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Оригинальная статья

ON THE ISSUE OF METAL REFINING AT ESR

I. V. Chumanov

Zlatoust Branch of the South Ural State University (16 Turgeneva Str., Zlatoust, Chelyabinsk Region 456209, Russian Federation)

chumanoviv@susu.ru

Abstract. The author examines the key mechanisms for the removal of non-metallic inclusions during electroslag remelting (ESR) emphasizing the importance of three reaction zones: a liquid film at the end of the electrode, droplets of electrode metal, and a liquid bath in the mold. The analysis is based on the application of the Stokes formula to estimate the rate of inclusions floating, where particle size plays a crucial role. The enlargement of inclusions contributes to their more efficient removal, while liquid inclusions float faster than solid ones due to their lower viscosity. An important factor is the shape of inclusions, which affects the rate of their removal, as well as convective flows in the metal contributing to the enlargement and removal of inclusions to the metal–slag interface. Experimental data demonstrate that the main refining occurs in the area of the liquid film at the end of the electrode, where up to 80 % of the inclusions turn into slag. Purification of metal droplets in slag is less effective, but its role increases with a decrease in droplet size and an increase in the time of interaction with the slag. The results confirm that a decrease in the melting rate of the electrode contributes to the formation of a thin film and improves the quality of the metal in terms of the content of non-metallic inclusions. It is noted that providing a metal bath that is not deep and uniform in height makes it possible to create an axial crystal structure and eliminates blocking the inclusions floating. The solution to this problem is based on the well-tested technology in the laboratory with rotating consumable electrode. The control of the centrifugal forces that arise in this case makes it possible to comprehensively solve the problem of reducing the concentration of non-metallic inclusions of 10 μm or less, while maintaining all the advantages of electroslag technology.

Keywords: refining, slag, melt, surface, non-metallic inclusions, inclusion size

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К ВОПРОСУ РАФИНИРОВАНИЯ МЕТАЛЛА ПРИ ЭШП

И. В. Чуманов

Южно-Уральский государственный университет (национальный исследовательский университет), филиал в г. Златоуст (Россия, 456209, Челябинская обл., Златоуст, ул. Тургенева, 16)

chumanoviv@susu.ru

Аннотация. Автор рассматривает ключевые механизмы удаления неметаллических включений при электрошлаковом переплаве (ЭШП), подчеркивая важность трех реакционных зон: жидкой пленки на торце электрода, капель электродного металла и жидкой ванны в кристаллизаторе. Анализ основан на применении формулы Стокса для оценки скорости всплывания включений, где размер частиц играет решающую роль. Укрупнение включений способствует их более эффективному удалению, при этом жидкие включения всплывают быстрее твердых из-за меньшей вязкости. Важным фактором является форма включений, влияющая на скорость их удаления, а также конвективные потоки в металле, способствующие укрупнению и выведению включений к поверхности раздела металл–шлак. Экспериментальные данные демонстрируют, что основное рафинирование происходит в зоне жидкой пленки на торце электрода, где до 80 % включений переходит в шлак. Очищение капель металла в шлаке менее эффективно, но его роль возрастает при уменьшении размера капель и увеличении времени взаимодействия со шлаком. Результаты подтверждают, что снижение скорости плавления электрода способствует образованию тонкой пленки и улучшению качества металла по содержанию неметаллических включений. Отмечено, что обеспечение неглубокой, равномерной по высоте металлической ванны позволяет создать осевую кристаллическую структуру и исключает блокирование всплывания включений. Решение рассматриваемой задачи основано на хорошо апробированной в лабораторных условиях технологии с вращением расходоуемого электрода. Управление возникающими в этом случае центробежными силами позволяет комплексно решать задачу снижения концентрации неметаллических включений размером 10 мкм и менее, при этом сохраняя все преимущества электрошлаковой технологии.

Ключевые слова: рафинирование, шлак, расплав, поверхность, неметаллические включения, размер включений

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INTRODUCTION

Electroslag remelting (ESR) is a metallurgical process with a pronounced refining effect. The large interfacial area between liquid slag (flux) and molten metal, together with intense mixing, promotes reactions in the slag–metal system. With an appropriate choice of slag composition, electrical parameters, and external effects, the nature and direction of metallurgical reactions can be controlled. For this reason, in the early stages of its development, ESR was regarded primarily as a refining process. As ESR technology advanced, considerable attention was also paid to producing a sound crystal structure and increasing ingot density; however, refining the metal from harmful impurities during remelting remained the main priority [1; 2]. This approach led to numerous studies aimed at improving the chemical cleanliness of electroslag metal. As a result, various flux compositions were developed [3 – 5] to provide the maximum refining effect for different classes of remelted steels. Practice has shown that ESR is most effective in desulfurization and oxygen removal. At the same time, because it is a high-temperature process, it is relatively ineffective in removing phosphorus and high-vapor-pressure impurities, including low-melting elements, which pose a serious risk to high-strength structural steels.

