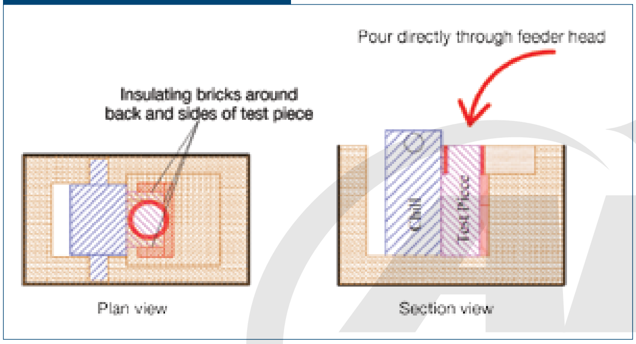
Figure 1



A schematic of the vertical centrifugal casting process.

Figure 2



The rectangular test block (RTB) molding.

Test Block Development and Validation — Most work rolls used in hot strip mills are centrifugally spun cast, as shown in Fig. 1. This entails first casting the "shell" metal against a cast-iron chill. This shell metal forms the working layer of the roll in contact with the strip and backup roll. Shortly after the shell metal has solidified, a butter layer is cast and then the remainder of the roll metal is cast as a spheroidal graphite iron (SG iron, or SGI).

The rate of novel roll developments can be enhanced enormously when small castings can be produced and tested in laboratory tests. A prerequisite is that the microstructure and physical properties obtained at the lab scale are representative of an industrial roll.

To simulate roll performance on small castings, a manufacturing methodology was developed by Union Electric Steel UK Ltd. (UESUK). This methodology was iteratively improved, utilizing the melting and heat treatment facilities at Tata Steel's Teesside Technology Centre. In December 2014, this research and development center was transformed into the independent Materials Processing Institute (MPI).

The method that was developed is similar to roll manufacture as the shell grade is cast against a thick hematite block coated with the standard chill paint produced by UESUK. Metal held within the induction furnace is cast directly through the large feeder head into the sand mold as quickly as possible and then the mold is allowed to cool (Figs. 2–4).

To validate this method, the standard HSS material at UESUK was cast into several test blocks. These test blocks were then heat treated using a small kiln. The cooling from the austenitizing hold was carefully controlled to simulate the temperature recorded by pyrometer on full-size rolls. Samples from both the test block material and the full-size rolls were

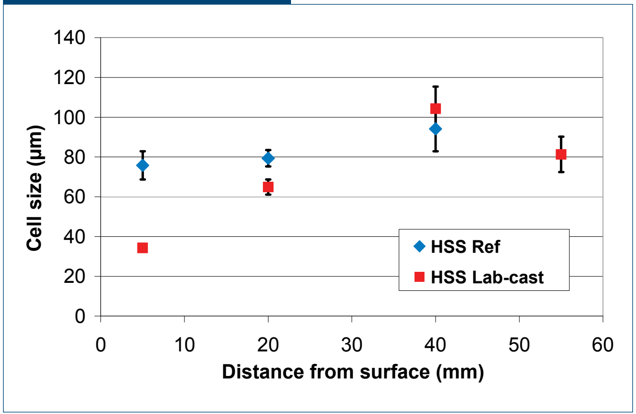
Figure 3

The molding used for RTBs.

Figure 4

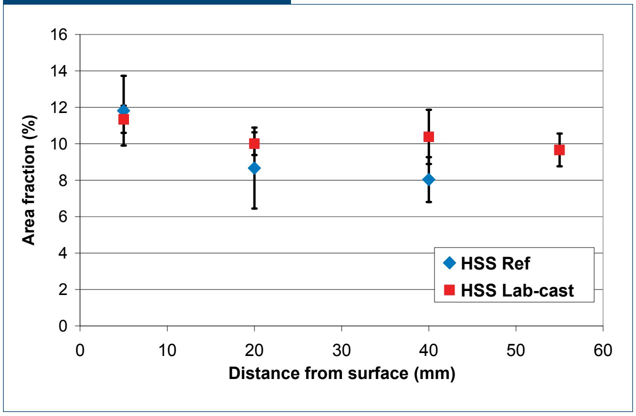
RTB4 immediately after casting at Tata Steel Teesside Technology Centre.

Figure 5



Cell size measurements according to ASTM-112, for high-speed steel (HSS) reference (roll) and HSS test block material.

