A Fast Response Sensor for Continuously Measuring Molten Steel Temperature

Jiu ZHANG,* Guohui MEI, Zhi XIE and Shumao ZHAO

College of Information Science and Engineering, Northeastern University, Shenyang, Liaoning, 110819 China.

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Response lag is an outstanding problem of the traditional blackbody cavity sensor for continuously measuring the molten steel temperature, which is due to the thick-walled structure of the sensor, caused by the limitation of the sensor's $\text{Al}_2\text{O}_3\text{-C}$ material in harsh environment. Thus, a fast response sensor with a thin-walled temperature measuring unit of blackbody cavity has been developed. A new sensor material of Mo-W-ZrO_2 cermet that had a small corrosion rate of about 0.05 mm/h was developed for making the thin-walled sensor with a thickness of 3 mm, while the thickness of the traditional sensor was 20–30 mm. The temperature measuring unit of the cermet tube was supported by an $\text{Al}_2\text{O}_3\text{-C}$ unit. In addition, the structure of the fast sensor was designed to form an online blackbody cavity approximately for a high accuracy (measurement error $\leq 3^\circ\text{C}$) as the sensor was dipped into molten steel, the length/radius ratio of the temperature measuring unit of the cermet tube should reach 12. Industrial test showed that the fast sensor improved the response speed significantly from 5–6 min to about 55 s. It was helpful to solve the problem for continuously measuring the molten steel temperature of these fields that needed a fast response.

KEY WORDS: temperature sensor; molten steel; fast response.

1. Introduction

Molten steel temperature is the critical parameter for the steel production. Generally, it is not only the key target parameter of the refining control, but also is the important foundation for solidification control of continuous casting.^{1,2)} That is to say, the temperature continuous measurement of molten steel plays an important role in guiding the steel production. However, the molten steel temperature is difficult to be measured continuously due to the destructive environment. To avoid the destructive environment, a non-contact measurement method of infrared computer vision has been proposed.^{3,4)} It has a fast response and low cost, but has a poor accuracy caused by the uncertainty emissivity of molten steel.

Thus, the contact sensor is needed to continuously measure the molten steel temperature and has to survive in the destructive environment, which has gone through two main stages. (1) A platinum-rhodium thermocouple with a protective tube has been developed.^{5–7)} It achieves the continuous measurement of the molten steel temperature, but is difficult to be widely applied in industrial fields due to the high cost of thermocouple. (2) In order to solve the cost problem, a blackbody cavity sensor has been developed, which is currently the most widely applied technology.^{8–10)} In detail, it dipped a measurement tube into molten steel with a certain

depth, and then reached thermal equilibrium with molten steel to form an online blackbody cavity approximately. Meanwhile, it generates a stable infrared signal that is received by a probe for representing the temperature. To meet the demands of strong thermal shock resistance and corrosion resistance in the destructive environment, both of the above sensors almost use carbon-containing refractories,^{5–12)} such as $\text{Al}_2\text{O}_3\text{-C}$, MgO-C , and $\text{ZrO}_2\text{-C}$. $\text{Al}_2\text{O}_3\text{-C}$ refractory is the optimal practical material, which hasn't the hydration problem of MgO-C refractory and has lower price than $\text{ZrO}_2\text{-C}$ refractory.

However, all of these refractories have poor strength and high porosity, resulting in a relatively poor corrosion resistance. The traditional sensor has to have a thick-walled structure with a thickness of 20–30 mm to obtain a good lifetime. As a result, the traditional sensor has an outstanding problem of response lag, and its response time is up to about 5–6 min. It is difficult to meet the fast response demand of the fields such as casting start, ladle change and refining furnace. For example, the endpoint temperature of the ladle refining that cannot be measured is only predicated by several models.^{2,13)}

Therefore, a fast blackbody cavity sensor with a thin-walled structure is investigated to solve the response lag problem for continuously measuring the molten steel temperature in this work. A Mo-W-ZrO_2 cermet is developed for manufacturing the fast sensor. Its thermal shock and corrosion are discussed, which are the two key problems. Meanwhile, the structure design of the sensor for forming

* Corresponding author: E-mail: zhangjiu@ise.neu.edu.cn
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an online blackbody cavity to ensure the measuring accuracy has been investigated. Finally, the response speed has been tested.

2. Sensor Description

The fast response sensor develops a thin-walled cermet tube with a thickness of 3 mm as the temperature measuring unit of blackbody cavity while the thickness of the traditional blackbody cavity sensor is about 20–30 mm as illustrated in **Fig. 1**. In order to reduce the cost, the support unit of the temperature measuring unit uses the $\text{Al}_2\text{O}_3\text{--C}$ refractory that is used for the traditional sensor.

