Visualization Study on the Droplet Evolution Behaviors in Electroslag Remelting Process by Superimposing a Transverse Static Magnetic Field

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(Received on October 21, 2015; accepted on November 13, 2015; J-STAGE Advance published date: January 14, 2016)

A transparent experimental model had been built to visualize the electroslag remelting (ESR) process. With the help of the transparent model, the evolution of the droplet happening at the tip of the consumable electrode was recorded clearly by a high-speed camera with the record frequency of 200 frames per second. Firstly, the physical simulations were done under different intensities of the transverse static magnetic field (TSMF) with a constant remelting current of 8 A. Then the experiments were carried out at different intensities of the remelting current with a constant TSMF of 0.7 T. The representative processes of the droplet evolution under different conditions were demonstrated. When the external TSMF was large enough, a special phenomenon was discovered: The liquid neck connecting the end of the electrode with the droplet would become longer, and then an inflated liquid bulge appeared in the middle of the liquid neck. After a short while, the liquid metal neck was smashed into a lot of smaller droplets by the strong electromagnetic vibration. The results under different conditions indicated that the smashing effect acting on the droplet neck would be improved with the enlarging of the external TSMF at the constant remelting current, but it got worse under the condition of a higher remelting current. The mechanism of the smashing effect was well discussed.

KEY WORDS: electroslag remelting; visualization model; static magnetic field; droplet evolution; electromagnetic vibration.

1. Introduction

High-quality ingots are required in critical application of some areas, such as aerospace, metallurgy, mining, engineering, electricity and so on with the rapid development of society. Electroslag remelting (ESR) process is a promising method for the production of high-quality ingots because non-metallic inclusions can be removed efficiently and sounder structure can be obtained during the fabrication of ingots.1–5) Thus, it is vitally necessary that ESR process is used during the refining process of the special alloys. Previous studies show that the non-metallic inclusions can be removed through the interface between metal and slag.6,7) The droplet evolution behavior becomes very important owing to its influence on the interface area. From a dynamic view, if the interface area becomes larger, the higher removal efficiency of the non-metallic inclusions will be obtained, which is beneficial for fabrication of high-quality ingots. So it is necessary to research the droplet evolution behavior at the end of the consumable electrode. In order to improve the contact area of metal/slag, the process named of Magnetic Field Control ESR (MFC-ESR)8–12) was taken into account as shown in Fig. 1.

It is well known that the ESR process cannot be observed and measured easily due to its hostile conditions of high temperature, strong electric current and thick wall of the water cooling mold. So some physical simulations and numerical simulations have been done to study the behaviors of the droplets during the ESR process. J. Campbell13) built a transparent model to simulate the ESR process. In his model, LiCl–KCl was used as molten slag and Pb, Zn, Al

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DOI: http://dx.doi.org/10.2355/isijinternational.ISIJINT-2015-581

Fig. 1. Schematic of magnetic controlled MFC-ESR.
and Cu bars were chosen as the consumable electrodes. The droplet evolution pictures provided by him were obscure and the droplet evolution process could not be observed detailedly because of the low photographic technology. Furthermore, the external magnetic field was not taken into account during his study. A. A. Troyansky et al.14 offered a simulated agents of ice (the electrode) and vegetable oil (the slag) with addition of kerosene for regulating the density and viscosity in his physical model. He clarified the particularities of the mechanism of the droplet transfer under ESR process, however electromagnetic field was not involved in the physical model. A. Kharicha et al.15,16 built a 3D VOF model to simulate the droplet formation during ESR process. Theirs numerical model predicted the electric and magnetic field distribution in function of the metallic distribution in the low electric conductivity slag. Q. Wang et al.17 developed a transient 3D finite-volume mathematical model. The temperature field, electromagnetic field, flow and solidification were taken into account. Their results showed that the falling metal droplets could lead to the oscillation of the slag/metal interface and bring the heat and momentum into the metal pool. A. Kharicha et al.18 also established a 3D magneto-hydrodynamic model to simulate the dripping process of droplets. They found that the superimposition of a transverse static magnetic field (TSMF) of 0.1 T could make the droplets become smaller, however the numerical model was conducted under the condition of the DC current. A comprehensive 3D numerical model was developed by X. H. Wang and Y. Li19 to predict the multi-physical phenomena for the industrial scale ESR process. Their results showed that the metal droplets fell in a discontinuous string under the tip of the electrode.