Figure 6



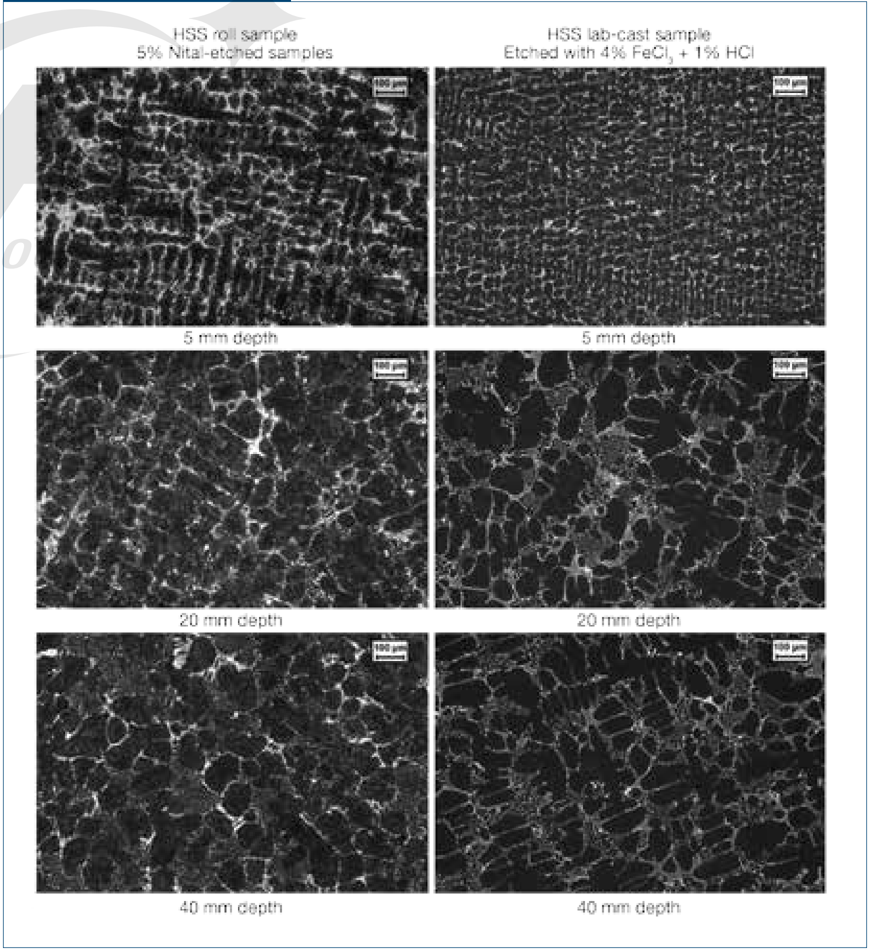
Area fractions of primary carbides as function of radial depth in for HSS reference (roll) and HSS (test block) material.

then provided for microstructural characterization (optical microscopy, scanning electron microscopy/energy-dispersive x-ray spectroscopy (SEM-EDX), x-ray diffraction (XRD) and microhardness testing) by Tata Steel and for analysis of thermophysical properties (as function of temperature) by ArcelorMittal. With regards to the latter analyses:

- Density (ρ(T)) and thermal expansion coefficients (α_L(T)) were measured by means of a Netzsch DIL 402C dilatometry device.
- Specific heat measurements (Cp(T)) were done by differential scanning calorimetry (DSC), using a Netzsch STA 449C differential thermal analysis (DTA) device with DSC-CP measurement head.
- Thermal diffusivity (a(T)) was measured with a Netzsch LFA 427 laser flash analysis device.
- Thermal conductivity, as a function of temperature, λ(T), is deducted from the previous measurements using the equation: $\lambda(T) = a(T)\ \rho(T)\ Cp(T)$.

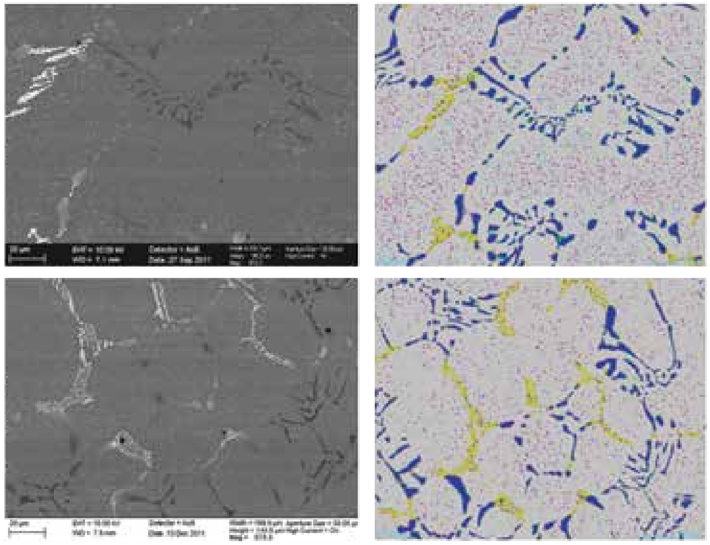
The following are some of the results from the comparison of the reference HSS material from full-size rolls and lab-cast samples:

Figure 7



Optical microscopy images of etched roll and lab-cast HSS reference samples taken at various radial depths.

