Секція: НОВІ МЕТОДИ ЗВАРЮВАННЯ, НАПЛАВЛЕННЯ, НАПИЛЕННЯ

УДК 621.326

Viktor Shapovalov, Kostiantyn Zlyhoriev, Vitalii Porokhonko, Farit Biktagirov, Volodymyr Barabash, Oleksandr Hnatushenko, Anatolii Ihnatov
E.O. Paton Electric Welding Institute of the NASU, Ukraine

EFFECT OF METAL BATH STIRRING INTENSITY ON STEEL INGOTS CONTAMINATION WITH SLAG INCLUSIONS

Abstract. For the conditions of producing steel ingots using a combined external influence in the form of electroslag heating and stirring of the metal (ESHS), it has been determined that, in order to prevent contamination of the metal with slag inclusions, the specific stirring power should not exceed $50*10^{-3}$ W/kg.
Keywords: steel ingot, heating and stirring of metal, stirring power, slag inclusions.

In many industries, such as nuclear power engineering, heavy machinery manufacturing, shipbuilding, and the chemical industry, large forgings are required for the production of critical large-scale components and mechanisms. These forgings are produced from ingots weighing tens to hundreds of tons, and their quality determines the reliability and service life of the final products. With the exception of specialized production methods, ingots are manufactured by pouring molten steel into molds. The prolonged solidification of large volumes of liquid metal is accompanied by the formation of various defects and inhomogeneities within the ingot body. To mitigate the causes of their formation, it is necessary to apply technologies that enable active control over the processes occurring during the transition of metal from the liquid to the solid state.

Such approaches may include methods of external influence [1,2], in particular the method developed at the E.O. Paton Electric Welding Institute, which involves electroslag heating and stirring of the metal (ESHS) during ingot formation [3]. According to this method, the schematic diagram of which is shown in Fig. 1, heating is achieved by Joule heat released during the passage of electric current through the slag layer, while stirring is performed by argon purging of the molten metal bath using a lance immersed into the liquid core of the ingot.

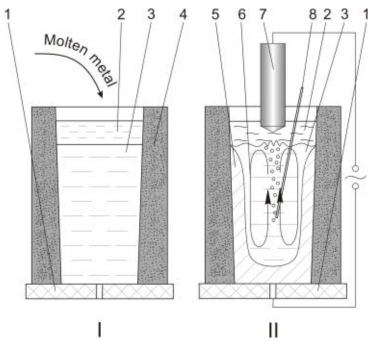


Fig. 1. Schematic diagram of ingot production by the ESHS method.
I - pouring of liquid metal into the casting mold;
II - heating and stirring of the metal:
1 - bottom plate; 2 - molten slag;
3 - molten metal; 4 - sand-clay mold;
5 - solid metal; 6 - direction of metal stirring;
7 - non-consumable electrode; 8 - lance.

The conducted studies using physical and mathematical modeling, as well as experiments on real steel ingots, have shown that this method makes it possible to significantly improve the homogeneity of cast billets [4].

One of the main technological parameters determining the efficiency of ingot production by the electroslag heating and stirring (ESHS) method is the intensity of metal stirring, which primarily depends on the gas flow rate used for purging. The effect of gas purging on the stirring intensity of the molten metal bath is commonly evaluated by such a parameter as the specific stirring power, i.e., the ratio of the stirring power to the mass of the treated metal [5]. The stirring power can be calculated using the formula presented in [6].

$$N = n^{'}RT \ln\left[\frac{\rho_2 + \rho' g H}{\rho_2}\right],$$

where N - stirring power, W; n' - gas molar flow rate, kmol/s; $n^{'} = \frac{V}{60} \cdot 22{,}4$; R - universal gas constant, J/(kmol·K); T - temperature, K; P_2 - atmospheric pressure, Pa; ρ' - density of the molten metal, kg/m³; g - acceleration due to gravity, m/s²; H - immersion depth of the lance in the metal, m; V - gas flow rate for purging, m³/min.

Experiments aimed at evaluating the stirring power during electroslag heating and stirring (ESHS) were carried out during the casting of two ingots of CT80 steel into sand-clay molds. The ingots had a diameter of 180-220 mm, a height of 450-500 mm, and a mass of 120-130 kg. The temperature of the slag bath (analogue of Wacker ESR2063 slag) with a thickness of 50-60 mm was maintained at 1550-1600 °C. The purging device (lance) was immersed to a depth of two-thirds of the calculated depth of the molten metal bath.

The maximum possible stirring intensity was selected based on the condition that gas purging should not cause excessive agitation of the slag bath in the gas exit zone or exposure of the metal surface, in order to prevent interaction of the steel with air. Preliminary experiments showed that, under the given experimental conditions, such requirements were satisfied 5 minutes after filling the mold with molten metal at an argon flow rate of less than 10 L/min. Therefore, during the production of the first ingot, in the first purging cycle, as shown in the data presented in the table, the argon flow rate was intentionally kept below this permissible value. The table also presents data on purging parameters and the specific stirring power, which was determined as the ratio of the stirring power (calculated using the above-mentioned formula) to the mass of the molten metal bath at the start of purging. The volume of the bath was estimated with a sufficiently high degree of accuracy by calculation, taking into account the results of macrostructural analysis and a Baumann sulfur print of a longitudinal axial template of the ingot (Fig. 2), where the position of the molten metal bath - along the boundary between its liquid and solid regions - is clearly distinguished in the form of light lines.