Most of the simulations20–25 are focused on the analysis of the electromagnetic field, temperature distribution, flow pattern and profile of the metal pool. Their researches make people know the ESR process better, and then the ESR process, superposing a TSMF during the ESR process, is believed to be a perfect way to decrease the average size of ingots.17,21,25 However, there are very few studies about the droplet evolution process under a TSMF. Additionally, it is difficult to clearly observe the droplet evolution process without the high-speed camera with a high record frequency. Obviously, if the droplets falling through the molten slag become smaller, the interface area between metal and slag will be increased and the removal efficiency of non-metallic inclusions can be expected to be improved. And the MFC-ESR process, superposing a TSMF during the ESR process, is believed to be a perfect way to decrease the average size of the droplets.

In the present work, a new physical simulative system has been proposed. Molten ZnCl₂ and zinc bar are used to serve as the molten slag and consumable electrode, and this physical simulative system is actually a kind of ESR process. Because the zinc bar is remelted from its tip by the Joule heat generated in the molten ZnCl₂. The physical theory of the experiment is the same as the industrial ESR process. Also this physical system can guarantee the observation of the droplet evolution process. The purpose of this paper is try to provide a new way to minish the average size of the droplets at the end of the consumable electrode by superposing a TSMF during the ESR process. So it is important to validate that the average size of the droplets can be minished by superposing a proper TSMF with a suitable remelting current. Two series of experiments have been done: one is to study the influence of different intensities of the TSMF on the droplet evolution behaviors, and the other is to research the impact of different strength of the remelting current with the TSMF of 0.7 T on the droplet evolution behaviors. A transient 3D numerical simulation had been performed to better illustrate the mechanism of the phenomenon which was found in this research.

2. Experimental Procedure

The study was carried out using the transparent model apparatus as shown in Fig. 2. To realize the visualization of the ESR process, transparent quarts glass tube with internal diameter of 0.031 m was chosen as the mold. Molten ZnCl₂ whose melting point was 548 K was used as the molten slag due to its physical characteristics of low electrical conductivity, fine liquidity and transparency. Zinc bar whose melting point was 692 K with diameter of 0.015 m was used as the consumable electrode. Although the size of the experimental device was small comparing with the industrial ESR furnace, the physical phenomena of the droplet evolution behaviors happening on one droplet were believed as the same with what happening on numerous droplets in the industrial ESR process. The used consumable electrode and slag in the experiments were all in AR grade. The quantity of molten slag was kept constant for each experiment. The concrete operating conditions are listed in Table 1. Experiments were done under different intensities of the TSMF and different strength of the remelting current. High-speed camera with the capture frequency of 200 frames per second was utilized to record the droplet evolution happening at the end of consumable electrode.

The ZnCl₂ powder was heated by a circular resistance

![Fig. 2. Experimental apparatus of the transparent model.](image)

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<th>Table 1. Operating conditions of the ESR.</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>Operating current, A</td>
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<tr>
<td>Current frequency, Hz</td>
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<td>Magnetic flux density, T</td>
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furnace surrounding the quarts glass tube. After ZnCl₂ was fully melted, the resistance furnace was turned off and lowered down. Then the consumable electrode was inserted in the molten ZnCl₂ at the depth about 0.01 m, and AC power supply was turned on so that the electric current passed through the consumable electrode and the molten slag pool. Large Joule heat would be generated by the remelting current for the high electrical resistivity of the molten ZnCl₂ and the temperature of the molten slag would be increased quickly. Then the electromagnet was turned on and adjusted to produce a TSMF with the required intensity. The feeding rate of the consumable electrode was manually controlled to keep the strength of the remelting current almost constant.

3. Results and Discussion

3.1. Droplet Evolution under Different Intensities of the TSMF

The experiments were done under different intensities (0 T, 0.1 T, 0.3 T, 0.5 T and 0.7 T) of the external TSMF with the constant strength of remelting current of 8 A. When no external magnetic field was applied during the ESR process, the Lorentz force generated by the induced magnetic field and the remelting current was very small, and it could be ignored in our experiments due to the small remelting current. While a large external TSMF was superimposed with the AC current, a forceful electromagnetic vibration \(F = J \times B\), where \(J\) is the current density and \(B\) is the magnetic field intensity, would be generated. The EMV is the Lorentz force whose amplitude and orientation is periodic changed corresponding with the time behavior of the AC current. Meanwhile, its action direction is perpendicular to the external TSMF and the current. The intensity of EMV effect is proportional to that of the current density or the external TSMF. Some mathematical analysis of the magnetic field application during ESR process has been done by M. Murgaš et al.\(^\text{10}\) The external TSMF can also generate the electromagnetic braking force\(^\text{30,32}\) which will also influence the evolution process of the droplets.