Figure 8

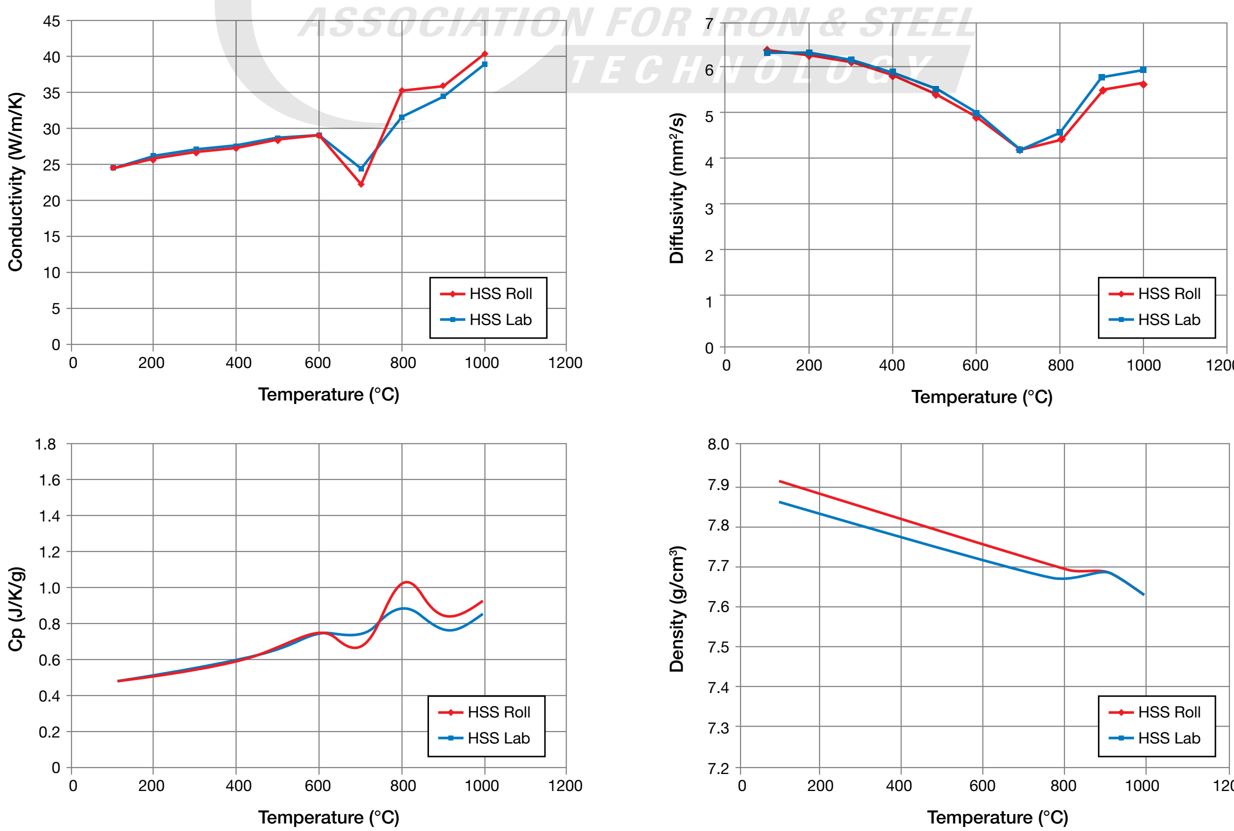


Examples phase cluster analyses by means of energy-dispersive x-ray (EDX) mappings of roll and lab-cast HSS reference samples.

- Optical microscopy images, cell size, primary carbide area fraction measurements and EDX mappings are shown in Figs. 5–8.
- The comparison of thermophysical properties is shown in Fig. 9.

From Figs. 5 and 7 it appears that, close to the surface, the HSS lab-cast sample exhibited a much finer microstructure (average cell size 34 µm) than the HSS roll sample (average cell size 76 µm). The fine microstructure at this near-surface location of the HSS lab-cast sample can be well understood from the fact that this area contains the rapid solidified initially chilled material. This material is not representative of a finish-machined roll as dispatched to a roll user

Figure 9



Comparison of the thermophysical properties of roll and lab-cast HSS reference samples.

(mill). From a full-size industrial roll, such a finely structured outer layer of the as-cast roll is included in the overstock that is machined away (typically up to radial depths of 20 mm). At greater distances from the surface, the HSS lab-cast sample has larger cell sizes, similar to the cell size in the HSS roll sample. Therefore, only analysis results obtained outside the chilled zone are taken into account for comparison.

The results are summarized in Table 1. The positive outcome in Table 1 implies that the developed lab-scale casting and heat treatment methodology had been validated for HSS grades and other roll grade families with a similar type of heat treatment (i.e., including an austenitized hold stage).

Multi-Technique Microstructure Analysis for Roll Grade Development — Well-targeted development and subsequent fine-tuning of innovative novel grades requires detailed insight into the differences in microstructural properties of existing and candidate roll grade alloys. Elaborate microstructure examination was, therefore, carried out on a range of test block samples and samples from full-size rolls by using several complementary techniques such as optical microscopy, SEM, EDX mapping, electron backscatter diffraction (EBSD) analysis and XRD analysis.

In a few instances, as-cast structures were compared to fully heat-treated structures.

Fig. 10 presents an illustrative example of details of the microstructure of the reference HSS roll grade, obtained by the powerful combination of SEM-EDX-EBSD.

By XRD and EBSD it could be shown that the carbidic makeup of a reference HSS consisted of, besides the dominant M_7C_3, M_2C and MC phases, $M_{23}C_7$, M_8C_7, M_2C_3 and M_6C types of carbide. The latter type appears preferentially after heat treatment. Moreover, XRD and EBSD were used to extract information on the microstructure of the steel matrix, i.e., on the amounts of ferrite, martensite and retained austenite.

The well-known compositional variability of the different carbides (as expressed by M in the above molecular formulas) was corroborated through SEM/EDX analyses. It was indeed observed that, in these carbide phases, the carbide-forming elements (Cr, V, Mo, W, Ti) usually occur intermixed. Separate Mo-rich, V-rich and Cr-rich carbides could be discerned. The MC type especially, albeit always rich in vanadium, shows a wide range of compositional values, with Mo substituting for V.

A noteworthy finding from these examinations is that seemingly modest changes in HSS alloy composition can lead to drastic shifts in the amounts and compositions of the separate carbides, and even to the appearance of a new phase.