Throughout the history of ESR, various techniques have been attempted to remove hydrogen and, to some extent, tested to remove hydrogen and, to some extent, nitrogen from the metal. These include purging the melt with inert gases and gas–powder mixtures, as well as using different electrical power supply schemes [6; 7 – 10]. The former approaches drew on extensive experience in injection metallurgy, whereas the latter relied on experience from electrochemical production. Nevertheless, the expected results were not fully achieved. In addition, in the conventional process, a substantial proportion of sulfur is known to be removed into the open gas phase, i.e., the atmosphere, as SO_2 [11]. When a protective gas is used in the mold chamber, this process becomes more difficult. Therefore, given the metallurgical production capabilities available at that time, ESR was concluded not to be an active degassing process for hydrogen and nitrogen.

It is becoming increasingly clear that further improvement in the quality of electroslag metal should primarily be achieved by substantially reducing the concentration of non-metallic inclusions, especially those smaller than 10 μm . At the same time, it is necessary to ensure

a uniform distribution of inclusions across the ingot section while preserving a directional columnar crystal structure, structural homogeneity, microcleanliness, isotropic mechanical properties, and high ingot density. These requirements must be met while reducing energy consumption and without compromising the productivity of electroslag metal production. It should be noted that the refining effect of the electroslag process is greater when the initial metal contains more impurities; in this case, the degree of metal refining increases.

MATERIALS AND METHODS

The electroslag process involves remelting consumable electrodes, droplet transfer of electrode metal, and sequential solidification in a water-cooled mold. Gradual melting of the electrode in the refining medium, i.e., slag, involves three interaction interfaces. During electrode melting, a liquid metal film forms at the consumable electrode tip, where it actively interacts with the refining phase. This liquid metal film, which flows down the melting surface of the electrode, is the first reaction zone and largely determines the removal of various impurities. This zone is characterized by a high impurity concentration, a large interfacial area, low metal superheat above the melting point, a flow pattern close to laminar flow, and a short reaction time with the refining phase. The second reaction zone is represented by the droplet, or droplets in the case of a large-diameter electrode with several droplet-formation cones, passing through the layer of refining slag. The third reaction zone is the liquid metal bath in the mold, which is characterized by a longer interaction time with the refining phase, significant superheating of the metal surface, and more intensive melt mixing. Thus, conventional ESR includes two main reaction zones: a low-temperature zone at the electrode tip and a high-temperature zone in the bath. This should be taken into account when considering chemical reactions. Unlike conventional metallurgical units and processes, melting and solidification of the entire metal volume do not occur simultaneously but proceed sequentially in each reaction zone. This sequence ensures high refining efficiency and high ingot quality [12]. Each zone is an open reaction system, in which liquid metal enters and leaves the zone simultaneously while heterogeneous reactions occur between the metal and the refining medium.

At each interface, the remelted metal can be refined from non-metallic inclusions. However, the degree of refining differs between interfaces. For example,

the highest degree of refining is achieved at the liquid metal film–slag interface on the melting surface of the electrode. To make full use of the refining potential of ESR, it is necessary to identify the rate-controlling stage of non-metallic inclusion removal and establish the mechanism by which inclusions are removed.

According to a number of researchers, non-metallic inclusion removal is determined primarily by their flotation in the liquid metal bath, since the density of most non-metallic inclusions is substantially lower than that of liquid steel. Stokes' law is commonly used for a quantitative assessment of the inclusion flotation rate [13]. According to Stokes' law, inclusion size has the greatest influence on the rate of inclusion removal. This is supported by the following considerations: within the temperature range typical of steelmaking processes, the viscosity of liquid metal changes by only 10 – 15 %, whereas the density difference between inclusions and liquid steel is 2 – 5 g/cm³. In contrast, the inclusion radius may vary from 0.0001 to 1.0 mm. This clearly indicates the importance of inclusion coarsening. The commonly used Stokes equation is applicable only to the removal of solid spherical inclusions. For liquid inclusions, an additional term must be introduced to account for their viscosity. It has been established that, at the same particle size, the flotation rate of a liquid inclusion is higher than that of a solid one. This is the basis for the use of complex deoxidizers in steelmaking: after their addition, low-melting inclusions are formed, since liquid particles have a much greater tendency to coalesce than solid particles. Therefore, it is desirable to form inclusions with a melting temperature lower than that of the remelted metal. To account for inclusion shape, a shape factor is introduced into the Stokes equation. For example, alumina inclusions float 4 – 8 times more slowly than silicate inclusions of the same size. This is due to the irregular, angular shape of alumina inclusions, whereas silicate inclusions are typically spherical.

