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Shrinkage porosity and its alleviation by heavy reduction in continuously cast strand

Qipeng Dong, Jiongming Zhang*, Bo Wang, Xinkai Zhao

State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, Beijing 100083, China

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ABSTRACT

Heavy reduction process was proposed as a novel strategy to alleviate the porosity during strand continuous casting, and a few studies were performed to investigate the formation of shrinkage porosity and the effect of heavy reduction on the porosity. A simplified model was applied to quantitatively predict shrinkage porosity, about 2.7 mm in diameter in the experimental conditions was obtained. A series of plant trials, including single-roll heavy reduction and multi-roll heavy reduction, were performed to study the effect of the application on porosity. The heavy reduction process effectively alleviated the porosity in the billets, and large reduction and a high central solid fraction showed a large contribution to the alleviation. Traditional soft reduction was also conducted for comparison, and heavy reduction was found to be more effective than the soft reduction in the improvement on porosity. The morphology of porosity during reduction process was analyzed with numerical simulation. Both the closure index and hydrostatic stress proved the effective role of heavy reduction in the alleviation of porosity.

1. Introduction

Porosity is a major defect in metal casting which will significantly decrease the mechanical performance of the resulting material due to degradation of fatigue resistance and tensile strength. Based on the size, porosity can occur as micro-porosity and macro-porosity (also called void). Porosity cannot be eliminated by subsequent heat treatment process, and the best strategy to reduce porosity is to better understand the formation of porosity to determine appropriate strategies to prevent its occurrence.

Early investigations by Pellini (1953) were conducted to study the formation of porosity. Results showed that temperature gradient plays an important role in the formation of porosity, and this was discussed in detail by Niyama et al. (1981) with a number of commercial casting experiments. Niyama et al. (1981) recognized that a threshold of temperature gradient, depended on both shape and size of a particular casting, should be obtained to avoid shrinkage porosity. Moreover, Niyama et al. (1982) experimentally plotted the critical temperature gradient, which was shown to be inversely proportional to the square root of cooling rate for each casting size against the calculated final solidification time. And this observation gives rise to the famous Niyama criterion, $Ny = G/\sqrt{R}$. Engstrom et al. (1983) studied the difference of temperature gradient between the two solidification fronts during solidification, and they pointed out that the difference will lead to porosity during strand continuous casting. Sigworth and Wang (1993) developed a number of numerical models to predict the formation of porosity in directional solidification. Compared to experimental results, the thermodynamic model was proved to be useful in the prediction of porosity. Recently, Carlson and Beckermann (2009) presented a dimensionless Niyama criterion, which could be used to directly predict the volume fraction of shrinkage pore during solidification of metal alloys.

Although technologies such as electromagnetic stirrer (EMS) and soft reduction were developed to improve the quality of strand, these techniques still allowed excessive porosity that compromised the integrity of the finished products. Therefore, hot rolling or forging have become standard for the elimination of porosity. The morphology of voids in swing forging process was studied by Chaaban and Alexander (1977) who demonstrated that the elimination of voids takes place in two steps: closure and welding. Tanaka et al. (1987) investigated the effective strain and the time integral of hydrostatic stress, which were reported to be the key factors governing the closure of void during forging. In order to predict appropriate parameters of hot rolling, Wang et al. (1996) experimentally investigated the closure and welding phenomena of holes, which were drilled in steel slabs at different depth below

* Corresponding author at: State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, No. 30, College Road, Haidian District, Beijing 100083, China.
E-mail address: jmz2203@sina.com (J. Zhang).

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the surface. Also, morphology of the holes was modeled with the FE software ABAQUS. Both the experiment and simulation suggested that closure of the holes would be affected by the parameters of hot rolling and position of the holes. Park and Yang (1997) investigated the welding process in ingot forging with a schematic model, which was developed based on nucleation in the bonding band and the introduction of an anti-bonding film. The appropriate amount of reduction, shape of upper tie and the position of void were found to be beneficial to the welding. Nakasaki et al. (2006) quantitatively described the closure of porosity with the integration of hydrostatic stress. It was found that the cross-sectional area of porosity was in proportion with the hydrostatic integration in single-pass rolling. To apply the result to continuous rolling, the hydrostatic integration was modified by introducing a coefficient. Another quantitative investigation on the closure of void during hot forging was implemented by Zhang et al. (2009) in large ingots. A criterion for the closure of void was proposed by them, and the significant effects of the Norton exponent, the remote stress and the remote effective strain on the closure of void were revealed with the criterion. Recently, Lee et al. (2011) studied the closure of internal voids during open die forging by both experiment and simulation. Results showed that a local effective strain value of 0.6 or greater must be achieved for the closure of void during forging.