Material Grade Development — To select innovative, novel grades for use in early HSM finishing stands, the required performance characteristics first needed to be identified:

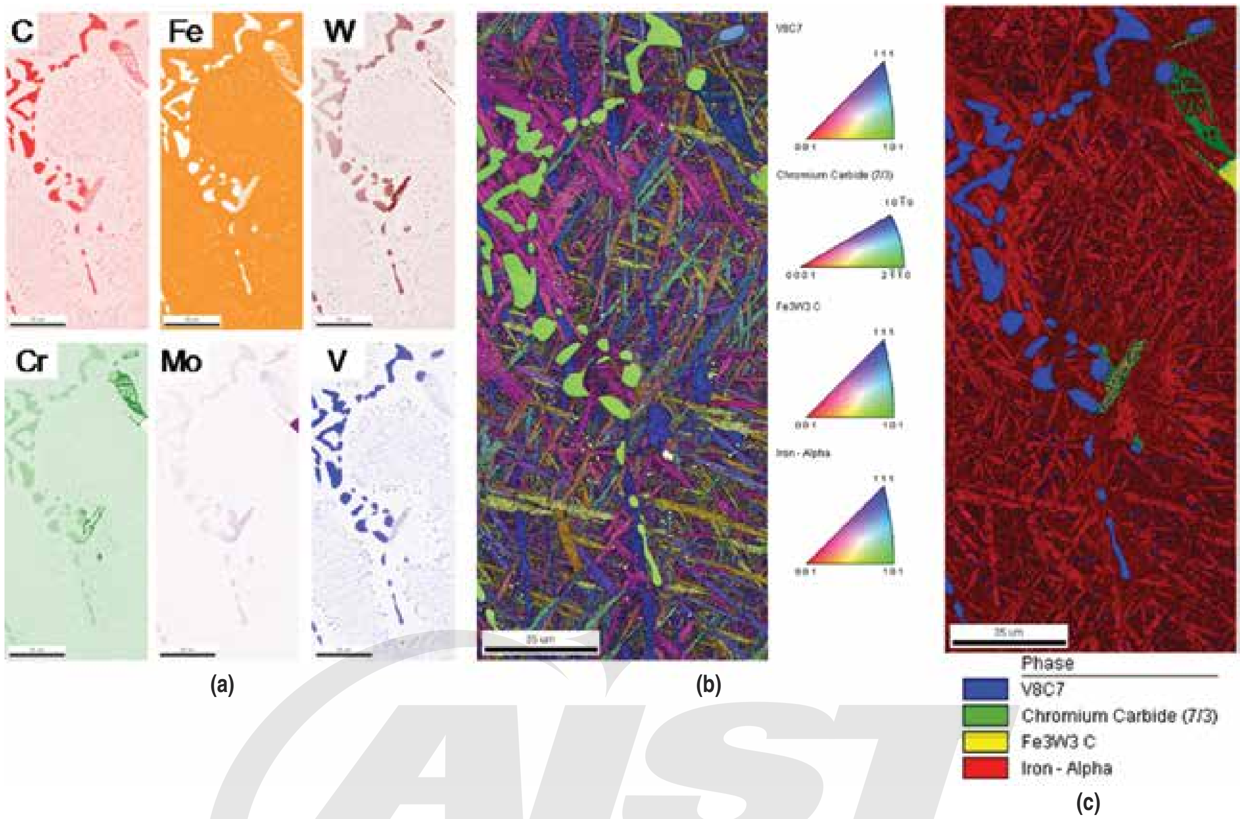
- **Reduced friction HSS** — required as there are a number of mills that have not been able to successfully apply standard HSS materials due to problems such as chattering. HSS has a higher

Table 1

Summary of Analysis and Testing Results for Lab-Scale HSS Versus Industrial HSS Samples

Properties	Comparison	Comments
Primary carbides	Very good	Nearly identical in type and amount across samples, except right at the surface (5 mm radial depth). This is easily explained as the outside diameter of the small test sample had not been machined and, therefore, still contained the initial chilled area.
Secondary carbides	Good	Same types of secondary carbides, with some differences in the amount, size and spatial distribution. Possibly due to small difference in solidification rate and/or heat treatment conditions. Differences insignificant when compared to overall microstructure.
Cell size	Very good	Nearly identical, with the exception being at 5 mm radial depth (test sample showed a much smaller cell size at 5 mm). This is easily explained as the outside diameter of the small test sample had not been machined and, therefore, still contained the initial chilled area.
Equiaxed vs. columnar depth	Reasonable	Comparable but with significant variability, related to limitations of test method and measurement accuracy
Matrix composition	Excellent	Element mapping showed excellent correlation
Hardness	Good	Macrohardness level is very similar. Both samples show minimal hardness drop through depth. Microhardness of roll sample matrix consistently harder than lab-cast sample at all radial depths. Results typically within margin of error and acceptable range.
Thermophysical properties	Very good	Measurement results for the conductivity, diffusivity, specific heat, density and coefficient of thermal expansion show a very good similarity
Mechanical properties	Very good	Measurements under tensile and compression loads at 100°C and 700°C show similar results for lab-cast and full-size roll HSS samples

Figure 10

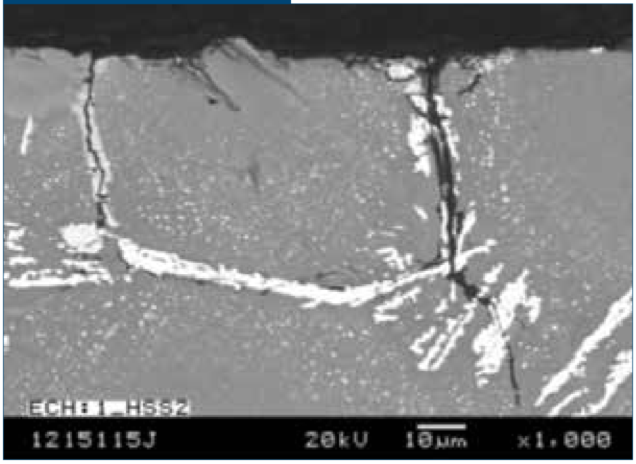


Scanning electron microscopy (SEM) + EDX+ electron backscatter diffraction (EBSD) microstructure details of the reference HSS alloy (heat treated), showing the same area: in chemical composition contrast (SEM-EDX mapping) (a); in crystallographic orientation contrast (EBSD) (b); and in crystallographic phase contrast (EBSD) (c).

