ASPECTS OF A TECHNOLOGY FOR OBTAINING SEMIFINISHED PRODUCTS OF LOW-CARBON STEEL ON A CONTINUOUS SECTION CASTER

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The Chelyabinsk Metallurgical Combine has mastered a technology for obtaining continuous-cast semifinished products of low-carbon (\(\{C\} < 0.10\%\)) steels SAE1006 and SAE1008. These steels are cast in an open stream on a continuous section caster with 100 \(\times\) 100 mm molds. It was determined that good-quality semifinished products and favorable casting conditions are assured by deoxidizing the steel with secondary aluminum during casting. The amount of aluminum used here is 1.2 kg/ton. The aluminum is introduced into the ladle before the ferroalloys. The value of the ratio \([\text{Mn}]:[S]\) in the finished steel should be no lower than 22, while the value of \([\text{Mn}]:[\text{Si}]\) should be at least 2.5. Casting speed is kept at or below 5.2 m/min, and the maximum pressure exerted on the semifinished product by the withdrawing rollers is 35 ton-f. Scanning electron microscopy and x-ray phase analysis were used to determine the composition of the sulfide compounds in the steels when the ratio \([\text{Mn}]:[S]\) has the values 14.8 and 17.7.

In 2005, the Chelyabinsk Metallurgical Combine successfully introduced a technology for obtaining semifinished products of low-carbon steel on a continuous section caster. The low-carbon (less than 0.10\% C) steel was cast in an open stream through 100 \(\times\) 100 mm molds with the use of a system that allowed quick changes of the pouring nozzles.

In the course of introducing this technology, specialists at the combine came up against several problems:
- breakouts under the mold and in the secondary cooling zone;
- swelling of the semifinished product and the formation of internal cracks, due to the accompanying increase in ferrostatic pressure.

To resolve these problems, researchers performed experimental castings of steels SAE1006 and SAE1008. Despite their rather similar chemical compositions (Table 1), the differences in these steels’ silicon contents resulted in different problems in the casting of the trial batches.

The section caster was used to cast 25 trial heats of steel SAE1008. It was found that a slag phase composed of products formed by the deoxidation operation and secondary oxidation of the steel was formed inside the molds when the heat being cast had a value of less than 2.5 for the ratio \([\text{Mn}]:[S]\). The formation of the slag phase led to breaks in the crystallizing skin of the casting underneath the mold. The mechanism responsible for these breakouts is depicted in Fig. 1. Solid nonmetallic inclusions (NI) that form on the meniscus of the molten steel inside the mold (see Fig. 1a) come into contact with

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the skin of the casting. Accumulation of these inclusions on the meniscus and oscillation of the mold cause the inclusions to become stuck to the skin of the cast semifinished product (Fig. 1b), i.e., an anomalous (defective) skin is formed. This skin grows at a different rate than the nondefective skin as the crystallizing semifinished product passes through the mold (Fig. 1c and d). The resulting variation in the thickness of the skin as a whole leads to the escape of molten steel in the defective section underneath the mold (Fig. 1e), the immediate cause here being the ferrostatic pressure of the liquid metal inside the semifinished product. “Holes” are usually formed on the surface of the semifinished product when such skin ruptures occur, and liquid steel flows through these openings. These events are referred to as slag breakouts.

The ratio of the manganese content of the steel to its silicon content when it is ready for casting should be equal to at least 3.0. When the ratio is less than 3.0, the product from the deoxidation reaction and the subsequent transformation is a solid with a high silica content. This compound is difficult to remove from the melt. Low-melting, easily removed manganese silicate is formed when the ratio [Mn]:[Si] = 3.0 or more. It follows from the MnO–SiO₂ phase diagram [1] that an increase in the content of SiO₂ from 45 to 55% is accompanied by an increase in the liquidus temperature from 1400 to 1705°C and the precipitation of a separate phase in the form of crystoballite. Thus, maintaining the optimum ratio [Mn]:[Si] makes it possible to obtain low-melting inclusions that are easily removed from the steel and thereby avoid the intensive precipitation of the solid inclusions that are formed during deoxidation of the steel and secondary oxidation of the steel in the stream (during casting) and in the meniscus (inside the mold).

