The Electroslag Remelting of High-Speed Steel Using a Magnetic Field

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The electroslag remelting process was studied when the consumable electrode made from the powder of M2 type high-speed steel was used and the effect of outside magnetic field was applied. The electromagnetic forces that arise from the interaction between the outside direct magnetic field and the one-phase electric current of the electroslag remelting process by a monofilar scheme alter the mechanism of the electrode remelting and thus, affect the solidification of a high-speed steel and its structure. The cast cutting tips made from ingots produced by this technology had tool life to be comparable to that of standard ones made from the wrought steel of the identical chemical composition and heat treatment.

It has been shown that a magnetic field also affects both the temperature ranges and the kinetics of phase transformation in a high-speed steel. This suggestion is proved by DTA measurements.

KEY WORDS: electroslag remelting; magnetic field; powder electrode; remelting mechanism; high speed-steel; structure; fracture; phase transformation.

1. Introduction

The main feature of electroslag (ES) remelting process is a high metallurgical quality of the produced ingots, but they have a typical cast structure as a consequence of the dendritic way of solidification and segregation processes. The method when a magnetic field is used to affect the solidification process of alloys did well in the development of ES technologies. It is based on the generation of Lorentz forces by the interaction between an alternating electric current that passes through the column of the ES process unit and a direct magnetic field imposed from outside. The industrial application of this process, when the conventional cast or rolled consumable electrodes were used showed that the magnetic field application at the conventional ES process and initiated the presented research.

Taking the inheritability effect of raw materials on a structure and properties of the castings and the possibility to control the process of the electrode remelting using the Lorentz forces into consideration, the experiments with a consumable electrode made by sintering of the powder semiproduct on the density lower than 85%, thus with the open residual porosity, were done. The aim was to prove the assumption, that the consumable sintered powder electrode can be used in order to activate the formation of crystal nucleuses in the melt. Lorentz forces acting on a tip of this electrode that has its strength depending on the residual porosity can control the process of its melting-down in the form of fragments. These fragments contain a certain portion of the solid phase that remains partly also during the slag pool passage and is fully melted in the molten metal pool. Here, they cause the local undercooling and then, in these sites the formation of the nucleators begins, what results in the primary structure refinement of cast materials.

2. Method of Affecting a Solidification Process

The electroslag process by monofilar scheme with one-phase current gives many possibilities. In this case, the strong electric current passes through a column of the ES process unit that includes a consumable electrode, a slag pool, a metal pool and an ingot. Due to the low heat conductivity of the slag, the strong cooling effect of the crystallizer’s water-cooled copper walls leads to the formation of a thin skin of the slag lining. For this reason the column is electrically insulated by a skin of the slag lining from the
generated Lorentz forces and their influence on the melt and the solidification zone into consideration, we can continue referring to the condition illustrated in Fig. 1.

On the molten metal volume element of $dx$, $dy$ and $dz$ dimensions, which is carrying the electric current of the mean current density $J$, the force $dF$ acts. Its intensity, according to Eq. (1) and under static conditions, is:

$$dF = J \times B$$ .........................................(2)

Following the arrangement in Fig. 1, we can, with a proper prediction, consider that the vectors $J$ and $B$ are perpendicular to each other and they have the components $J$ and $B$ with following coordinates: $J(0, 0, J_z)$ and $B(0, B_z, 0)$.

According to Eq. (2), the component $dF_z$ of Lorentz force produces the pressure on the volume element front:

$$dp_z = \frac{dF_z}{dydz} = J_z B_z dx$$ .........................................(3)

From Eq. (3) it follows that the total pressure value depends on the ingot dimensions in the $x$ axis direction and on the diameter $b$ for the circular section of the crystallizer. Because the method supposes the control of the ES process by the alternating current of a $50$ Hz system with the sinusoidal behavior, the pulsating pressure will be acting in the molten metal volume in the $x$ direction and its instantaneous intensity will change with the time according to equation:

$$P_z = \int_0^b J_z B_z dx \sin \omega t + p_0 = J_z B_z b \sin \omega t + p_0$$ .........................................(4)