friction coefficient than HiCr iron materials, thus it behaves differently in the mill. By developing grades with increased matrix hardness, the friction effect of the very hard carbide present in HSS materials will be reduced. Reduced friction HSS would be used in mills that have struggled to adapt to HSS, and although the performance of low-friction grades might be less than standard HSS, they would greatly exceed the performance of HiCr iron.

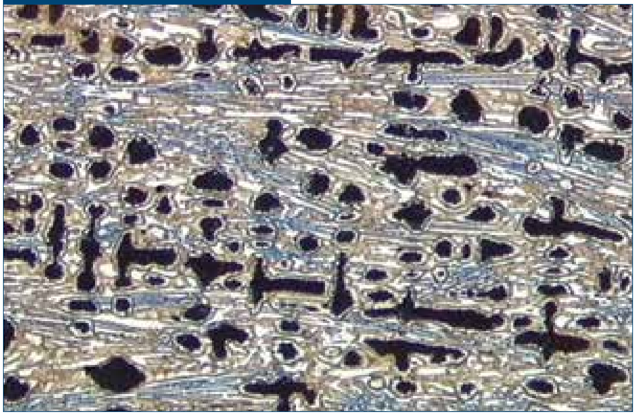
- **Increased performance HSS** — to improve the performance of existing HSS material. Typically, HSS materials show very little wear in use. Degradation of the surface comes mainly from fire crazing and associated pitting. Fire crazing has been shown to follow the primary carbide on grain boundaries (Fig. 11), so by breaking up the carbide network, the depth of fire cracking will be reduced. This will mean HSS rolls can stay longer in the mill and require less redress between campaigns.

Figure 11



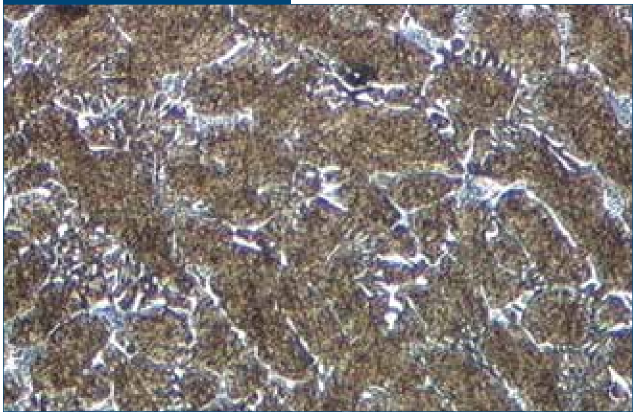
Example of fire-crazing cracks propagating preferentially along the grain boundary carbide network. Microstructure observed at an HSS sample after use in the hot rolling simulator at Centre de Recherches Mètallurgiques.

Figure 12



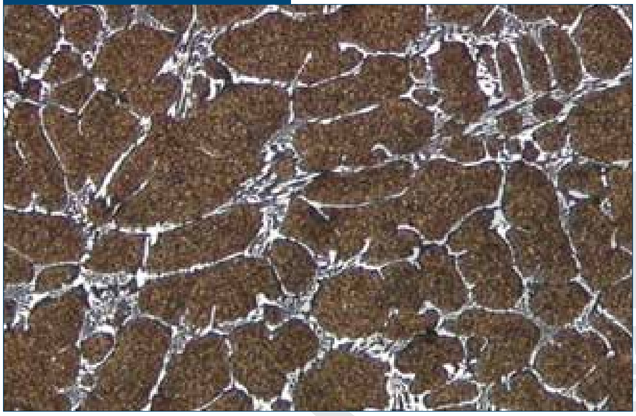
HiCr iron microstructure. hfw = 2,000 μm.

Figure 13



Standard HSS microstructure. hfw = 2,000 μm.

Figure 14



HiCr steel microstructure. hfw = 2,000 μm.

