Effects of the Thermal Expansion Coefficient on the Cooling Process of the Fused Zirconia-Alumina Material

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Abstract—The solidification process simulation of the fused cast AZS material to predict porosity and cavity has not been extensively researched. Using software Any-casting, effects of the thermal expansion coefficient on solidification sequence, solidification percentage, solidification time, difference of temperature gradients, probabilities of macro-defects and micro-defects were studied. The results showed that: the thermal expansion coefficient less than 19.2E-06K^{-1} at 250℃ generated a bottom-up solidification sequence, which was conducive to the feeding capacity of riser; When the thermal expansion coefficient was less than 27.2E-06K^{-1}, solidification percentage at the bottom center of riser was larger than that at the center of cast; Considering solidification time, the thermal expansion coefficient should be less than 27.2E-06K^{-1}; According to Niyama criterion, the probability of shrinkage cavity and its area in AZS casting were small when the thermal expansion coefficient was less than 19.2E-06K^{-1}. So the preferred thermal expansion coefficient of AZS material should be less than 19.2E-06K^{-1}.

Keywords-AZS; the thermal expansion coefficient; solidification sequence; solidification percentage; shrinkage prediction

I. INTRODUCTION

The fused Zirconia-Alumina (AZS) is a kind of refractory material used for glass furnaces lining. It is made from highly purified Al_2O_3 sand, Zircon sand (SiO_2 and ZrO_2) and other raw materials, melted in electric melting furnace and followed by cooling process of cast [1]. It features low yield, high cost and easily contains defects. The analysis for the casting status and some defect reason for the head of vermicular iron cylinder of YC M3500 was done by Huang Zonghui using the 3D simulation software Any-casting [2-5]. The optimized production process for lowering the casting defect was given. Using Any-casting software in this thesis, we simulated to analyze effects of the thermal expansion coefficient on the solidification sequence, solidification percentage and temperature gradient, etc, hoping to know the optimal value of material's thermal expansion coefficient that we should select during the practical production process.

II. SIMULATED CONDITIONS

A. *Basic Conditions*

In Any-casting simulation software, AZS material was set as casting system and silicon dioxide material as sand mould. Main parameters of these two kinds of materials were shown in Table 1. The initial mould temperature was set 25℃, mould thickness 50mm and 500000 uniform grids for the system. Before the filling process, the initial temperature of melted AZS was 1900℃. Radius of flowing fluid was 70 mm and filling time was 10 s. The uniform temperature and homogeneous components were assumed. Here was mould size: 600 mm (length) × 400mm (width) × 300 mm (height), volume $7.2 \times 10^7 mm^3$. Riser was located at the surface center of 600mm × 400mm. The riser size was: bottom surface 150mm × 150mm, upper surface 450mm × 450mm, height 250mm.

TABLE I. RELATED PARAMETERS

Items	AZS casting	SiO_2 mould
Volume density （$kg \cdot m^{-3}$）	3000	Variable （1520-1482）
Specific heat （$J \cdot kg^{-1} k^{-1}$）	3	Variable （676-1260）
Thermal conductivity （$W \cdot m^{-1} k^{-1}$）	Variable (4.618-8.391)	Variable （0.737-1.05）
Liquidus temperature （℃）	1790	1720
Solidus temperature （℃）	1420	1500
Dynamic viscosity （$kg \cdot m^{-1} s^{-1}$）	Variable (0.00093-0.00451)	-
Surface tension （N/m）	Variable (1.925-1.973)	-
Latent heat （$J \cdot kg^{-1}$）	3476	-

B. *Variable Conditions*

As the thermal expansion coefficient of AZS varied with temperature, the representative simulation data of AZS at 250℃ were shown in Table 2.

TABLE II. SETTINGS OF THERMAL EXPANSION COEFFICIENT

Number	Thermal expansion coefficient (K^{-1})
1	0.0640E-06
2	0.640E-06
3	6.40E-06
4	19.2E-06
5	27.2E-06
6	32.0E-06

III. SIMULATION RESULTS AND ANALYSIS

A. *Solidification Sequence*

The riser's feeding capacity was affected by solidification sequence of casting system. When riser solidified later than cast, the solidification sequence would benefit riser's feeding capacity. Solidification sequence figures of the central cross section of different simulation were cut out to study effects of the thermal expansion coefficient on solidification sequence (Fig .1).

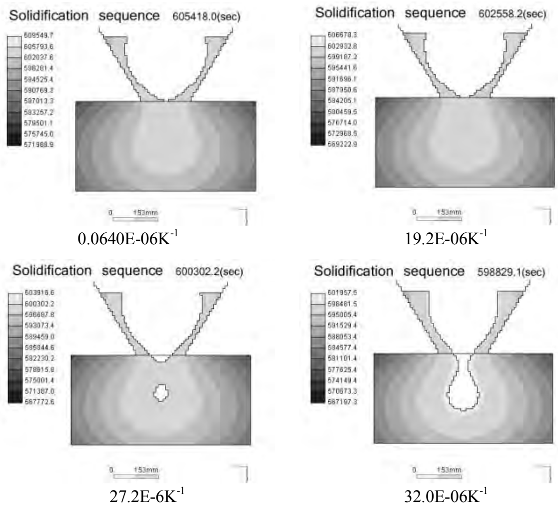

Figure 1. Solidification sequence in the central cross section of different casting system

When the thermal expansion coefficient was greater than 27.2E-06K^{-1}, it caused a posterior solidification sequence at the center of cast to increase the probability of shrinkage or dense defects there. The riser's feeding capacity was poor. Such situation should be averted because it would affect the cast lifetime. Therefore, the thermal expansion coefficient less than 19.2E-06K^{-1} were advisable due to the riser's good feeding capacity.

