International Journal of Heat and Mass Transfer 119 (2018) 614–623

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Quantitative prediction of oxide inclusion defects inside the casting and on the walls during cast-filling processes

Liu Cao, Fei Sun *, Tao Chen, Yulong Tang, Dunming Liao

State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 6 May 2017
Received in revised form 16 October 2017
Accepted 27 November 2017

Keywords:
Oxide inclusion
Formation rate
Wall adhesion
Quantitative prediction
Cast-fillingprocess
OpenFOAM

ABSTRACT

Oxide inclusions are a common defect in casting production, but their formation and evolution processes are difficult to directly observe experimentally. To accurately predict these, one should calculate the formation rate of the oxide inclusion as well as its wall adhesion. Here, we propose a formation rate model that is relevant to the volume fraction of liquid metal, the temperature, and the current oxide inclusion density. A boundary condition was developed to handle the adhesion and accumulation on the wall; thus, a quantitative indicator is available to directly obtain the content of the oxide inclusion defects on different parts. We used the open source computational fluid dynamics (CFD) software OpenFOAM to predict oxide inclusion defects inside the casting and on the walls during cast-filling processes. A representative aluminum alloy-casting technology was simulated to analyze the effects of different runner systems on the oxide inclusion distributions inside casting and on the wall. The simulation results largely coincide with experimental data from the literature. A practical copper alloy-casting technology was then calculated, and the simulation results of the oxide inclusion defects are consistent with the actual casting defect distribution. This confirms the utility of the model.

1. Introduction

Oxide inclusions are a common defect in casting production. They can significantly decrease the surface accuracy of the casting and can even lead to cracking and casting scraps [1–3]. At the beginning of the filling process, a paper-thin oxide film is instantly generated on the liquid front due to the good oxidation capacity of the liquid metal. This becomes thicker over time. During the filling process, some of the oxide film adheres to the wall of the mold and accumulates—this affects the surface quality of the casting. Other oxide films are drawn into the liquid metal to form oxide inclusions that are the base of heterogeneous nucleation. This impedes the cast feeding, and induces gas pore, resulting shrinkage porosity, inferior mechanical properties of the casting, and even fatigue cracking during use [5,6].

Fig. 1 presents secondary electron images of the two opposing surfaces of an aluminum alloy tensile fracture [4]. The crack was initiated in the oxide film inside the casting. Current experimental measures can only analyze the final oxide inclusion distribution of the casting. This makes it difficult to directly observe the formation and evolution of the oxide inclusion. Thus, numerical simulation plays an important role. The formation of the oxide inclusion is a complex chemical reaction and oxide inclusions easily adhere to the wall of mold. Thus, accurately predicting the defect involves calculating the formation rate of the oxide inclusion as well as its adhesion; unfortunately, correlational studies remain preliminary. Therefore, quantitative models that optimize the casting technology and improve the overall casting performance could have a large impact.

There has been a recent increase in studies that numerically predict oxide inclusion defects during cast filling. Many distinctive simulation methods have been developed [7–13]. These can be divided into the following three categories.

(1) Criterion model

Lai et al. [14] considered the "surplus" free surface area—the area difference between the transient free surface generated by the turn-up free surface and the free surface generated during the smooth filling process—to be the criterion of oxide inclusion involvement. More "surplus" free surface area resulted in oxide inclusion being more likely. This simulation method only considers oxide inclusions near the free surface. It does not track the subsequent movement of oxide inclusions with liquid metal. Thus, the final distribution of oxide inclusions cannot be predicted. In

* Corresponding author.
E-mail address: fsun@hust.edu.cn (F. Sun).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.127
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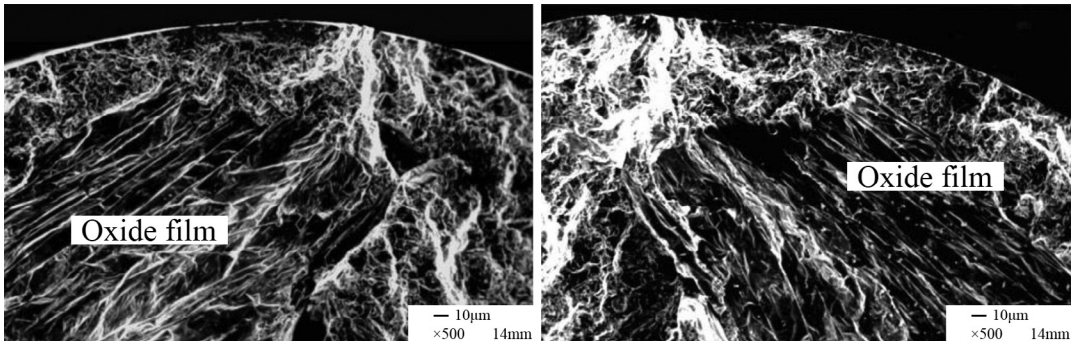

Fig. 1. Secondary electron images of the two opposing surfaces of an aluminum alloy tensile fracture [4].

addition, it is difficult to confirm the free surface area during smooth filling when the casting geometric shape is complex.