Figures 3 to 7 show the representative formation and detachment process of the droplet under the TSMF of 0, 0.1, 0.3, 0.5 and 0.7 T, respectively. In order to demonstrate the whole evolution process of the droplet better, the time when the droplet detached from the consumable electrode was set as T second and different time intervals of the continuous pictures were chosen.

The droplet evolution under different TSMF can be observed clearly from Figs. 3 to 7. Under the conditions with no external magnetic field or the TSMF of 0.1 T and 0.3 T, no significant differences can be observed as shown in Figs. 3 to 5. The concrete droplet evolution is that liquid metal film slowly aggregates at a cone-shaped end of the consumable electrode and a liquid bulge soon occurs. As the liquid bulge grows bigger, the critical size of the liquid bulge is reached. Afterwards, the liquid bulge begins to fall. And a slender metal neck which connects the liquid bulge and the electrode appears. The metal neck becomes more and more slender until it is snapped. Finally, the detached droplet sinks quickly in molten slag in the shape of a saucer. The metal neck which still connects with the end of the electrode may rise upwards to the surface of the electrode quickly or form into one or two smaller droplets. Here the bigger droplet is called as ‘main droplet’ and the smaller droplets formed from the metal neck are called as ‘satellite droplet’. When there is no external magnetic field, the liquid bulge just detaches from the tip of the consumable electrode because the action of the surface tension cannot withstand the action of gravity. And the formation of the few satellite droplets is mainly due to the function of the surface tension and the power of gravity which act on the frail liquid neck. The EMV with the TSMF of 0.1 T and 0.3 T are too small to impact the droplet evolution processes. So the representative droplet evolution processes under the conditions of 0 T, 0.1 T and 0.3 T are almost the same.

When the TSMF of 0.5 T is superimposed, there are remarkable differences in droplet evolution as shown in Fig. 6. It can be discovered that the longitudinal length of the metal neck connecting the electrode with the liquid

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**Fig. 3.** The representative droplet evolution conducted under the condition of the remelting current of 8 A and no external magnetic field.
Fig. 4. The representative droplet evolution conducted under the condition of the remelting current of 8 A and the TSMF of 0.1 T.

Fig. 5. The representative droplet evolution conducted under the condition of the remelting current of 8 A and the TSMF of 0.3 T.

Fig. 6. The representative droplet evolution conducted under the condition of the remelting current of 8 A and the TSMF of 0.5 T.
bulge becomes larger and the neck can persist a little more time under the action of the electromagnetic braking force whose action direction is mainly in a vertical direction to counteract part of gravity. The separation of the liquid bulge firstly happens in the middle of the long neck, and then the neck is separated by the EMV.

While the intensity of the TSMF reaches 0.7 T, an interesting phenomenon appears during the evolution process of the droplet as shown in Fig. 7. An inflated liquid bulge appears in the middle of the long liquid neck. After a short while, the liquid neck is smashed into a lot of smaller droplets by the strong EMV.

To demonstrate the impact of the TSMF better, statistical work of the video captured by the high-speed camera for each experiment had been done for quantitative analysis. The number of all the main droplets \((N_m)\) and the number of the satellite droplets \((N_s)\) generated in each dripping process were recorded. So the average number of the satellite droplets with each main droplet \((A_s)\) can be simply calculated by the equation as following:

\[
A_s = \sum \frac{N_s}{N_m}
\]  

The changes of \(A_s\) under different intensities of the TSMF are shown in Fig. 8. Obviously, the values of \(A_s\) change less when the intensity is below 0.5 T. However, when the intensity reaches 0.5 T, the value of \(A_s\) has a little increase. The main reason is that a longer liquid metal neck will appear due to the electromagnetic braking force as described earlier, the longer droplet neck is easier to form some satellite droplets by the action of surface tension and EMV. When the external TSMF is beyond 0.5 T, the long metal neck will suffer from a significant EMV. So the liquid neck can be smashed into many satellite droplets easily, which is corresponding to the differences of the representative evolution processes of the droplets discussed above. The quantitative data \(A_s\) indicates the average number of the satellite droplets generated from the liquid metal necks during each detachment process. Thus, a higher average number stands for a better smashing effect, meaning that the interface area between slag and metal will be improved with a higher intensity of the TSMF.