Proceeding on the basis of the standard chemical composition of the steel (see Table 1), we made steel SAE1008 mainly with values of the ratio [Mn]:[Si] smaller than 3.0 (average of 2.6). Casting of SAE1008 with the ratio 2.5–3.0 showed that no solid nonmetallic inclusions are formed if the steel is initially (before the addition of silicon- and manganese-bearing ferroalloys) deoxidized with aluminum during tapping. If the steel is deoxidized only with ferroalloys (ferrosilicon, ferro-

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE1008</td>
<td>≤0.10</td>
<td>0.30–0.50</td>
<td>0.15–0.30</td>
<td>≤0.030</td>
<td>≤0.030</td>
</tr>
<tr>
<td>SAE1006</td>
<td>≤0.08</td>
<td>0.25–0.40</td>
<td>≤0.15</td>
<td>≤0.030</td>
<td>≤0.040</td>
</tr>
</tbody>
</table>

**Table 1. Chemical Composition of Steels SAE1006 and SAE1008, mass %**

![Diagram of the formation of slag inclusions](image)
manganese, silicomanganese), then some of the strands of the caster will usually be lost due to slag breakouts on the semifinished product. An analysis of all such breakouts that have occurred during the casting of steel SAE1008 showed that the following is necessary to allow continuous casting of the steel in an open stream with the optimum ratio \([\text{Mn}]:[\text{Si}] = 2.5–3.0\) and without the formation of solid NI:

- deoxidation during tapping should first be done with secondary aluminum in amounts of at least 1.2 kg/ton;
- the casting operation should be performed with the installation of a protective tube on the slide gate of the pouring ladle; the tube should extend into the molten steel inside the tundish, in order to reduce secondary oxidation;
- the slag in the tundish should be reconditioned by pumping off the spent portion of the slag and inducing the formation of a new slag with the use of a special slag-forming mixture.

The continuous casting of reinforcement steel 35GS in an open stream at the Chelyabinsk Metallurgical Plant showed that most of the heats are cast with a ratio \([\text{Mn}]:[\text{Si}]\) less than 2.5 (average 2.0) and that the nonmetallic phase on the meniscus is either substantially smaller in volume or is absent altogether [2]. This can be attributed to the fact that the carbon in medium-carbon steel 35GS – being a chemically active element – decreases the probability that atmospheric oxygen will react with the silicon in the steel. At the same time, the effect of the ratio \([\text{Mn}]:[\text{Si}]\) on slag formation in low-carbon steels of type SAE1008 is considerably greater than for medium-carbon steels of type 35GS.

No problems have been encountered with slag breakouts under the mold in the casting of SAE1006, since its chemical composition (see Table 1) makes it possible to obtain a ratio \([\text{Mn}]:[\text{Si}]\) greater than 2.5 or even 3.0. Different problems arose in mastering the production of semifinished products made of SAE1006.

**The occurrence of breakouts under the mold due to the greater probability of hanging of the ingot in the mold.** Due to the small degree of linear and volumetric shrinkage that takes place in low-carbon (less than 0.1% C) steel with an increase in casting speed and due to the fact that the casting operation is sometimes performed on new molds (new sleeves), breakouts are more likely to occur under the mold. The use of a new sleeve to cast low-carbon steel affects the probability of hanging of the ingot in the mold due to its greater conicity, i.e., the semifinished product can become stuck in the lower part of the sleeve. This explains the fact that the molten steel can splash up to the 8-mm level or higher from its normal level of 4–5 mm inside the mold. The probability of hanging is reduced if the caster is provided with a sleeve that has already been in service (that has been used to cast more than 1200 tons of steel), which in turn makes it possible to perform the casting operation without breakouts under the mold. Several corrective measures were introduced to decrease the likelihood of breakouts caused by hanging of the ingot in the mold: low-carbon steel was cast only on used sleeves and at speeds no greater than 5.2 m/min.

**Convexity greater than 2 mm in the cross section of the semifinished product.** Convex surfaces are formed on semifinished products of ferritic steel SAE1006 due to the highly ductile nature and small thickness of the skin formed during the casting operation. The rate of increase in the thickness of the skin decreases as the rate of crystallization slows when the skin separates from the walls of the mold sleeve. Excessive compression of the semifinished product in the rollers of the withdrawal mechanism also changes the shape of the casting – convexity develops on the side walls as well. This defect is less common on semifinished products of steel SAE1008 and is almost never seen on semifinished products made of steels with a higher carbon content.

In the course of mastering the production of steels SAE1008 and SAE1006, it was established that the following is necessary to make the formation of convexity on 100 × 100 mm squares less likely at the Chelyabinsk combine:

- cast the steel at speeds no greater than 5.2 m/min;
- reduce the pressure exerted by withdrawing rollers on the semifinished product to 35 ton-f instead of the specified 48 ton-f;
- keep steel in the tundish from being heated more than 45°C above the liquidus temperature;
- keep water discharge for secondary cooling at or above 2.0 liters/kg.