Figure 15

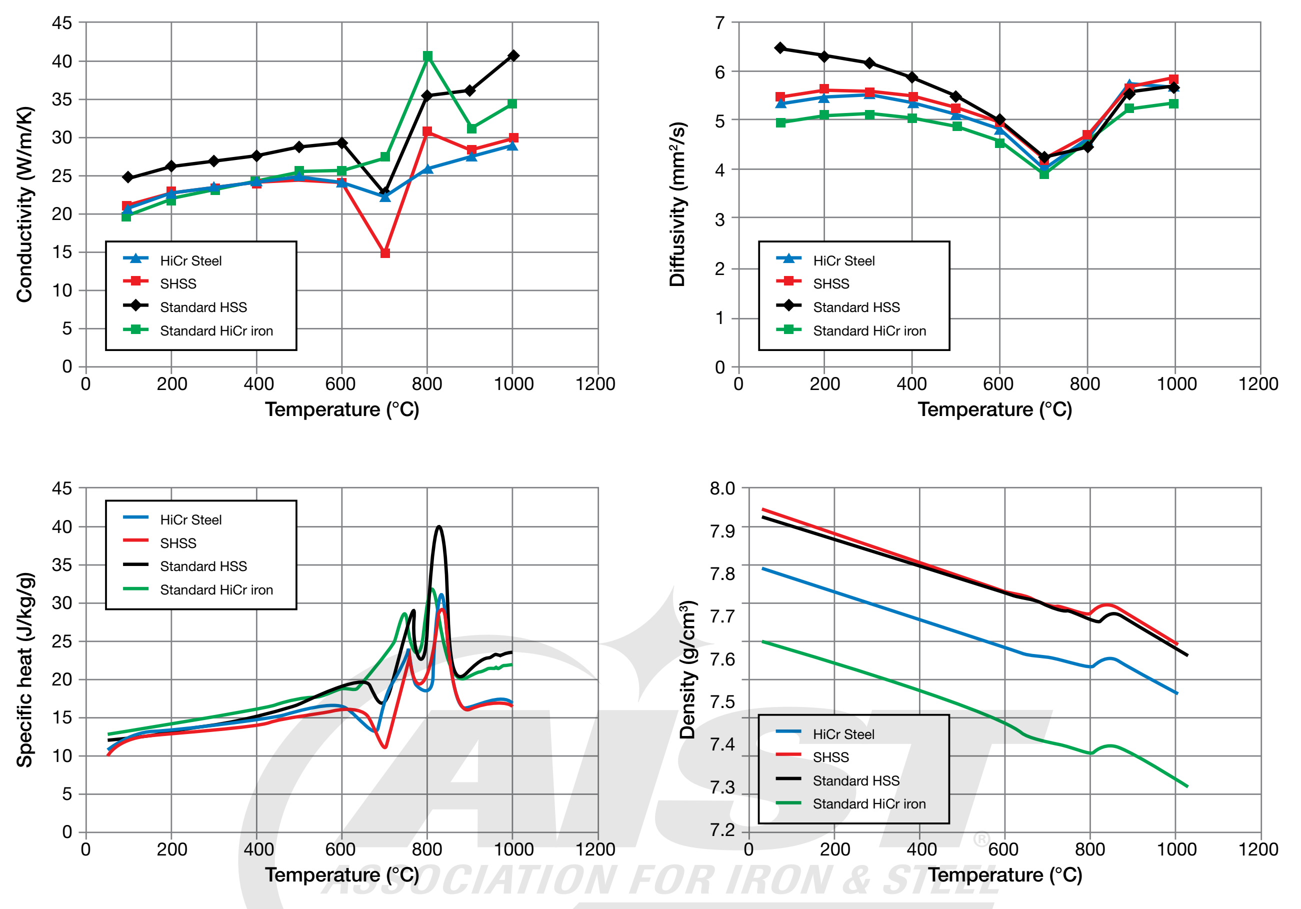
SHSS microstructure. hfw = 2,000 μm.

Reduced Friction HSS — To understand the higher friction coefficient of HSS compared to HiCr iron, the microstructures were considered. HiCr iron consists of a large volume fraction (~25%) of mainly M_7C_3-type carbide surrounded by a bainite/martensite matrix (Fig. 12). HSS consists of a smaller fraction of carbides surrounded by a bainite/martensite matrix (Fig. 13), but these carbides represent a far more complex mix of different carbide types. The classical picture (as presented in literature, e.g., Reference 1) that spun-cast HSS rolls typically contain ~10% carbides in a mix of M_2C-, M_7C_3- and MC-type carbides appears to be somewhat oversimplified. First, SEM-EDX analysis revealed significantly higher total carbide volume fractions in HSS alloys (~16% for the reference HSS roll sample in Fig. 8) than observed by optical microscopy (~10% for the reference HSS roll sample in Fig. 5). Note the presence of finely dispersed secondary carbide particles in the SEM-EDX images in Fig. 8, which cannot be discerned by optical microscopy (Fig. 5). Second, as mentioned in the previous section, a wider range of carbide phases (also of $M_{23}C_7$, M_8C_7, M_2C_3 and M_6C types of carbide) has been detected besides the dominant M_7C_3, M_2C and MC phases, which is important to understand varying in-use properties of different HSS roll grades.

When comparing HSS alloys to HiCr iron, it is noteworthy that M_2C- and MC-type carbides are significantly harder than M_7C_3 carbides. The relative hardness of the carbide in HiCr iron means it will wear more quickly than HSS but the higher volume fraction of carbide means the softer matrix has a small effect on wear. Conversely, the lower volume fraction of carbide in HSS means that as the matrix wears carbide can be left "upstanding," increasing friction in the roll bite. Therefore, to reduce the friction coefficient in HSS, the wear resistance of the matrix can be increased and a reduction in carbide hardness and volume can also be considered to try to achieve a lower and more even rate of wear.

A starting point was to investigate the typical materials used in the roughing stands of hot mill: HiCr steel and SHSS (Figs. 14 and 15).