Under electroslag remelting conditions, where the liquid metal bath exists for a relatively short time, inclusions larger than 10 µm can be removed by flotation. For inclusions larger than 100 µm, the controlling factor is no longer the flotation rate but melt turbulence. In general, convective flows in the liquid metal have a favorable effect on non-metallic inclusions removal. As the intensity of convective mixing increases, inclusions collide more frequently, which promotes particle coarsening and increases the probability that they will reach the metal–slag interface. It should be noted, however, that intensive bath mixing not associated with natural convection affects the removal of non-metallic inclusions and gases differently, although the gas-removal mechanism is largely similar to that of inclusion removal. Gas removal is facilitated, whereas non-metallic inclusions flotation may be impeded. In addition, efficient removal of gases

dissolved in the metal during ESR is promoted by their solubility in slag, which is almost an order of magnitude higher than in liquid metal. Therefore, concentration-driven diffusion involving rising gas bubbles may occur at the metal bath–slag interface.

The condition for spontaneous transfer of non-metallic inclusions reaching the metal–slag interface is expressed as follows:

$$(\sigma_{m-incl} - \sigma_{m-slag}) > \sigma_{slag-incl}, \quad (1)$$

where σ_{m-incl} is the interfacial tension at the metal–inclusion interface, J/m²; σ_{m-slag} is the interfacial tension at the metal–slag interface, J/m²; $\sigma_{slag-incl}$ is the interfacial tension at the slag–inclusion interface, J/m².

This condition is satisfied for most oxide systems. The degree of non-metallic inclusions removal by flotation during ESR is determined by two factors: the shape and depth of the metal bath and the difference between the solidification-front velocity and the inclusion flotation velocity. At a low bath shape factor, with a low mold filling ratio as a special case, crystals grow radially. Under these conditions, non-metallic inclusions, as well as gases, are likely to be captured by the arms of growing dendrites.

With axial solidification, flotation and removal of non-metallic inclusions and gases from the metal bath are more likely. Therefore, to maximize the removal of non-metallic inclusions from the metal, axial or radial–axial solidification should be promoted. However, directional axial solidification of the metal bath alone does not solve all problems; the crystal growth rate is also important. Therefore, the electroslag ingot build-up rate should be considered, since non-metallic inclusions removal is most effective at the lowest build-up rate. To some extent, this requirement constrains process productivity in favor of metal quality.

When using the Stokes equation, it should be taken into account that it does not include physicochemical interactions of inclusions either with one another or with liquid metal. These interactions substantially alter the actual mechanism of metal refining from non-metallic inclusions during ESR.

There is also a well-founded view that inclusion removal occurs primarily in electrode metal droplets. Early studies [14; 15] investigated the effect of metal droplet motion through slag on non-metallic inclusions removal, using ShKh15 and EI961 steel droplets in ANF-6 flux. It was established that the dependence of the degree of purification C_0/C where C_0 is the amount of inclusions in the initial metal and C is the amount of inclusions in the droplet after passing through the slag layer, on droplet size (r_d), inclusion size (δ_{incl}), and droplet path length (l_d) is described by Eq. (2) [16]:

$$\ln \frac{C_o}{C} = 3.4 \frac{\delta_{\text{incl}} l_d}{r_d^2}, \quad (2)$$

in other words, the smaller the droplets, the more effectively they are refined from inclusions. For example, after slag treatment, droplets weighing 0.12 g contained half as many inclusions as before treatment, whereas in droplets weighing 1 g, the inclusion content decreased by only 12 %. As the path length traveled by a droplet in slag increases, the degree of refining also increases. In addition, there is a clear relationship between droplet size and the inclusion content in the initial metal and in the metal after slag treatment. The larger and more numerous the inclusions in the initial metal, the more intensive the refining process.

As noted above, some non-metallic inclusions in steel have an irregular shape, such as ellipsoidal or parallelepiped-like particles, with one dimension exceeding another by a factor of 1.5 – 2.0. Owing to convective flows inside the droplet, inclusions rotate around their own axes and reach the metal–slag interface with their larger face. In addition, as a droplet moves through slag, the velocity of its surface layers is 3/2 times higher than the velocity of the droplet itself [16]. Taking these corrections into account gives a coefficient of 3.4 in Eq. (2).

