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

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). 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 spinning 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 for their mill. 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.

• 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 grades by producing small-scale test blocks that provide material comparable to that from a full-size roll.
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
then provided for microstructural characterization (optical microscopy, scanning electron microscopy/energy-dispersive x-ray spectroscopy (SEM-EDX), x-ray diffraction (XRD) and micro-hardness testing) by Tata Steel and for analysis of thermophysical properties (as function of temperature) by ArcelorMittal. With regards to the latter analyses:

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

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

**Figure 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.

**Figure 7**
Optical microscopy images of etched roll and lab-cast HSS reference samples taken at various radial depths.
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.

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

Comparison of the thermophysical properties of roll and lab-cast HSS reference samples.
By XRD and EBSD it could be shown that the carbide makeup of a reference HSS consisted of, besides the dominant $M_2C_3$, $M_23C_6$ and $MC$ phases, $M_{23}C_7$, $M_6C_7$, $M_2C_3$ and $M_C$ 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

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

---

**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 Métallurgiques.
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 $M_{23}C_7$, $M_6C_7$, $M_2C_3$ 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).
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...
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$_2$C carbides can be seen (Figs. 17 and 18).

**Increased Performance HSS:** TiC and TiN are known to nucleate primary carbide in low-carbon steel. 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.
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.

Acknowledgments

The authors of this paper gratefully thank the Commission of the European Communities for the support of this work. The work is funded in part with a grant from the Research Fund for Coal and Steel under research Grant Agreement No. RFSR-CT-2011-00010.

References