**The occurrence of breakouts in the secondary cooling zone (SCZ) due to deviation of the ratio \([\text{Mn}]:[S]\) and casting speed from the specifications.** It is known that high sulfur content and excessive heating facilitate the formation of internal cracks. Overheating results in the formation of a columnar structure that predisposes the steel to the formation of cracks with a simple (linear) trajectory. The temperature range associated with the solid–liquid phase \((T_l – T_s)\) determines structure
formation in the zone that has been damaged the most by hot cracks. Due to the high rate of crystallization, continuous-cast semifinished products contain MnS and/or complex sulfides (Mn, Fe)S, (Fe, Mn)S, and even FeS. The lower the manganese content of the steel, the lower the rate of crystallization at which complex sulfides and iron sulfides will form. Both of these types of sulfides are usually film-like and are formed at temperatures below 1100–1000°C. During crystallization at temperatures up to 1100–1000°C, films of high-sulfur liquid remain present in the spaces between branches of the dendrites and at the boundaries of the latter [3]. This leads to the formation of both internal and external cracks. Examining the combined effect of manganese and sulfur on hot shortness, most researchers have come to the conclusion that increasing the ratio of manganese to sulfur (to a value greater than 20) helps reduce the number of internal cracks in the semifinished products.

The manifestation of hot shortness during continuous casting leads to emergency shutdowns of the strands, since massive breakouts of steel occur in the SCZ under these conditions.

TABLE 2. Contents of the Chemical Elements in Specimens of Steel SAE1006, mass %

<table>
<thead>
<tr>
<th>No. of specimen</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>A_{tot}</th>
<th>O_{tot}</th>
<th>[Mn]:[S]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.39</td>
<td>0.095</td>
<td>0.022</td>
<td>0.022</td>
<td>0.004</td>
<td>0.0097</td>
<td>17.7</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.37</td>
<td>0.110</td>
<td>0.025</td>
<td>0.019</td>
<td>0.003</td>
<td>0.0110</td>
<td>14.8</td>
</tr>
</tbody>
</table>

TABLE 3. Results of Spectral Analysis of Inclusions in Specimens 1 and 2

<table>
<thead>
<tr>
<th>No. of specimen</th>
<th>No. of figure</th>
<th>Content of the element, mass %/atom. %</th>
<th>Type and location of inclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O</td>
<td>Si</td>
<td>S</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>21.60/42.92</td>
<td>18.07/20.46</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>32.72/45.64</td>
<td>36.41/29.64</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>4a</td>
<td>27.94/51.82</td>
<td>15.32/16.19</td>
</tr>
</tbody>
</table>

^ The high content of the element is connected with the fact that the dimensions of the inclusion were comparable to the diameter of the electron beam of the microscope (≈4 μm).

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Fig. 2. Fragment of the macrostructure of a 100 × 100 mm continuous-cast semifinished product of steel SAE1006 (SBC_{axial} 2.5 points).
Fig. 3. Random fine oxysulfide inclusions in the metal of specimen 1.

Fig. 4. The metal of specimen 2 from the continuous-cast semifinished product:  

a) edge of crack (complex sulfides in an axial crack);  
b) central part of the semifinished product (complex eutectic sulfide inclusions);  
c) random fine oxysulfide inclusions.
To evaluate the effect of the ratio $[\text{Mn}]:[\text{S}]$ on crack formation in steel SAE1006, we analyzed specimens from the center of a cast semifinished product with axial segregation bands and cracks $\text{SBC}_{\text{axial}}$ rated at 2.5 points and values of 14.8 and 17.7 for the ratio $[\text{Mn}]:[\text{S}]$ (Fig. 2). The dashed line in Fig. 2 shows where the sample was obtained. Scanning electron microscope JEOL JSM-6460LV was used to determine the chemical composition and morphology of the nonmetallic inclusions (Table 2), while a DRON-2.0 diffractometer was used to determine their phase composition.

No cracks containing sulfides were seen in specimen 1. Sulfur was present in the steel in the form of globular oxysulfide inclusions about 3 $\mu$m in diameter (Fig. 3). Globular oxide and oxysulfide inclusions were precipitated before crystallization in the form of liquid drops. These inclusions turned out to be located at random in the solidified steel, and dendrites and dendritic branches could be found in any cross section [3]. Examination of the specimens on the DRON-2.0 diffractometer in radiation from an iron anode did not reveal any sulfides in the steel.

