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Transient motion of inclusion cluster in vertical-bending continuous casting caster considering heat transfer and solidification

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ABSTRACT

A coupled three-dimensional finite-volume computational model has been developed to simulate the transient fluid flow, heat transfer and solidification processes in a vertical-bending continuous casting caster. The turbulence of molten steel inside the liquid pool is calculated using the large eddy simulation (LES). The enthalpy–porosity approach is used to simulate the heat transfer and solidification of steel in the caster. Based on the fractal theory and the conservation of mass, a kind of inclusion cluster model was developed. A new criterion was developed using the user-defined functions to model the motion and entrapment of inclusion cluster in the caster based on the Lagrangian approach. Firstly, the predicted growth of solidified shell was compared with the plant measurements, and the asymmetrical flow pattern was compared with the dye-injection observations of water model experiments. Secondly, the validated model was used to predict the instantaneous motion and entrapment distribution, statistical data, escape and entrapment positions of different inclusion clusters in the caster. Many known phenomena and other new predictions were reproduced in this part, and the center inclusion band defects in the steel plates found by the UT method can be interpreted using the current model. Finally, two methods were proposed to optimize the inclusion cluster motion and entrapment in the caster.

1. Introduction

Continuous casting (CC) has been widely developed as the most important production process in the steel industry. In the casting process, molten steel flows from a ladle, through a tundish into a mold. Inside the mold, molten steel freezes against the water-cooled copper mold walls and forms a solid shell. Wide-Thick-Slab (WTS) CC technology [1] is presented for the production of slabs with wide ranging from 1500–3000 mm and thicknesses ranging from 200–400 mm. Combining the advantages of conventional CC technology, the WTS-CC can meet different production targets such as high casting capacities, high-quality special steel production and highly economical plate production. And this casting process is highly flexible and well suited for casting slabs used for a wide range of applications, such as large marine engineering and shipbuilding, large bridge, large pressurized vessel, nuclear equipment, and so on.

Through the LF, RH and tundish refining, most of large argon bubbles and non-metallic inclusions have been removed and the purity of molten steel has been raised [2,3]. However, many smaller bubbles and inclusions still stay inside the molten steel, would be carried deep into the mold and collide together to form larger clusters, and finally these large clusters would be entrapped by the solidified shell forming defects, as shown in Fig. 1 which were the ultrasonic flaw detection maps (three cross sections: casting direction section, transverse section, and side section respectively) of two rolled steel plates, obtained from a vertical-bending WTS-CC caster. As can be observed from the visual analysis, the etch-pits, viewed as dots are the entrapped argon bubbles and non-metallic inclusions. There are many defects along the casting direction in the first plate, Fig. 1(a), most of them located at the thick center of the plate, be called "center inclusion band". Compared with the result of Fig. 1(a), the number of inclusions decreases as shown in Fig. 1(b), however it can be seen that there is a macro cluster inclusion found inside this steel plate. Then this macro inclusion cluster is magnified into view, as shown in Fig. 1(c); it can be seen that the outside dimension of this macro inclusion is 5 × 300 × 2151 mm. And it is composed with various smaller inclusions, such as Al_2O_3 inclusions. However, according to many previous works [4–6], most of monomer bubbles and inclusions would locate at the inner-curved section of the vertical-bending continuous caster due to the buoyancy of bubbles and inclusions. Previous researches would not be able to explain the reason for the center inclusion band defect which locates on the center of slabs.

Turbulent flow in the mold is important to the steel quality, because it influences the transport and entrapment of inclusions and bubbles, the fluctuation and shape of slag–metal interface, the transport and dissipation of superheat, the entrainment of mold flux at the top surface, and the growth of initial solidified shell. According to the recent plant observations and detections, the distribution of argon bubbles and