In this case, the constant of integration $p_0$ is the sum of the atmospheric pressure and the pressure of the column of the slag and molten steel. The highest values of the pressure attained at the peak values of electric current under the real electroslag process parameters and the intensities of a magnetic flux density are in the range from $2$ to $3$ kPa. The pressure, having the amplitude varying periodically between maximum values with negative and positive orientation, transmits through the molten metal pool into the solidification zone where it favorably affects the macrostructure formation. The pulsating pressure propagating in molten metal in all directions improves the ingot contouring in the crystallizer and decreases probability of the internal defect incidence in the ingot.

In the metal pool and solidification zone, there are commonly occurring objects and some volumes with different electric conductivity in comparison to their surrounding. They are, e.g. the growing dendrites, nonmetallic inclusions, gases, the phase boundaries, the zones of molten metal with the higher concentration of alloying and other elements etc. The density of the electric current, passing through them, is directly proportional to their electric conductivity. In Eq. (2) the vector $J$ can be substituted by the relation $J = \sigma E$ expressing the dependence of the electric current density on the electric conductivity (and the electric field intensity $E$). If the objects have small dimensions, we can regard the magnetic field as homogeneous, and then, in two adjacent volume elements of the melt with the different electric conductivity $\sigma$ and $\sigma_1$ the forces $dF$ and $dF_1$ of the

3. Phenomena Caused by the Magnetic Field Application

The presence of the magnetic field during the ES process affects the character of solidification directly or indirectly. The Lorentz forces, acting on the consumable electrode tip, cause its vibrations in the slag pool and thus, improve the heat transfer between the slag and surface of a melting electrode tip. Simultaneously, Lorentz forces accelerate the tearing and conveying of the molten metal drops into the slag. Such intervention into the thermal balance and the character of the material conveying explains the perceivable acceleration of the ingot formation process despite the same volume of generated heat.\(^5,8\) Taking the character of internal walls of the crystallizer. The electric conductivity of the solidified slag is low and thus, negligible regarding to the voltage and electric current of the ES process. Because of this, we can take the column in the crystallizer as a conductor carrying the electric current of the definite orientation, as a rule, in the direction of the crystallizer’s geometric axis. To produce the electromagnetic—Lorentz—forces in those parts of the column where the effect on the melting process and the primary structure formation is expected, exposing these parts to enough strong magnetic field with the force lines directed perpendicularly to the crystallizer axis is necessary, as it is shown in Fig. 1. To avoid the magnetic screening of the working space by the crystallizer shell, the copper crystallizer was used.

The intensity of Lorentz forces $f$ (force per unit of volume) acting on the conductor that is carrying the electric current of the density $J$ and is exposed to the action of a magnetic field of magnetic flux density $B$, is given by relation:

$$f = (J \times B)$$ .........................................(1)

From Eq. (1) follows that the spatial orientation of the force is given by the result of the vector product $(\mathbf{F} \times \mathbf{B})$, which represents the force intensity per $1 \text{ m}^3$ of the conductor. The distribution of generated forces depends on the time behavior of the variables $J$ and $B$ and their correlation. Since the method supposes the application of a direct magnetic field and the alternating electric current of the ES process, the generated forces alter their amplitude and orientation corresponding with the time behavior of electric current and therefore, the forces have the character of vibrations.

\[ \text{Fig. 1. Unit lay-out and the principle of Lorentz force generation: 1- water-cooled copper crystallizer, 2- electromagnet, 3- metal pool, 4- consumable electrode, 5- slag pool, 6- ingot} \]

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different intensities are acting. If we neglect the influence of the elements themselves on the homogeneity of the electric field distribution, the intensity of differential force acting between both elements is:

\[ dF = dF_i = dxdyz (\sigma - \sigma_j)(E \times B) \] ........................(5)