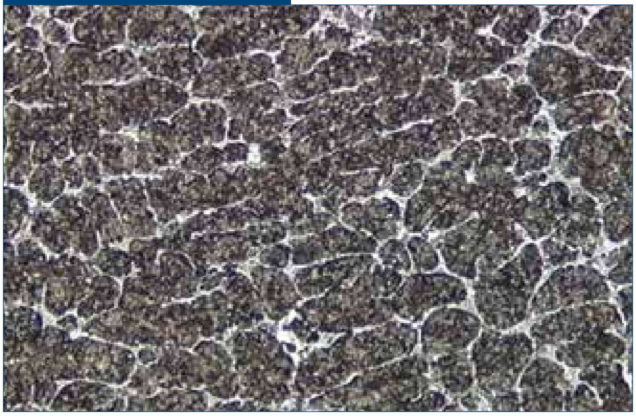
Figure 16



The thermophysical properties of HiCr steel and SHSS compared to standard HSS and HiCr iron material.

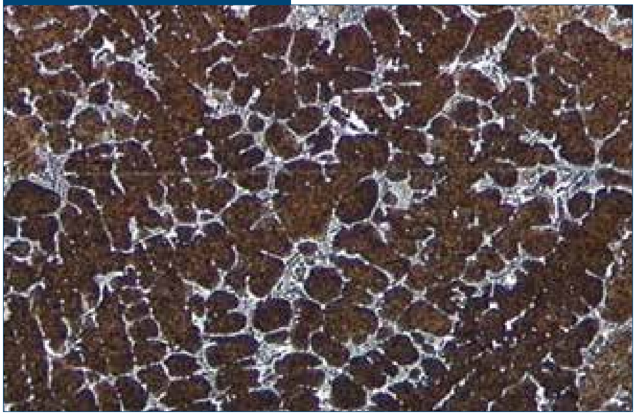
In simple terms, HiCr steel is a lower C- and Cr-version of HiCr iron with increased Mo. This will form a reduced amount of M_7C_3-type carbide. Although this will produce a higher carbide content than HSS, it is likely that the wear performance will be lower as the M_7C_3 carbide is less hard than the majority of HSS carbides. SHSS in similar terms has reduced C, V and W compared to the reference HSS material to reduce the overall carbide content and the amount of very hard carbide. With reduced levels of MC-type

Figure 17



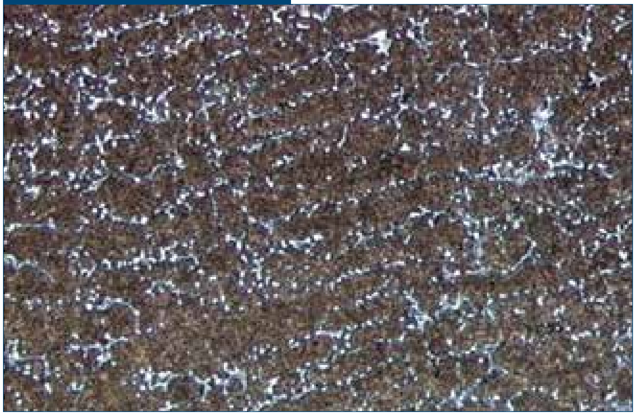
Hi-Mo HSS test block microstructure. hfw = 2,000 µm.

Figure 18



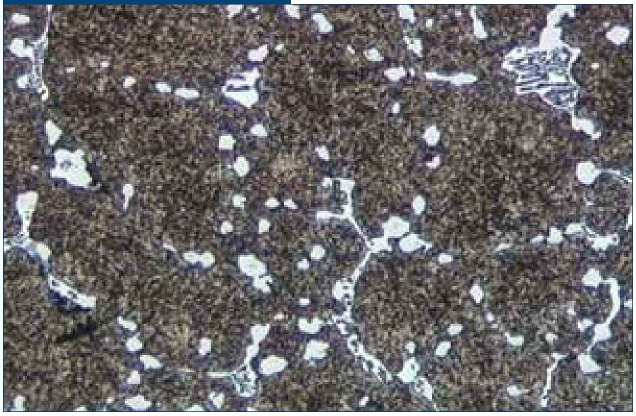
Hi-Mo HSS roll microstructure. hfw = 2,000 µm.

Figure 19



HSS6 microstructure. hfw = 2,000 μm.

Figure 20



HSS6 microstructure. hfw = 500 μm.

carbide, the friction coefficient should also be lower. HiCr steel and SHSS should show an increase in wear resistance and thermal fatigue resistance compared to HiCr iron. A comparison of the thermophysical properties of HiCr steel and SHSS with standard HSS and HiCr iron grades is shown in Fig. 16.

To reduce the amount of hard MC-type carbide in a HSS material, a new grade was developed with reduced W and V and increased Mo content. This grade, designated HSS4, was developed to offer a low-friction grade with comparable performance to standard HSS. The initial test results on this material were promising, so Tata Steel ordered two rolls to be applied in its DSP mill at IJmuiden. The microstructure is very similar to standard HSS, although more Mo-rich M_2C carbides can be seen (Figs. 17 and 18).

Increased Performance HSS: TiC and TiN are known to nucleate primary carbide in low-carbon steel.[3] To try to break up the primary carbide network, a large Ti addition was made. A new HSS material, designated as HSS6, and the carbide were considerably broken up (Figs. 19 and 20). Two rolls were, at the time of this writing, in production for Tata Steel IJmuiden DSP.