3.2. Droplet Evolution under Different Strength of Remelting Current

The experiments were done under different strength (6 A, 7 A, 9 A and 10 A) of the remelting current with the constant external TSMF of 0.7 T. Although the remelting current was small, the intensity of the external magnetic field was strong enough to generate a forceful EMV. So the evolution process of the droplet could be influenced greatly. Figures 9 to 12 show the representative formation and detachment process of the droplet at the tip of the consumable electrode under different strength of the remelting current respectively. All the five representative evolution processes of the droplets are similar to the one described above which is conducted under the conditions of the remelting current of 8 A and the TSMF of 0.7 T as shown in Fig. 7. However, there are still some differences with the increase of the intensity of the remelting current. The first difference can be noted that the liquid metal neck is better smashed into a lot of satellite droplets under the intensities
Fig. 9. The representative droplet evolution conducted under the condition of the TSMF of 0.7 T and the remelting current of 6 A.

Fig. 10. The representative droplet evolution conducted under the condition of the TSMF of 0.7 T and the remelting current of 7 A.

Fig. 11. The representative droplet evolution conducted under the condition of the TSMF of 0.7 T and the remelting current of 9 A.
of 7 A, 8 A and 9 A. However, the smashing effect acting on the liquid metal neck is not obvious under the condition of the intensities of 6 A and 10 A as shown in Figs. 9 and 12. A simple calculation has been done to explain the reason. The whole remelting current is assumed to flow through the metal neck due to the low electrical conductivity of the molten slag around. The radius of the liquid metal neck is about 0.0025 m measured from the droplet evolution picture. The shape of the liquid metal neck is columnar before it is changed by the EMV, so the cross section of the neck is circular. Because the remelting current is alternating with the frequency of 50 Hz, the amplitude of the remelting current is adopted here. Then the maximum current density can be easily worked out by the amplitude of the remelting current and the cross-section area of the liquid neck. The magnetic flux density of the TSMF is already known as 0.7 T. Thus, the maximum intensity of Lorentz force acting on the metal neck can be calculated.

The calculated value of Lorentz force is $3.53 \times 10^5$ N/m$^3$ corresponding to the effective value of remelting current of 7 A. It is believed that when the maximum intensity of Lorentz force is equal or greater than $3.53 \times 10^5$ N/m$^3$, the smashing effect acting on the metal neck will be remarkable in this study. However, when the effective value of remelting current reaches 10 A, the calculated value of Lorentz force will be $5.04 \times 10^5$ N/m$^3$ which is 1.4 times than that of 7 A. This large Lorentz force can avulse the liquid bulge from the metal neck earlier before the metal neck provides enough time for the EMV to smash the metal neck well, which phenomenon can be observed from video captured by the high-speed camera under the conditions of the remelting current of 10 A and the TSMF of 0.7 T.

The other reason is that the tips become sharper and sharper with the increase of the remelting current as shown in Fig. 13. Because a larger Joule heat will be generated around the tip of the electrode by a larger remelting current. So the tips of the consumable electrodes become sharper and sharper. The sharpest tip is gained when the intensity of the current reaches 10 A. As observed from Fig. 12, the metal neck becomes shorter and the main droplet becomes smaller than that observed from Figs. 9 to 11. Smaller droplet and shorter liquid neck will be generated under a smaller consumable electrode. The droplet detached from a sharper tip of the electrode is just like that the droplet detached from a smaller consumable electrode, which leads to the phenomenon appearing in Fig. 12. Meanwhile, the shorter liquid metal neck will lead to a poor smashing effect. Because the space between the tip of the electrode and the detached main droplet is small, so the satellite droplets smashed by the EMV can be easily merged with the main droplet or the liquid film on the end of the electrode.

The statistical values of $A_t$ have been illustrated in Fig. 14. The changes of $A_t$ show that the smashing effect is improved firstly, and then it is reduced when the remelting current is equal or greater than 9 A. This change is in accord with the differences of the representative evolution processes of the droplets discussed above. Here, it can be concluded from the value of $A_t$ that the remelting current is not the larger the better. The metal neck will be better...
smashed into many satellite droplets under a proper remelting current during MFC-ESR process.