The metal pool with the solidification zone is not a compact conductor, but electrically, it is a complex of large quantity of free moveable elementary conductors with the different electric conductivity. As a result, in the metal pool there is non-uniform distribution of the current density and intensity of generated Lorentz forces in the whole affected volume. These forces do not exert on the molten metal pool as the whole, but they are distributed into the zones where microvolumes or objects with the different electric conductivity in comparison to their surrounding are in contact. Considering, the forming solid phase has the electric conductivity from 2 to 4 times higher than surrounding molten metal, it is therefore clear that Lorentz forces are the agents that can effectively interfere in the process of primary structure formation affecting the volume fraction, morphology and distribution of structure constituents. 4–8)

4. Experimental Technique

Experiments were done with the powder atomized by nitrogen into the water. It was used without any pretreatment and its chemical composition was corresponding to the M2 type high-speed steel. The granulometric composition of the powder is given in Table 1.

The chemical composition of the material, before (in the electrode) and after remelting (in the ingot), is given in Table 2.

The electrodes were made from the powder poured into the thin-walled corundum tubes of the diameter 20 mm and the length of 300 mm and then, sintered on density of 60–85% in the vacuum furnace for 5 h at the temperature ranging from 1 223 to 1 423 K. After sintering and cooling, the electrodes were welded by resistance welding into the compact conductor, but electrically, it is a complex of large microvolumes or objects with the different electric conductivity. As a result, in the metal pool there is non-uniform distribution of the current density and intensity of generated Lorentz forces in the whole affected volume. These forces do not exert on the molten metal pool as the whole, but they are distributed into the zones where microvolumes or objects with the different electric conductivity in comparison to their surrounding are in contact. Considering, the forming solid phase has the electric conductivity from 2 to 4 times higher than surrounding molten metal, it is therefore clear that Lorentz forces are the agents that can effectively interfere in the process of primary structure formation affecting the volume fraction, morphology and distribution of structure constituents. 4–8)

For the classical ES process, the main feature of the melting mechanism is the high superheating of metal by the molten slag, whose temperature is usually 423–473 K higher than the temperature of electrode metal melting. 1) resulting in the relatively low cooling speed during solidification. For this reason a strong segregation of alloying elements occurs and results in the coarse cast structure. In particular, for conventionally remelted high-speed steels (the compact electrode, B=0 T) the total volume fraction of the eutectic structures is 28%. As a consequence, eutectic carbides form a continual network, which lies at the primary grain boundaries, Fig. 2(a). The average grain size of the matrix is 42 μm.

A eutectic network is known to have a significant influence on the path of fracture and hence on the effective fracture surface energy. 12) Indeed, in the present case the pre-

Table 1. Granulometric composition of the powder.

<table>
<thead>
<tr>
<th>Mesh (mm)</th>
<th>1.5</th>
<th>0.7</th>
<th>0.315</th>
<th>0.16</th>
<th>0.063</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction (%)</td>
<td>1.5</td>
<td>15</td>
<td>39.5</td>
<td>54</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Chemical composition of material. (mass%)
cipitation of eutectic carbides leads to a brittle intergranular fracture of the cast high-speed steel, Fig. 3(a). Observation of the corresponding fracture surfaces confirms that the crack travels over a major portion of its length through the eutectic carbides. Figure 3(b) shows that in this case the fracture surfaces are covered with grain boundary facets with the morphology coinciding with morphology and size of carbides in the lamellar and rod-like (Fig. 2(b)) eutectics. In consequence of such fracture behavior the toughness of the high-speed steel remelted by conventional ES process is only 4 J/cm².

The substitution of the compact electrode with a sintered powder one did not result in a positive effect for the high-speed steel at remelting without magnetic field. The peripheral parts of ingots were depreciated by porosity and in their center, the pronounced zone with typical coarse cast structure was observed. But in general, the structure was distinct finer, however, with the continual skeleton of eutectic carbides.