During ESR, the radius of detached droplets is approximately 0.005 m. The path traveled by droplets in slag, equal to the distance from the tip of the consumable electrode cone to the surface of the liquid metal in the mold bath, is 0.10 – 0.12 m. Therefore, according to Eq. (2), for inclusions $3.6 \cdot 10^{-5}$ m in size, for example, and an initial non-metallic inclusions content of $C_o = 0.6 \cdot 10^{-2}$ %, the inclusion concentration decreases to $C = 0.57 \cdot 10^{-2}$ %, i.e., only slightly. It follows that the stage of metal refining from non-metallic inclusions associated with droplet movement in flux is not decisive. Nevertheless, its role increases with a substantial decrease. Nevertheless, its role increases substantially as droplet size decreases and residence time in slag increases, including under external effects.

RESULTS AND DISCUSSION

To clarify the contribution of each interface to inclusion removal, the following test was performed. During melting, droplets were collected from beneath the electrode using a thick-walled cup, and samples were taken from the metal bath. As a result of rapid solidification of the metal in the cup, all inclusions present in the liquid metal at the time of sampling were retained in the solidified metal. After melting, samples were cut from the ingot horizon corresponding to the liquid metal bath at the time of cup sampling. Their inclusion content was compared with that of the sample collected in the cup and with that of the droplet. The data are presented in the table. As can be seen from the results, the main inclusion removal occurs before the metal droplets enter the mold, namely from the liquid film at the electrode tip or from droplets at the initial moment after their detachment from the electrode. As shown above, inclusion removal from droplets during their movement through slag is insignificant. Therefore, it follows that the main interface responsible for inclusion removal is the liquid metal film at the electrode tip–slag interface. The authors of [17] recommend carrying out ESR at the lowest possible electrode melting rate, which ensures the formation of a liquid metal film of minimum thickness at the electrode tip. This is supported by the data reported in [18], which show that ESR of Kh16N15M36 stainless steel using ANF-1P flux produced cleaner metal with a lower non-metallic inclusions content than remelting with ANF-6 flux. This can be attributed to the lower ingot build-up rate, the thinner liquid metal film at the electrode tip, and the smaller size of liquid metal droplets when ANF-1P flux is used. Further research should focus on technology involving a rotating consumable electrode, which has been well tested under laboratory conditions [19; 20].

Thus, evaluation of the refining efficiency of ESR with respect to non-metallic inclusions showed that up to 80 % of inclusions are transferred to the slag from the surface of the liquid metal film at the electrode tip, whereas approximately 20 % are removed from electrode

Changes in the content of non-metallic inclusions at various stages of electroslag process

Изменение содержания неметаллических включений на различных стадиях электрошлакового процесса

Sampling site	Number of samples	Area occupied by non-metallic inclusions, μm^2 , by inclusion size, μm			
		10 – 25	3 – 10	1 – 3	Total
Electrode	4	560	730	1530	2820
Droplet	6	–	350	1050	1400
Bath	18	–	560	740	1300
Ingot	5	–	640	680	1320

metal droplets during their passage through the slag and by flotation from the liquid metal bath.

The efficiency of inclusion removal at this interface depends directly on inclusion size in the liquid metal film: the thinner the film, the more complete the refining, primarily for inclusions whose size is comparable to or exceeds the film thickness. The thickness of the liquid metal film on the melting surface of the electrode is not uniform; the film becomes thicker toward the axis of the consumable electrode.

CONCLUSIONS

The regions of the consumable electrode most contaminated with non-metallic inclusions are those subjected to the least favorable refining conditions. Therefore, it is necessary to reduce the thickness of the liquid metal film on the melting surface of the consumable electrode, especially in the areas with the highest contamination, without further decreasing the already low process productivity. The size of electrode metal droplets should also be reduced, their contact time with the working flux should be increased, and droplets should be prevented from entering the liquid bath along the ingot axis. Creating conditions for a shallow metal bath of uniform depth promotes the formation of an axial crystal structure and prevents obstruction of inclusion flotation. These conditions can be achieved using technology involving a rotating consumable electrode. Control of the resulting centrifugal forces makes it possible to comprehensively reduce the concentration of non-metallic inclusions of 10 μm or smaller while preserving all the advantages of ESR technology.

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Information about the Author

Ilya V. Chumanov, Dr. Sci. (Eng.), Prof., Head of the Chair "Technique and Technology of Materials Production", Zlatoust Branch of the South Ural State University

ORCID: 0000-0003-0433-1846

E-mail: chumanoviv@susu.ru

Сведения об авторе

Илья Валерьевич Чуманов, д.т.н., профессор, заведующий кафедрой «Техника и технологии производства материалов», Южно-Уральский государственный университет (национальный исследовательский университет), филиал в г. Златоуст

ORCID: 0000-0003-0433-1846

E-mail: chumanoviv@susu.ru

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