Although porosity can be effectively eliminated by hot rolling or forging, a high compression ratio is important for the process. However, the high compression ratio lowers the efficiency of production and is costly. Thus, in order to increase productivity, a new process named “Forging” was developed by Kawasaki Steel. In the process, a pair of flat anvils was installed at the final stage of solidification to provide large reduction to eliminate porosity. Using the technology “Forging”, Araki et al. (1999) tried to produce qualified heavy plate with continuously cast slabs, instead of ingots. Plant trial showed that, with large widthwise reduction ratio and appropriate ratio of anvil block contact length and thickness of slab, it is possible to obtain excellent internal properties in the manufacture of heavy steel plates with thickness of up to 240 mm. Later, Sumitomo Metal developed the PCCS process, Porosity Control of Casting Slab, to reduce the porosity in the slab continuous casting. Research by Hiraki et al. (2009) showed that the porosity can be effectively improved by PCCS process while central solid fraction of roll position is 0.8–0.95. Recently, POSCO had developed a new technology called the PosHARP to prevent and minimize internal defects of slab. Compared with soft reduction, the macrostructure of thick slabs was improved better with PosHARP and segregation was improved apparently, porosity was also notably reduced by almost one-third (Yim et al., 2012).

In the present work, a few studies including the formation and reduction of the shrinkage porosity during strand continuous casting were performed. Firstly, the formation of shrinkage porosity was quantitatively predicted with a two-dimensional mathematical model. Then, a novel technology called heavy reduction process was proposed as a method to reduce porosity. Next, the effect of this technology on the porosity was studied experimentally. Finally, the morphology of porosity during heavy reduction process was modeled to discuss the effect of the novel technology.

2. Formation of shrinkage porosity

A two-dimensional mathematical model that expands the work of Lally et al. (1990) was applied to calculate the evolution of temperature in continuous casting process, and the simulated results for the center and surface temperatures are shown in Fig. 1 as a function of the distance from meniscus. Due to the high cooling intensity in mold, the surface temperature sharply drops to 1340 K at the exit of mold. After that, affected by the decline of cooling

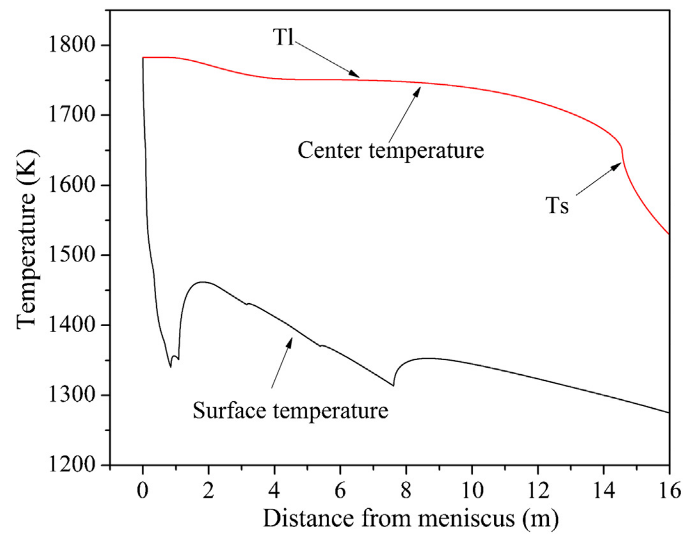

Fig. 1. Predicted temperature at the surface and the center of billet.

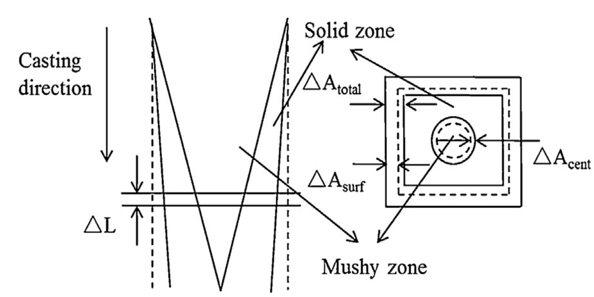

Fig. 2. Schematic diagram of the solidification model.

intensity and the release of latent heat from the central portion of billet to the surface, the surface temperature rises at secondary cooling zone. The maximum surface temperature, larger than that at the exit of mold about 110 K, arises at about 2 m away from meniscus. The temperature at the center changes slightly at the early stage of solidification as a result of the release of latent heat. As the solidification proceeds, the decrease in evolved latent heat will result in the rapid decrease of temperature at the center of billet, as shown in Fig. 1. The billet shell and release of latent heat during solidification might allow difference in temperature gradients, which would lead to differences in volume shrinkage. At the early stage of solidification, the distinction between the two volume shrinkage did not affect the internal quality of billets. However, the situation was severe at the final stage, large shrinkage took place at the solidification front and the billet shell contracted slightly. These events would cause shrinkage pores at the center of billets.

In this work, a simplified model (Raihle and Fredriksson, 1994) was used to predict shrinkage during the solidification of billet. A schematic diagram of the model is shown in Fig. 2. Three variables were defined to describe the shrinkage at different positions:

$$\Delta V_{cent} = \Delta V_{total} - \Delta V_{surf} \quad (1)$$

where, ΔV_{total} denotes the volume of shrinkage at solidification front, ΔV_{surf} and ΔV_{cent} stand for the shrinkage at the surface and center of billet, respectively.

The ratio of longitudinal heat flux to the total is only about 3–5% (Sun and Zhang, 2013), so the heat transfer in casting direction was ignored in this work. A slice of billet with small thickness (ΔL) was defined as the computational domain:

$$\Delta V = \Delta A * \Delta L \quad (2)$$