The magnetic field applied during ES remelting of the conventional compact electrode caused only the light positive changes in the structure. From the shape of the electrode tip, one could judge that such process did not alter the dropping mechanism of material conveying from the consumable electrode through a slag pool to a metal pool to be conventional for classical ES remelting.

Another mechanism was observed in the sintered powder electrode with the density from 60 to 85% remelted with the application of a magnetic field. The reason for this seems to be that the volume of contact heating is higher in the case of a sintered powder electrode resulting in the local melting of the powder granular boundaries in the whole volume of electrode tip from which entire fragments are torn off under the action of Lorentz forces. As a result the shape of the consumable electrode tip was quite different in comparison with classical electroslag remelting that was illustrated in the previous paper of the authors.

This way of metal conveying from the consumable sintered powder electrode into the metal pool increases the rate of remelting that is of great importance for the practice of ES remelting. Then the process, due to the decrease of temperature in the melt pool and the shorter period of metal being in a molten state, suppresses the arising of segregation phenomena. Last but not least it seems to be that such remelting mechanism makes it possible to keep the effect of inheritability of raw materials in the melt. The powder particles, which are in the solid–liquid state being entered into

![Fig. 2. Optical (a) and scanning (b, c) electron micrographs of the cast M2 high-speed steel remelted (a, b) in the absence of a magnetic field using conventional electrode and (c) in a magnetic field ($B=0.1$ T) using powder electrode.](image1)

![Fig. 3. Scanning electron fracturegraphs of the cast M2 high-speed steel remelted (a, b) in the absence of a magnetic field using conventional electrode and (c) in a magnetic field ($B=0.1$ T) using powder electrode.](image2)
metal pool, function as nucleators for ferrite and produce inoculating effect in the steel. The metallographic investigations have confirmed these assumptions.

After remelting of a sintered powder electrode under the magnetic field action of induction 0.1 T (limited by the electrode strength), the macrostructure of the whole ingot cross-section consisted only of crystallites which average size (29 μm) was comparable with the dimension of the smallest original powder particles (Table 1). Due to the strong refinement of equiaxed grain matrix the total volume fraction of eutectic decreased from 28 to 19%. As a consequence the smaller eutectic colonies with considerably finer eutectic carbides formed in the high-speed steel at the primary grain boundaries, Fig. 2(c). Studies of a fracture surface of Charpy impact samples of the cast high-speed steel showed that after remelting of the sintered powder electrode under the action of a magnetic field the above mentioned structural changes were accompanied by a transition from the intergranular fracture to transgranular one. Figure 3(c) represents a typical fracture surface appearance when the crack has propagated to a major extent transgranularly. The fracture properties of the high-speed steels correlate with the results of mechanical tests, according to which the toughness of high-speed steel increases up to 10 J/cm² what is higher than that of the high-speed steel remelted by the conventional process, 4 J/cm². Due to structural improvement the cast cutting tips had tool life (about 18 min) comparable to that of standard ones made from wrought steel of the identical chemical composition and heat treatment.

In order to make sure that the effect of inoculation in the steel is not due to the larger fraction of oxides in its structure, another ingots were also melted from the electrodes, which were made by the same way, but using the powder of higher quality with the fractions to be less than 160 μm and with oxygen content not exceeding 0.01 wt%. In the range of current between 700 and 800 A the structure refinement was found to be more pronounced. This effect can be only explained by the finer granulometry of the powder.

Our assumption that the magnetic field being applied to the high-speed steels during their solidification affects on the kinetics of phase transformation was proved by the results of DTA measurements. Figure 4 shows the DTA data on the kinetics of phase transformations in the high-speed steels. Solidification of the high-speed steel without the application of a magnetic field occurs as follows. Precipitation of ferrite starts at 1 641 K and finishes at 1 584 K. The peritectic reaction leading to the formation of austenite starts at 1 514 K and finishes, according to the corresponding DTA peak at 1 479 K. The eutectic reaction, completing the primary solidification, begins at 1 472 K. The reaction ferrite + liquid → austenite + carbide did not manifest itself as a separate reaction, but it may occur at the same time as the eutectic reaction.13)

The DTA curve obtained on the high-speed steel solidification in a magnetic field shows that the sequence of phase transformations is virtually unchanged. However, the starting temperatures of primary ferrite precipitation and peritectic reactions decrease; and these reactions occur in narrower temperature ranges, which indicates that they are intensified under the effect of the magnetic field. The temperature ranges of ferrite solidification and peritectic transformation decrease by 20 and 27 K, respectively, (Fig. 4).