Measurement principles of the fast response sensor are as follows: firstly, it is dipped into molten steel; and then, the cermet tube achieves thermal equilibrium in molten steel to form an online blackbody cavity approximately that generates a stable infrared signal according to the temperature of molten steel; finally, a probe receives the infrared signal and the special processor calculates the temperature. A fume exhaust system uses N_2 to remove the fume generated by the support unit, which has been investigated in previous work.⁹⁾ The temperature measuring unit of the cermet tube only should suffer the thermal shock and molten steel corrosion. It avoids the molten slag corrosion that is suffered by the $\text{Al}_2\text{O}_3\text{--C}$ support, which has been solved in the development of the traditional $\text{Al}_2\text{O}_3\text{--C}$ sensor.

3. Sensor Material

The cermet tube is the key part of the fast sensor. It should solve the two critical problems of thermal shock resistance and corrosion resistance in molten steel. A sensor material of Mo–W– ZrO_2 cermet has potential to be used. On the one hand, the metal phase of Mo–W can be used to toughen the ceramic phase, bridging the crack during the thermal shock fracture as shown in **Fig. 2**. And its plastic deformation can also consume the crack propagation energy. On the other hand, the ceramic phase of ZrO_2 can be used for improving corrosion resistance in molten steel, attributing to that it cannot be wetted and dissolved by molten steel. On the basis of

these, the Mo–35W–35 ZrO_2 cermet has been developed. To obtain high temperature strength, the weight ratio of Mo/W should be near 1/1,¹⁴⁾ the ratio of 30/35 has been used in this work. In addition, the ceramic phase content is about 55 vol.%, which is used for good corrosion resistance and thermal shock resistance. As the ceramic phase content is more than about 65 vol.%, the thermal shock of the cermet is poor, leading to that the thermal shock crack generates and the molten steel penetrates into the cermet tube (as shown in **Fig. 3**) as the cermet tube is dipped into molten steel. On the contrary, as the ceramic phase content is less than about 40 vol.%, the corrosion of the cermet is fast.

To clarify the chemical phases of the cermet, the XRD (X-ray diffraction) is used. The corresponding patterns are illustrated in **Fig. 4**. Remarkable reflection peaks of ZrO_2 and Mo–W are observed. The reflection peaks of the Mo–W

Fig. 2. Schematic diagram of the toughening mechanism in cermet: L_1 (crack length of the ceramic), L_2 (crack length of the cermet).

Fig. 1. Schematic diagram of the fast response sensor. (Online version in color.)

Fig. 3. (a) Original cermet tube, (b) Thermal shock crack of the cermet.

are attributed to that the Mo and W form the solid solution. Additionally, the reflection peaks of the Mo and W may also exist, attributing to that their reflection peaks are covered by the reflection peaks of the Mo–W solid solution and cannot be observed obviously. Meanwhile, the microstructure of the cermet that has been checked by the scanning electron microscopic (SEM) is illustrated in Fig. 5. It includes ceramic phase (C), metal phase (M) and pore (P). The ceramic phase (ZrO_2) was the matrix, which is benefit to improve the corrosion resistance. The metal phase (Mo–W) has formed a semi-continuous network structure and distributed in the cermet uniformly. It plays an important role in improving the thermal shock resistance through toughening the ceramic phase. In detail, the metal phase prevents the thermal shock crack from propagating and forms a semi-continuous network for bridging the crack. As the fracture occurs, the metal phase has a plastic deformation that can consume the fracture energy, which toughens the cermet and has been verified by O. Sbaizero *et al.*¹⁵⁾ The network for bridging the crack can seal the crack propagating in the metal phase network as soon as possible, improving the thermal shock resistance significantly. The composition

and microstructure are the root causes for the good thermal shock resistance of the cermet, which also govern the corrosion resistance.

The cermet has good corrosion resistance and its corrosion rate is only about 0.05 mm/h (corroded thickness: about 0.5 mm for 10 h, see Fig. 6(a)) in molten steel (test conditions: 40Cr steel, about 1 520°C). Due to the fact that the cermet tube has been corroded for a long term, its corrosion may be in dynamic equilibrium. As a result, the microstructure of the corroded cermet may also have reached dynamic equilibrium. Figure 6(b) shows the microstructure of the corroded cermet, indicating the corrosion mechanism. It can be found that a ZrO_2 layer with a thickness of 73 μm formed on the corroded cermet surface during the corrosion, which implies that the corrosion rate of the ceramic phase (ZrO_2) is much slower than that of the metal phase (Mo–W). The black area in the ZrO_2 layer was slag (S). The slag area originally belongs to molten steel. Its formation is as the following processes: (1) as the cermet tube is pulled out of the slag layer, the molten steel flows out from the ZrO_2

Fig. 4. X-ray diffraction patterns of the cermet.