3.3. Analysis on Smashing Effect under the MFC-ESR Process

The phenomenon of the smashing effect under the MFC-ESR process is worthy to be paid attention to. To figure out why the liquid metal droplet necks are smashed into a lot of smaller satellite droplets, a transient 3D numerical simulation has been performed by using a commercial software FLUENT. Two-phase flow, alternating electric field and static magnetic field are combined in each iteration. The time step of the numerical simulation is 0.001 second which is one twentieth of cycle in 50 Hz. The detailed physical properties, geometry and operating conditions corresponding to the experiment parameters are listed in Table 2.33–37

The evolution behavior of the droplet has been simulated with the TSMF of 0.7 T. The droplet evolution of the simulation result is similar to the phenomenon of the experiment. The distribution of

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<tr>
<td>Physical properties of slag</td>
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<tr>
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<tr>
<td>Electric conductivity (S m)</td>
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<tr>
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<tr>
<td>Geometry</td>
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<tr>
<td>Ingot diameter (m)</td>
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<tr>
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<td>Current (A)</td>
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</tr>
<tr>
<td>Frequency (Hz)</td>
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<tr>
<td>Melting rate (kg/s)</td>
<td>2.5 × 10⁻⁴</td>
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<tr>
<td>Interfacial tension between slag and metal (N/m)</td>
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</tr>
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current density and Lorentz force with the droplet evolution under the MFC-ESR process are shown in Fig. 15. The mechanism of the smashing effect acting on the metal neck can be explained as following: The TSMF of 0.7 T is superposed toward the positive direction of Y axis, and the direction of the alternating current (50 Hz) goes along the direction of Z axis, so the direction of EMV (50 Hz) is in the X direction as shown in lower-left corner of Figs. 15(a) or 15(b). To minimize the electric resistance, the intensity of remelting current will mainly flow through the metal neck as shown in Fig. 15(a) (T=0.07) second, meaning that a violent EMV can be generated as shown in Fig. 15(b) (T=0.07) second. As the liquid metal neck becomes longer, the EMV acting on the metal neck becomes more significant and it will undermine the stability of the liquid neck. The forceful EMV changes the shape of the liquid metal neck from a column into a flat strip as shown in Fig. 15(b) (T=0.01) second. As the strong EMV effect and gravity act on the flat strip, the middle area of the strip becomes thinner and its border area begins to expand outward in the YZ plane. That’s why it seems the appearing of an inflated liquid bulge in the middle of the metal neck. Before long, the center area of the strip becomes so thin that a small hole appears and grows bigger as shown in Fig. 15(b) (T+0.01) second. After that, the alternating current focuses on flowing through the margin area of the liquid strip around the big hole, so the EMV becomes so large that it can smash the whole liquid droplet neck into a lot of satellite droplets as shown in Fig. 15(b) (T+0.14) second. And it is believed that the mechanism of the smashing effect acting on the droplet necks is a kind of physical phenomenon, which can also appear during the real MCF-ESR process.

4. Conclusion

In this paper, physical simulations of the ESR process were done with the aid of the transparent model apparatus. The effects of different intensities of the external TSMF on the droplet evolution with a constant remelting current of 8 A were studied. Also, the effects of different strength of the TSMF on the droplet evolution at the tip of the electrodes under different conditions were obtained and demonstrated. Meanwhile, the mechanism of the smashing effect was discussed by a numerical simulation. The obtained main results in this study are following:

(1) After superimposing an external TSMF of 0.7 T during ESR process with the remelting current of 8 A, 50 Hz, a special phenomenon will occur: The liquid neck connecting the end of the electrode with the droplet will become longer, and then a growing liquid bulge appears in the middle of the liquid neck. After a short while, the liquid metal neck is smashed into a lot of smaller droplets by the strong EMV. The interface area between metal and slag is increased enormously due to the smashing effect acting on the metal necks which means the technique of ESR process can be expected to be improved.

(2) The smashing effect will be improved with the enlarging of the external TSMF under the condition of the constant remelting current of 8 A.

(3) The smashing effect will get worse under the condition of a bigger remelting current with the TSMF of 0.7 T due to the large Lorentz force and the sharper tip of the electrode.

Acknowledgement

The authors gratefully acknowledged the financial support of National Natural Science Foundation of China (Key Project No. 51034010), Science and Technology Commission of Shanghai Municipality (Key Project No. 13JC1402500), Natural Science Foundation of Jiangsu Province (BK2011501), Innovation Fund for Technology Based Firms (12C26213202452) and Open Project Shangh Key Laboratory of Modern Metallurgy & Materials Processing (SELF-2014-02).

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