The sulfide inclusions were distributed in a different manner in specimen 2. Complex sulfide inclusions were seen near the end of the axial crack in the specimen (10–15 mm from the center of the semifinished product). Some of these inclusions were inside the crack (Fig. 4a) and some were located along the boundaries of the grains in the steel. No sulfides were present in the central region of the axial crack. The sulfur located at the center of the $\text{SBC}_{\text{axial}}$ defect was present in the form of eutectic sulfide inclusions. In the eutectic sections, the sulfide phase appeared as points less than 1 $\mu$m in diameter (Fig. 4b). As in specimen 1, specimen 2 also contained fine oxysulfide inclusions 3–4 $\mu$m in diameter (Fig. 4c). However, there were significantly fewer of these inclusions in specimen 2. Table 3 shows the results of spectral analysis of specimens 1 and 2 under a microscope.

x-Ray diffraction study of specimen 2 on the DRON-2.0 diffractometer showed that the steel did contain sulfides. Thus, examination of specimens 1 and 2 showed that different types of sulfide inclusions were precipitated in the central zone of the semifinished product. These two specimens differed from one another in the value of the ratio $[\text{Mn}]:[\text{S}]$. Specimen 2, with the lower ratio $[\text{Mn}]:[\text{S}] = 14.8$, contained complex sulfides $(\text{Mn, Fe})\text{S}$ and $(\text{Fe, Mn})\text{S}$ that were mainly of the eutectic (film) type. No sulfides were detected in specimen 2, which had the ratio $[\text{Mn}]:[\text{S}] = 17.7$. Sulfur was present in the steel of this specimen in the form of globular oxysulfide inclusions.

With an increase in casting speed, the value of $[\text{Mn}]:[\text{S}]$ will have more of an effect on crack formation [4]. Thus, it is necessary to know precisely the casting speeds that are permissible for specific cross-sectional dimensions of the casting and specific designs of caster. Calculations performed for the radial section caster at the Chelyabinsk combine (caster radius 9 m) in the production of 100 $\times$ 100 mm squares of low-carbon steel showed that the ratio $[\text{Mn}]:[\text{S}]$ should be at least 22 and that the ingot should be withdrawn from the mold at a rate no greater than 5.2 m/min.

The macrostructure of all the finished products made of steels SAE1006 and SAE1008 satisfies the requirements for further hot deformation except when the products contain axial segregation bands and cracks $(\text{SBC}_{\text{axial}})$ rated at 2.5 points (the norm is no higher than 2.0). Some of the metallographic sections of steel SAE1006 contained this defect (see Fig. 2), which is caused either by significant compression of a semifinished product that still has a liquid core, bending of the semifinished product at high withdrawal speeds, or high casting temperatures. Another defect – convexity of the semifinished product – is associated with the formation of central cracks and an increase in $\text{SBC}_{\text{axial}}$ to more than 2.0 points. These cracks do not reach the surface of the semifinished product. To reduce the size of the $\text{SBC}_{\text{axial}}$ defect and lessen the probability of its formation, steelmakers use the same measures that are employed to alleviate convexity.

**Conclusions.** The Chelyabinsk combine has mastered the production of continuous-cast semifinished products made of low-carbon steels SAE1006 and SAE1008. These steels are cast in an open stream on a continuous section caster with molds 100 $\times$ 100 mm in cross section. To obtain quality semifinished products, the combine has made corrections to the parameters used for making and casting the steel.

In examining the reasons for the formation of defects on semifinished products made of low-carbon steel, we sought to theoretically substantiate the processes which take place in the production of continuous-cast semifinished products – from the steelmaking operation to crystallization of the semifinished product. We used scanning electron microscopy and x-ray phase analysis to study sulfide inclusions in low-carbon cast steel with values of 14.8 and 17.7 for the ratio $[\text{Mn}]:[\text{S}]$.

The quality of the low-carbon steel semifinished products obtained on the caster is influenced by the following factors: secondary aluminum is used in the amount 1.2 kg/ton to deoxidize the steel during tapping, the aluminum being added
to the ladle before the ferroalloys; the value of the ratio $[\text{Mn}]:[\text{S}]$ in the finished steel is at least 22, and the value of the ratio $[\text{Mn}]:[\text{Si}]$ is at least 2.5; casting speed is no greater than 5.2 m/min and the maximum pressure exerted by withdrawing rollers on the $100 \times 100$ mm semifinished product is 35 ton-f.

**REFERENCES**