An increase in the rate of solidification of ferrite and austenite (by peritectic reaction) in iron–carbon alloys, including high-speed steels, is accompanied by a redistribution of alloying elements between the liquid and solid phases participating in primary solidification.14,15) For this reason it is likely that the eutectic concentration of alloying elements in the melt of high-speed steel solidifying in a magnetic field is reached sooner and the solidification of the eutectic liquid begins earlier. This suggestion is indirectly confirmed by a distinct increase in the eutectic temperature under the effect of a magnetic field. A magnetic field applied during solidification also affects the character of the above phase transformations. In the absence of a magnetic field the solidification reactions follow each other smoothly, and the temperature decreases virtually without any stops in the entire temperature range. At the same time, the DTA curve of solidification in a magnetic field exhibits a distinct separation of the events of primary ferrite precipitation and the peritectic transformation of ferrite to austenite. This is shown by a small inflection in the DTA curve at 1 535–1 511 K. The release of latent heat in this range seems to be caused by the precipitation of either VC carbides directly from the melt or Fe3W3C carbides from the supersaturated by tungsten ferrite. A similar feature was observed between the reactions of primary ferrite solidification and allotropic transformation of ferrite to austenite in the study of the effect of a magnetic field on solidification of commercially pure iron.16) It was established that this specific “incubation period” preceding the α→γ transformation increases with increasing magnetic induction.12,16) Taking into account that, at high temperature, all phases participating in solidification are paramagnetic, we are unable explain the altered kinetics of phase transformations only by the direct effect of a magnetic field on the critical temperatures of these transformations. It is known that a magnetic field directly affects the thermodynamics, mechanism, and kinetics of phase transformations only during heat treatment of steel articles at temperatures near or below the Curie temperature.17,18) Therefore, we should primarily consider only an indirect effect of magnetic field. However, the observed decrease in the starting temperatures
of primary ferrite solidification and peritectic transformation and increase in the rate of these reactions may be associated with changes in the thermophysical conditions of solidification under the effect of a direct magnetic field. It is likely that the changes in solidification conditions under the effect of a magnetic field also cause the redistribution of ferrite and austenite stabilizers between the liquid and solid phases. This redistribution may be the main cause of the change in the kinetics of phase transformations in steels. This suggestion is confirmed by the differences in the structure and properties of the same high-speed steel solidified with or without the application of a magnetic field.

The steel solidified in a magnetic field has a refined grain structure (the average grain size of 26 μm vs. 44 μm in the case of the absence of a magnetic field) and a finer and more distinct network of the eutectic carbides at the boundaries of the primary grains. Both the eutectic colonies and the carbides that form these colonies are refined in this structure (Fig. 5). The positive effect of the treatment in a magnetic field at the stage of the primary solidification is also proved by the fact that this treatment increases the impact toughness of a completely heat-treated high-speed steel from 9 to 13 J/cm².

It has been found that the density of the consumable electrode is a very important technological parameter of the process. The lower the density of the sintered powder electrode, the faster its melting-down. On the other hand, the drop of electrode density causes the increase in its electrical resistance and thus, its overheating. As a result a decrease of mechanical strength, thermoplastic deformation or even failure of the electrode can occur during remelting. From this viewpoint, the lowest electrode density applied was restricted to 65% of theoretical one. On the other hand it was also experimentally proved that if the electrode density was over 80%, the effect of a magnetic field decreased and coarse structure was formed in the ingot.