B. *Solidification Percentage*

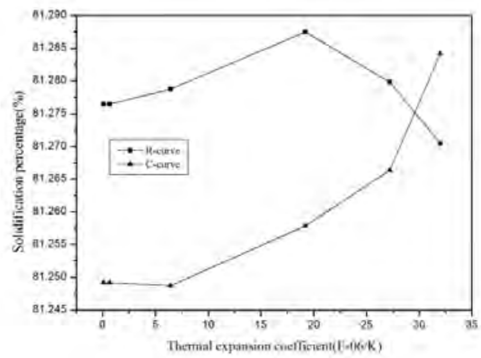

Figure 2. Effects of the thermal expansion coefficient on the solidification percentage

As shown in Fig .2, when the bottom center of riser began to solidify, solidification percentage of the whole casting system (R-curve) would get the maximum value if the thermal expansion coefficient was 19.2E-06K^{-1}. When the center of cast began to solidify, solidification percentage of the whole casting system (C-curve) would increase with the increasing thermal expansion coefficient. But when the thermal expansion coefficient was less than 27.2E-06K^{-1}, R-curve was higher than C-curve. This suggested that the bottom center of riser solidified after the center of cast. This benefited the feeding of riser. When the material's thermal expansion coefficient was a certain value between 27.2E-06K^{-1} and 32.0E-06K^{-1}, the two positions would solidify at the same time. This would be the critical state when riser began to have good feeding capacity. When the thermal expansion coefficient was

32.0E-06K^{-1}, the bottom center of riser solidified earlier than the center of cast to decrease the riser's feeding capacity. Therefore, considering the solidification percentage, the thermal expansion coefficient of no more than 27.2E-06K^{-1} was conducive to increase the riser's feeding capacity.

C. Solidification Time

The Fig .3 showed: both at the bottom center of riser and at the center of cast, the solidification time decreased with the increasing thermal expansion coefficient. So did the solidification time of the whole system. When the thermal expansion coefficient was no more than 27.2E-06K^{-1}, the bottom center of riser solidified after the cast center, it generated a bottom-up solidification sequence that benefited riser's feeding capacity. Therefore, considering the solidification time of these two positions, we should choose the thermal expansion coefficient no more than 27.2E-06K^{-1}.

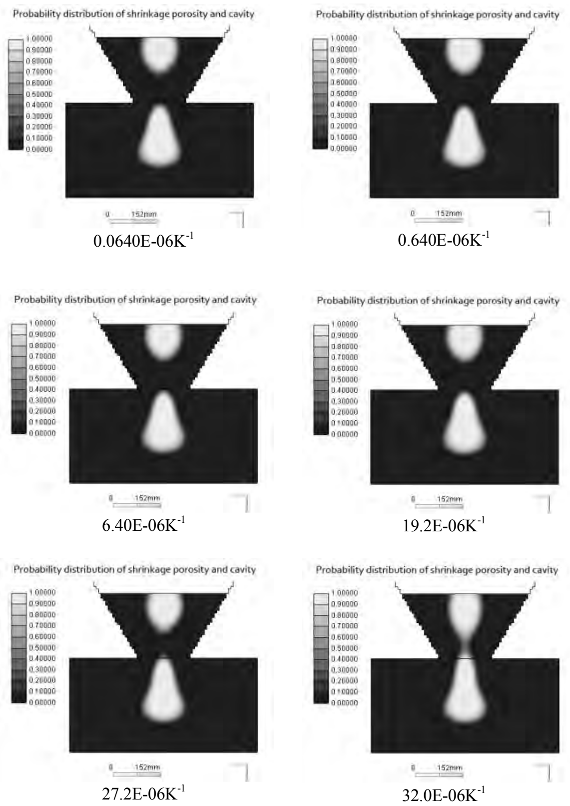

Figure 5. Probability distribution of shrinkage porosity and cavity according to Niyama criterion

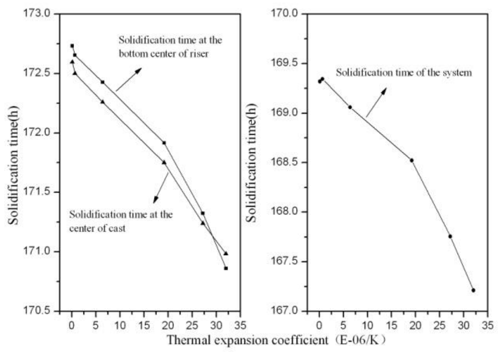

Figure 3. Effects of the thermal expansion coefficient on the solidification time

While the thermal expansion coefficient increased from 32.0E-06K^{-1} to 0.064E-06K^{-1}, the overall solidification time decreased by 1.246% about 2.11 hours. This had a little effect on actual production. Therefore, the thermal expansion coefficient could be chosen on the basis of actual production.