Table

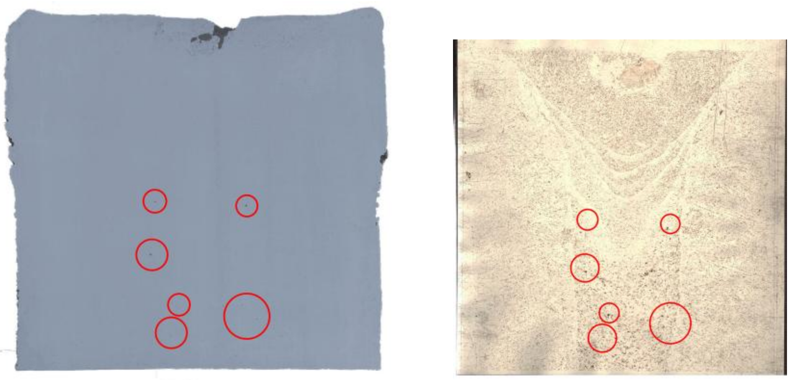
Stirring regimes of molten metal during casting of experimental CT80 steel ingots

Ingot №	Stirring cycle	Start time, min	Argon flow rate, L/min	Purging duration, s	Immersion depth, cm	Specific stirring power, 10^{-3} W/kg
1	1	10	8,5	30	35	67,1
	2	15	6,5	30	27	68,4
	3	21	5,5	40	20	49, 8
	4	27	4,5	40	15	44,4
	5	33	4,0	30	15	39,9
2	1	8	6,5	30	34	39,9
	2	17	5,5	40	25	37,2
	3	25	4,5	40	15	46,3
	4	32	4,0	30	14	39,1

In the investigated ingot, due to the application of heating and stirring, no pronounced defects of the internal structure were observed. In particular, no shrinkage cavity was present, and neither axial looseness nor porosity was revealed after etching. However, despite the absence of shrinkage defects, slag inclusions were detected in the upper part of the first experimental CT80 steel ingot. They are especially clearly visible on the polished surface of the template prior to etching for macrostructural examination (Fig. 3a). Highlighting their locations on the Bauman print (Fig. 2b) clearly shows that they are mainly located on or near the boundary of the molten metal bath that existed during the first and second stirring cycles.

a b

Fig. 2. Baumann sulfur print (a) and macrostructure (b) of the upper part of the longitudinal axial template of CT80 steel ingot No. 1.



a b

Fig. 3. Appearance and distribution of slag inclusions on the polished surface of the upper part of the first experimental CT80 steel ingot template (a), and their locations on the sulfur print (b).

In our opinion, the primary cause of slag inclusions entering the ingot is associated with two factors. The first is the high argon flow rate during the first two stirring cycles, which leads to the formation of intense metal flows at the slag-metal interface. This increases the tendency for slag particle detachment from the slag bath and their entrainment into the ingot. The second factor is the presence of a relatively small-diameter molten metal bath, which, as clearly seen from the sulfur print, approximately corresponds to the boundary between the solid and liquid phases. This is due not only by the heat removal conditions but also by the fact that CT80 steel has a wider solidification interval and a more extended two-phase (mushy) zone. As a result, during the production of the first experimental CT80 steel ingot, a relatively high argon flow rate was applied to a comparatively small volume of the liquid portion of the ingot. This led to the entrainment of some liquid slag particles by downward metal flows into the two-phase zone, where they became trapped in the more viscous semi-solid metallic melt.

Based on the above, to prevent contamination by exogenous slag inclusions during the production of the second CT80 steel ingot, the argon flow rate in the first stirring cycle was reduced to 6.5 L/min, and purging was initiated 8 minutes after pouring instead of 10 minutes (see Table).

As the study of the second CT80 steel ingot showed, no exogenous slag inclusions were detected in it (Fig. 4).

Fig. 4. Polished surface of the specimen taken from the upper part of the second experimental CT80 steel ingot.

Based on the analysis of the above data, it can be concluded that, under the conditions of producing CT80 steel ingots with electroslag heating (AN-295 slag at a temperature of 1550-1600 °C) and metal stirring by gas purging, the specific stirring power should not exceed 50 * 10^{-3} W/kg in order to prevent contamination of the metal by exogenous slag inclusions.

It should be noted that, according to the data reported in [5], during steel treatment at an ASEA-SKF unit in a 50-ton ladle, where metal stirring is performed by argon purging, the specific stirring power ranges from 50 to 500 * 10^{-3} W/kg. Under such processing conditions, there is no risk of slag entrainment into the metal with subsequent contamination by non-metallic inclusions. Moreover, such entrainment is even desirable for increasing the efficiency of slag refining of the metal. Most likely, it is at a specific stirring power of about 50 * 10^{-3} W/kg that the covering slag begins to be entrained into the molten metal bath, thereby facilitating the removal of impurities. Therefore, it may be assumed that the upper limit of stirring power determined in this study for gas purging of the liquid core of an ingot is applicable not only to relatively small ingots but also to multi-ton ingots.

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