Fig. 5. Microstructure of the cermet (SEM): ceramic phase (C), metal phase (M) and pore (P).

Fig. 6. (a) Thickness of the original and corroded cermet tubes, (b) Microstructure of the corroded cermet (SEM): slag (S), metal phase (M), ceramic phase (C).

layer; (2) the cermet tube is adhered by the molten slag that penetrates into the ZrO_2 layer. The ZrO_2 layer can prevent molten steel from penetrating into cermet, slowing down the melting corrosion of the metal phase. As the melting corrosion rate of the metal phase is decreased to the physical erosion rate of the ceramic phase, the corrosion of the cermet reaches dynamic equilibrium. It is critical to form a ZrO_2 layer on the cermet surface for obtaining good corrosion resistance during the corrosion. In addition, there is an oxidation problem of the metal phase (Mo–W) during the sensor manufacture that has been solved in previous work.¹⁶⁾

As a result, the fast response sensor can be made into a thin-walled structure with a thickness of about 3 mm while the thickness of the traditional sensor is 20–30 mm.

4. Sensor Design and Performance Test

Besides the sensor material, the structure of the fast response sensor is investigated. Generally, the measurement accuracy of the blackbody cavity sensor depends on the integrated effective emissivity of the temperature measurement cavity (ε^c), which can be expressed by the flowing equation:

$$E_b(\lambda, T_i) = \varepsilon^c E_b(\lambda, T_t) \quad (1)$$

where E_b is the blackbody radiation intensity determined by the Planck formula, T_i and T_t are the indicated temperature and true temperature of molten steel respectively. The measurement error can be expressed as Eq. (2):

$$\Delta T = |T_i - T_t| \quad (2)$$

It can be found that the measurement accuracy of the fast sensor depends on the integrated effective emissivity of the cermet tube that is used as the temperature measuring unit. The temperature measurement principle can be illustrated by Fig. 7. As the fast sensor is dipped into molten steel, the length/radius ratio of the cermet tube should reach a certain value, to obtain a high integrated effective emissivity of the temperature measurement cavity and form an online blackbody cavity approximately. The length/radius ratio of the cermet tube is studied by the theoretical analysis firstly and then determined through the experiment test. The integrated effective emissivity of the cermet tube ε^c is equal to the integrated effective emissivity of the target A to detector D (ε_A^c), which is illustrated in Fig. 8. According to

Fig. 7. Emission and reception of the radiation energy of the sensor: target (A), detector (D). (Online version in color.)

Fig. 8. Schematic of the ray-tracing: the solid and dotted lines represent the direction of an incident ray and the reflected rays, respectively. (Online version in color.)

the blackbody cavity law, the integrated effective emissivity of the cermet tube is calculated by the integral equation method,^{17,18)} which is expressed by the Eq. (3).

$$\varepsilon^c = \varepsilon_A^c = \frac{\int_A \varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho}) E_b(\lambda, T_{\text{ref}}, \bar{\rho}) F_{\bar{\rho}D} dA}{\int_A E_b(\lambda, T_{\text{ref}}, \bar{\rho}) F_{\bar{\rho}D} dA} \quad (3)$$

where $\varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho})$ is the spectral effective emissivity of any point $\bar{\rho}$ in the target A , T_{ref} is the reference temperature that is the temperature of the target A (reaching a thermal equilibrium with the molten steel), $F_{\bar{\rho}D}$ is configuration factor from any point $\bar{\rho}$ to detector D .

Due to the fact that the detector D only receives the parallel axial heat radiation emitted by the target A , the configuration factor $F_{\bar{\rho}D}$ can be omitted, the Eq. (3) can be simplified to the following Eq. (4):

$$\varepsilon_A^c = \frac{1}{A} \int_A \varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho}) dA \quad (4)$$

On the basis of these, the spectral effective emissivity of any point $\bar{\rho}$ in the target A $\varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho})$ is calculated by the Monte-Carlo method. The incident radiation is considered to consist of a rather large number of rays ($N=10^9$),¹⁹⁾ and each ray is assigned the unit energy (E_0). To calculate the $\varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho})$, all the incident rays hit the point $\bar{\rho}$. As a ray hits the cavity wall, its energy can be absorbed or reflected, which is depended on the pseudo-random number u_ε , its range is (0, 1). If the $u_\varepsilon < \varepsilon$ (the emissivity of the wall, $\varepsilon=0.7$), the energy is absorbed. Otherwise, it is reflected. The direction of the reflection ray is also random, which can be expressed by the elevation and direction angles (ψ and φ):

$$\psi = \arcsin \sqrt{u_\psi}, \quad \varphi = 2\pi u_\varphi \quad (5)$$

where u_ψ and u_φ are a pair of pseudo-random numbers, their ranges are (0, 1).