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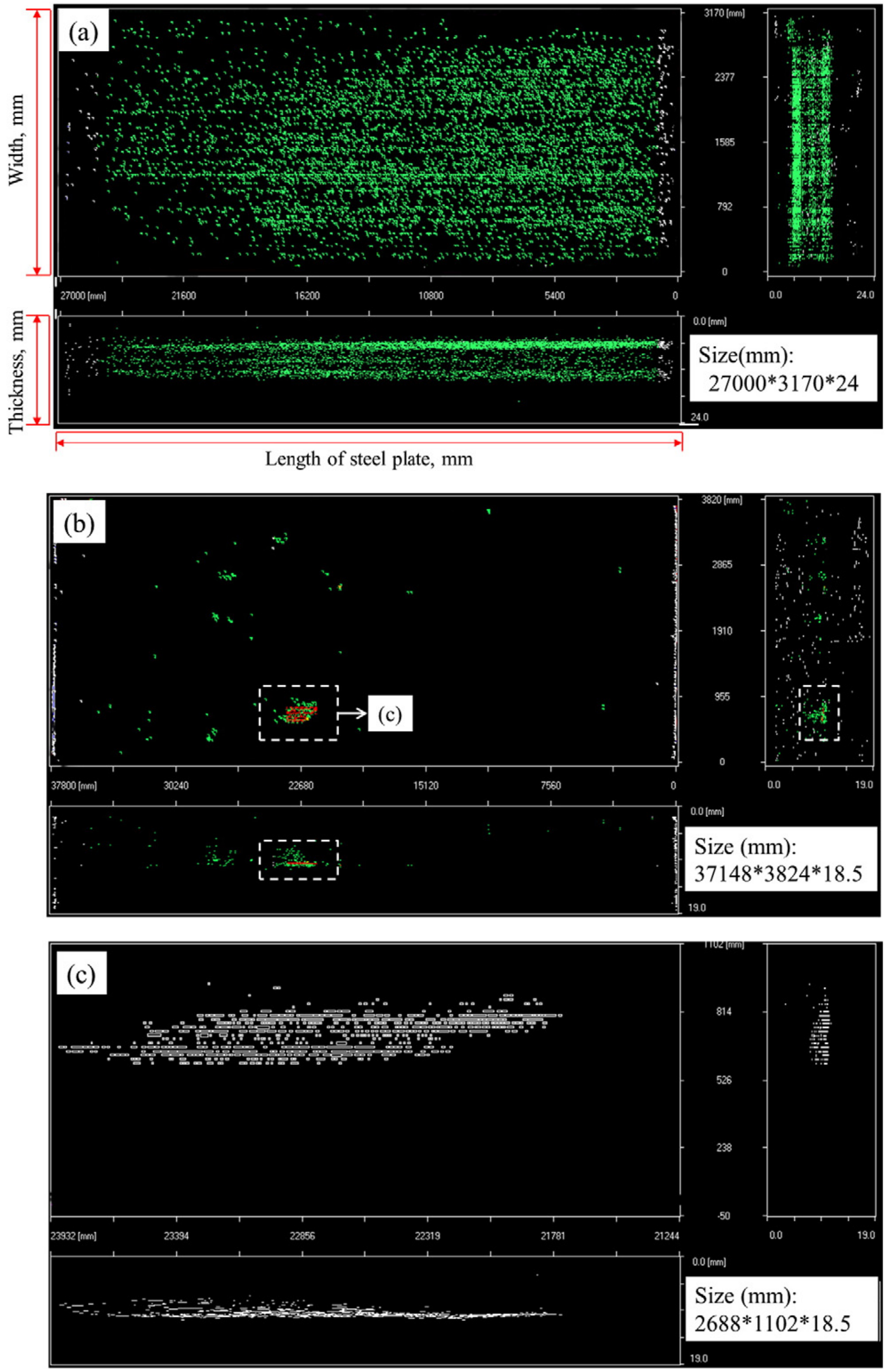

Fig. 1. Ultrasonic testing of different steel plates.

non-metallic inclusions captured by solidified shell in the rolled steel plates was intermittent and asymmetric [7,8]; suggesting that the fluid flow inside the mold was unsteady and instable. Several physical modeling studies [7–10] have been carried out to reproduce the asymmetrical and oscillating fluid flow inside the casting mold. However, experimental measurements on an actual slab continuous casting machine are very difficult, dangerous and expensive. Numerical modeling provides an alternative tool to understand and solve this kind of problem. Most of the reported mathematical models have been performed using the Reynolds averaged Navier–Stokes (RANS) models [2,11,12], such as the k-ε or Reynolds stresses. These models predict time-averaged velocities with reasonable accuracy and at a reasonable computational. However, these models, limited by the RANS's nature, are not suited for modeling the evolution of transient flow pattern triggered by flow instabilities. In recent studies [7,8,13,14], the large eddy simulation (LES) has been successfully applied to obtain the transient asymmetrical flow inside the mold. Authors developed different LES models for the single phase (molten steel) flow [8] and the two-phase (molten steel and argon gas) flow [7] inside the slab mold, respectively. Both of simulation results agree acceptably well with the water model