D. Difference of Temperature Gradient

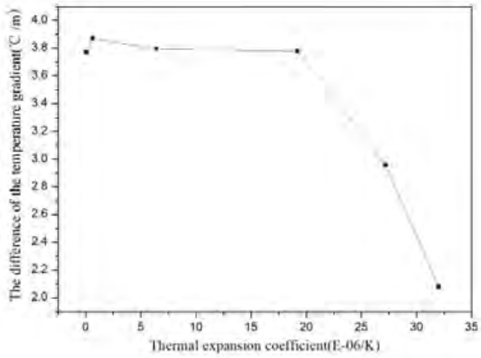

Figure 4. Effects of the thermal expansion coefficient on the difference of temperature gradient

As shown in Fig .4, the difference of the temperature gradient at the bottom center of riser and the center of cast could reflect the feeding capacity of riser. The greater the difference was, the better feeding effect riser had. So the thermal expansion coefficient less than 19.2E-06K^{-1} made the cast produce defects uneasily.

E. Macroscopic Shrinkage Prediction

The retained melt modulus in Any-casting was the ratio of retained melt volume to retained melt surface area. During casting process, the smaller the value, the less quantity of isolated melt in the casting, thus the tendency of shrinkage porosity and shrinkage cavity was smaller, and the quality of the casting was better [6].

Simulation results showed that when the thermal expansion coefficient was less than 32.0E-06K^{-1}, there was no macroscopic shrinkage in the cast. While the coefficient of thermal expansion was 32.0E-06K^{-1}, a probability of shrinkage cavity at the center of cast produced. Therefore, the thermal expansion coefficient should be less than 3.20E-05K^{-1} to reduce macro shrinkage.

F. Microscopic Shrinkage Prediction

Niyama criterion, known as G/R criterion, could give the conclusion through the comparison of the $G \cdot R^{-0.5}$ (where G is the gradient of temperature, R is the cooling rate) and critical criterion value of shrinkage porosity and cavity. When the solidification ended, the $G \cdot R^{-0.5}$ at somewhere in cast was less than or equal to M, the shrinkage produced. M represented the critical criterion value of shrinkage porosity and cavity. Different materials had different M values which had nothing to do with the size and shape of the cast. The smaller the $G \cdot R^{-0.5}$ criterion value in solidification area was, the higher the tendency to produce shrinkage; conversely, shrinkage tendency was smaller. Niyama $G \cdot R^{-0.5}$ was a suitable criterion for judging the tendency of micro shrinkage [7-10]. As shown in

Fig .5, the software converts it for distribution probability.

Seen from Figure 5, when the thermal expansion coefficient was less than 19.2E-06K^{-1}, the shrinkage areas in the cast (white areas in the graphs) were small, and with the decrease of the thermal expansion coefficient, the area of high probability shrinkage (white area) reduced. So according to Niyama criterion, the thermal expansion coefficient of no more than 19.2E-06K^{-1} was conducive to get a smaller distribution probability and area of shrinkage porosity and cavity.

IV. CONCLUSION

1) In this simulation, when the thermal expansion coefficient was no more than 19.2E-06K^{-1} at 250℃, it generated a bottom-up solidification sequence, which was conducive to the feeding capacity of riser.
2) When the thermal expansion coefficient was less than 27.2E-06K^{-1}, solidification percentage at the bottom center of riser was larger than that at the center of cast. Considering the solidification percentage, the thermal expansion coefficient of no more than 27.2E-06K^{-1} was conducive to increase the riser's feeding capacity.
3) Both at the bottom center of riser and at the center of cast, the solidification time decreased with the increasing thermal expansion coefficient. The overall solidification time decreased by 1.246% about 2.11 hours. Considering the solidification time at the bottom center of riser, the thermal expansion coefficient should be less than 27.2E-06K^{-1}.
4) As for the difference of temperature gradients at the bottom center of riser and the center of cast, the thermal expansion coefficient less than 19.2E-06K^{-1} made the cast produce defects uneasily.
5) According to Niyama criterion, the thermal expansion coefficient of no more than 19.2E-06K^{-1} was conducive to get a small distribution probability and a small area of shrinkage porosity and cavity.
6) The optimized value of the material's thermal expansion coefficient was less than 19.2E-06K^{-1}.

ACKNOWLEDGMENTS:

This work was supported by the Project of the National Natural Science Foundation of China (51372229), the National Twelfth Five-Year Technology Support Program (2013BAE03B01), the Zhengzhou Technology Innovation Team (131PCXTD602) and the National University Student Innovation Program (201310459029, 201410459026).

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