The reflected rays propagate according to ψ and φ (as shown in Fig. 9), which hits a cavity wall again or escapes through the opening aperture. The paths of the ray are pursued until the energy of the ray is absorbed or the ray escapes through the opening aperture after reflections in the cavity. The number of absorbed rays is counted as N_α . According to the Kirchhoff's law, the effective absorptivity of the cavity can be expressed by Eq. (6):

$$\varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho}) = \alpha_e(\lambda, T_{\text{ref}}, \bar{\rho}) = \frac{\sum_{i=1}^{N_\alpha} E_0}{N \cdot E_0} = \frac{N_\alpha}{N} \quad (6)$$

where $\sum_{i=1}^{N_\alpha} E_0$ is the total energy of the absorbed rays, $N \cdot E_0$ is the total energy of the incident rays. Equation (6) means that $\varepsilon_e(\lambda, T_{\text{ref}}, \bar{\rho})$ is equal to the ratio of the number of absorbed rays to the number of the incident rays.

The relationship between the length/radius (h/r) ratio of the cermet tube and the integrated effective emissivity ($\varepsilon_{e,A0}$) is calculated and illustrated in Table 1. And the h and r ($r=10$ mm) are the length and radius of the cermet tube, respectively.

Furthermore, the corresponding measurement error (ΔT) is calculated through Eqs. (7)–(8) and also showed in Table 1. It is assumed that the true temperature of molten steel is 1 500°C. Relationship between the indicated temperature (T_i) and true temperature (T_t) of molten steel is expressed

as:²⁰⁾

$$T_i = T_t \sqrt[4]{\varepsilon_A^c} \dots\dots\dots (7)$$

Measurement error (ΔT) can be expressed as:

$$\Delta T = T_t - T_i = T_t \left(1 - \sqrt[4]{\varepsilon_A^c} \right) \dots\dots\dots (8)$$

On the basis of these theoretical analysis results, the experiment test is taken and shows that when the h/r ratio of the cermet tube reaches 12, the fast response sensor has a high accuracy. Its measurement error is $\leq 3^\circ\text{C}$, compared with the second class standard type B thermocouple, which is illustrated in Fig. 10. This temperature measuring accuracy is equal to that of the traditional sensor.⁹⁾

The response speed of the fast sensor is tested in Nanjing steel factory (in China) as illustrated in Fig. 11(a). The molten steel temperature in the test is about 1 520°C. Figure 11(b) shows the temperature response curve of the fast sensor. Meanwhile, a temperature response curve of the traditional sensor is used as a reference. It can be found that the response time is reduced significantly from 350 s to

Fig. 9. Schematic of the temperature measurement principle. (Online version in color.)

Table 1. Effect of the h/r ratio on the integrated effective emissivity of the cavity and corresponding measurement error.

h/r	ε_{e, A_0}	Measurement error ($^\circ\text{C}$)
10	0.9954	2.04
11	0.9963	1.64
12	0.9971	1.29
13	0.9976	1.06
14	0.9980	0.89

Fig. 10. Accuracy test of the fast response sensor. (Online version in color.)

Fig. 11. (a) Industrial test of the fast response sensor, (b) Temperature response curves of the fast response sensor and traditional sensor. (Online version in color.)

55 s, which is due to the fact that the thickness of the fast sensor is much thinner than that of the traditional sensor. It is helpful to solve the problem for continuously measuring the molten steel temperature of these fields that need a fast response.

5. Conclusions

A fast response blackbody cavity sensor for continuously measuring the molten steel temperature has been developed. It developed a Mo–W–ZrO₂ cermet that had a small corrosion rate of about 0.05 mm/h to make a thin-walled blackbody cavity temperature measuring unit with a thickness of 3 mm, while the traditional sensor had a thick-walled structure with a thickness of 20–30 mm. The temperature measuring unit of the cermet tube was supported by an Al₂O₃–C unit.

In addition, the structure of the fast sensor was designed to form an online blackbody cavity approximately for a high accuracy (measurement error $\leq 3^{\circ}\text{C}$) as the sensor was dipped into molten steel, the length/radius ratio of the temperature measuring unit of the cermet tube should reach 12. Compared with the long response time (5–6 min) of the traditional sensor, the fast sensor had a much shorter response time of about 55 s, which is helpful to solve the problem for continuously measuring the molten steel temperature of these fields that need a fast response.

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