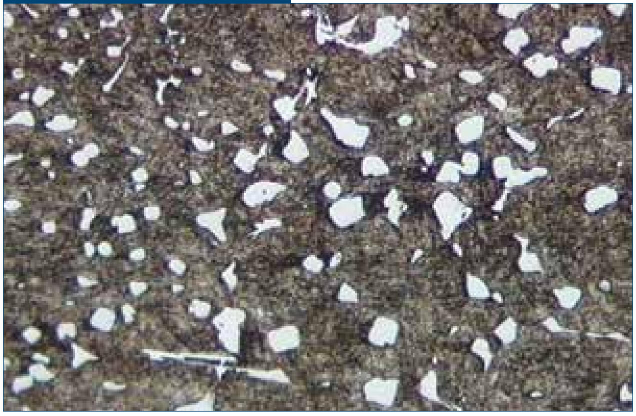
An alternative to breaking up the primary carbide is to reduce the amount formed. To achieve this, the HSS chemistry is radically altered with a large increase in V content to greatly increase the amount of eutectic carbide formed. This grade, designated as HSS5, has no discernible carbide network a majority of individual MC-type carbides (Figs. 21 and 22). The thermophysical properties of the new HSS grades are in Fig. 23.

The development of high-speed steel grades HSS4, HSS5 and HSS6 illustrates the application of the proposed development logic and methodology to derive a potential solution to specific targeted mill applications without the major cost of full roll development processes. Getting the final specifications of these grades to a point where a viable full-roll trial stage involved several staged iterations at the test development stage.

Figure 21

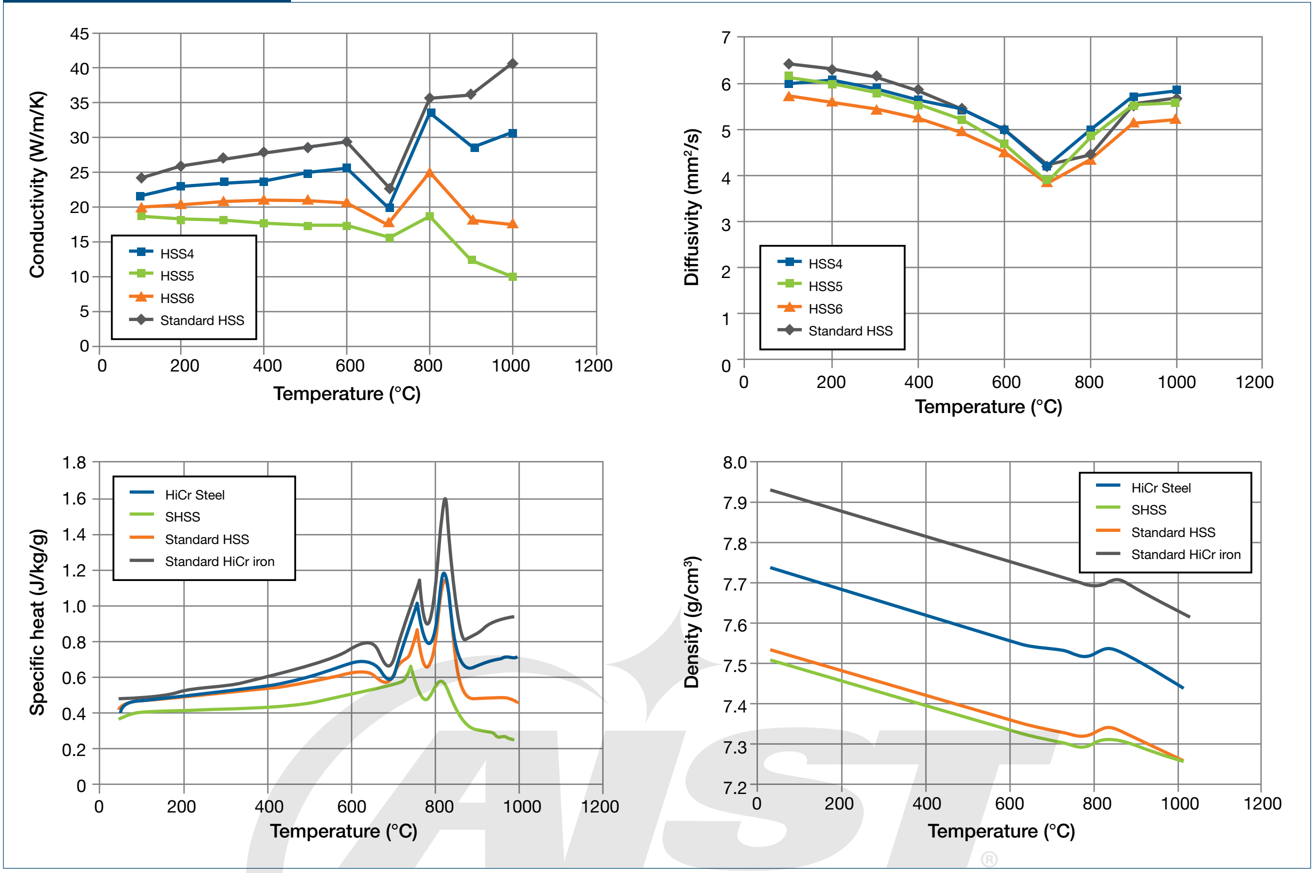
Fully heat-treated microstructure of RTB7 (HSS5). hfw = 2,000 μm.

Figure 22



Fully heat-treated microstructure of RTB7 (HSS5). hfw = 500 μm.

Figure 23



The thermophysical properties of HSS4, HSS5 and HSS6 compared to standard HSS material.

Conclusions

A methodology for the manufacture of small castings has been developed and validated using microstructural and thermal-mechanical testing provided by Tata Steel and ArcelorMittal. Using this methodology, multiple new material grades have been produced, analyzed and refined, including two grades that have now been cast as full-scale rolls. Specific grades have been developed to target mills that have difficulty using standard HSS materials and to further improve the performance of HSS in service.

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