(2) Scalar model

A scalar field can record the oxide inclusion distribution in a scalar model. The movement of an oxide inclusion with liquid metal was calculated via the transport equation. This can be used to calculate the oxide inclusion distribution inside the casting. The difference between the scalar models is the formation rate model of the oxide inclusion. Barkhudarov et al. [15] showed that the formation of an oxide inclusion on a free surface gradually accumulated with a wavy deformation and the folding of an inordinate free surface. This showed an increasing trend at a constant speed. Backer et al. [16] used the experimental results [5] of Campbell to study the oxide inclusion formation, and showed that the oxide inclusion could be generated with an inordinate free surface when the free surface velocity of an aluminum alloy liquid metal exceeded 0.5 m/s. This simulation method can track the movement of an oxide inclusion with the liquid metal. Thus, the final distribution of the oxide inclusion can be predicted, but the oxide inclusion distribution on the wall cannot be calculated because it fails to account for the adhesion phenomenon between the oxide inclusion and the wall of the mold.

(3) Eulerian-Lagrangian model

The Eulerian-Lagrangian model combines the macroscopic fluid model with a discrete particle dynamic model. It replaces the oxide inclusion with discrete particles. Reilly et al. [17] adopted a particle tracking method to judge the involvement of an oxide inclusion near the free surface with a Boolean Logic Criteria. Xu et al. [18] calculated the movement process and the locations of liquid metal and inclusions injected into the mold. This used two dimensions and the Eulerian-Lagrangian model. The results were verified by water simulation experiments.

Dai et al. [19] described the movement of oxide inclusions on a free surface by the Lagrangian-VOF method. They then developed a two-dimensional Oxide Film Entrainment Tracking algorithm to calculate the liquid aluminum flow and movement as well as the folding and entrapment of oxide inclusions during mold filling. This simulation method can explicitly track the movement of oxide inclusions, but the equivalence of discrete particles to oxide inclusions requires further validation. Meanwhile, many particles must be traced to guarantee computational accuracy under complex situations. This makes it difficult to guarantee computational efficiency.

This analysis indicated that there are no robust numerical models with computational accuracy that provide quantitative predictors of the formation and distribution of oxide inclusion defects during cast-filling processes. Therefore, a formation rate model that is relevant to the volume fraction of the liquid metal, the temperature, and the current oxide inclusion density is proposed here. This was based on an in-depth investigation of the oxide inclusion mechanism during cast-filling. A boundary condition was developed to handle the adhesion and accumulation on the wall. This work used the CFD software OpenFOAM for the relevant solver.

To prove the veracity and practicability of the model, we first simulated a representative aluminum alloy casting technology. This was used to analyze the effect of different runner systems on the oxide inclusion distributions inside casting and on the wall. The simulation results were compared with experimental data from the literature. Next, a practical copper alloy casting technology was calculated, and the simulation results of oxide inclusion defects on different parts of the wall were compared to the actual casting defect distribution.

2. Mathematical and numerical modeling

2.1. Evaluation mechanism of oxide inclusion

In most cast-filling processes, the liquid metal has a large area contact with the air. An oxidation reaction between the hot liquid metal and the air is inevitable—especially for the alloys with strong oxidability such as aluminum alloy and copper alloy. When the liquid front has accumulated sufficient oxide inclusions, the oxidation reaction between the liquid metal and the air will stop by the oxide inclusions generated between them. This results in a relatively smooth filling process. However, there is a relatively disorganized filling process due to the fluctuation in the liquid front. A portion of the oxide inclusion collides with the mold and then adheres to it. Another portion of the generated oxide inclusion is then drawn into the liquid metal, and this follows the liquid flow. When the arrangement of the pouring system is unreasonable or the filling process is too disorganized, the resulting oxide inclusion cannot be effectively intercepted by the pouring system. This seriously affects the surface quality and mechanical properties.

2.2. Formation rate model of oxide inclusion

Calculating the oxide inclusion formation rate is one of the keys to accurately predicting oxide inclusion defects. Taking a single simulation element as an object, the formation process of oxide inclusion can be regarded as a chemical reaction process between the liquid metal and the air in the element. When the element is full of liquid metal or air, the formation rate is considered to be zero. There are larger formation rates at higher temperatures. The current oxide inclusion in the element can block the continued formation of oxide inclusions. Consequently, from the point of