As it follows from the analysis of the action of Lorentz forces in the ES process’s column, they provoke two basic mechanisms. The first one is the presence of the vibrations in the whole column’s volume as it is formulated by Eq. (4), and the second one is the character of the action of generated forces in the solidifying molten metal that is the media with the nonuniform electrical conductivity, where the dependence of the force’s intensity on the electrical conductivity is formulated by Eq. (5). These mechanisms participate additively in the control of the ES process and in the formation of the structures. The main role can be attributed to the control of the melting-down process of the sintered powder electrode in the fragments that initiate the formation of the big quantity of the nucleators in the molten metal pool after the slag pool passage and so they share in the grain refinement decisively. The Lorentz force’s action on the crystallization front and the presence of the vibrations in the solidifying molten metal volume allow to explain the elimination of the ingot’s porosity.

The mathematical analysis of the mechanism of the Lorentz force’s action in molten metal and the results of the metallography tests showed that the achieved structural improvement cannot only be explained by the mechanical effect caused by these electromagnetic forces but also by the inheritability effect of the raw material of the sintered powder electrode, and the magnetic field’s effect on the kinetics of the primary crystallization’s phase transformation. The magnetic field alone, taken so far for a substance being only necessary to produce the Lorentz forces, is another factor actively interfering into the solidification process. It shifts the phase transformation’s temperatures of the primary crystallization of the steels towards the lower values and affects their kinetics entirely by interfering in the thermodynamic conditions of the solidification. According to DTA measurements the increase in the undercooling and the avalanche course of the primary crystallization’s phase transformations indicate the recalescence and the intensification of the phase transformations, which are the phenomena observed in the molten metal solidifying after the metallurgical processing by the modification.

6. Conclusions

To refine the cast structure of a high-speed steel to be produced by ES process the sintered powder electrode was remelted with the application of a magnetic field. Then, the effects of Lorentz forces generated by the interaction of electric current passing through the column of ES process unit and a magnetic field imposed from outside were studied through mathematical analysis, metallography, fracture and mechanical tests. The effect of a magnetic field on the kinetics of phase transformations in the high-speed steel during primary solidification was also studied by the method of differential thermal analysis. As a result, the following findings were obtained.

(1) Based on the mathematical analysis of the magnetic field application during ES remelting, it is estimated that Lorentz forces are the agents, which can effectively interfere in the mechanism of electrode remelting and metal solidification.
If the sintered powder electrode is remelted under the magnetic field action of induction of 0.1 T the Lorentz forces alter the mechanism of the electrode remelting and thus affect the process of primary structure formation of a high speed-steel which has a refined equiaxed grain matrix and smaller eutectic colonies with considerably finer eutectic carbides.

The structural improvement led to a transition from the intergranular fracture to transgranular one. The fracture properties of the high-speed steels correlate with results of the mechanical tests. The toughness of the high speed-steel remelted by the electroslag process using a sintered powder electrode and a magnetic field is 10 J/cm² which is higher than that of the high speed-steel remelted by conventional process, 4 J/cm².

The cast cutting tips made by new technology had tool life comparable to that of standard ones made from wrought steel of the identical chemical composition and heat treatment.

Differential thermal analysis showed that the magnetic field also affected both the temperature ranges and the kinetics of phase transformations in the high speed-steel. To summarize, the magnetic field can take for a factor, which is able to make the changes of the thermodynamic conditions of the steel solidification possible.

The presented technology invokes the complex of the mechanisms, such as the presence of the vibrations, the inheritability effect of the material of the consumable sintered powder electrode, the mechanical effect of Lorentz force in the solidification zone, and the effect of the magnetic field alone on the solidification’s character, which additively take part in the resultant effect of improving in the properties of the ES remelting steels.

REFERENCES


4) M. Murgas and M. Pokusová: Zvařování, 41 (1992), No. 4, 73.


16) M. Murgas and A. Biacovská: Chemical Papers, 45 (1991), No. 6, 731.


