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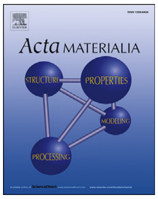

Full length article

Experimental study and two-phase numerical modeling of macrosegregation induced by solid deformation during punch pressing of solidifying steel ingots

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ABSTRACT

Ingot punching tests are performed on the already formed solid shell of a 450 kg steel ingot during solidification. Such test is designed in order to be representative of the thermomechanical conditions that give rise to macrosegregation during secondary cooling in steel continuous casting. In order to understand the different physical phenomena, a numerical model of the test has been developed, consisting of a two-dimensional planar finite element simulation in the median section of the ingot. A two-phase formulation has been implemented, in which the velocities of the liquid and solid phases are concurrently solved for. The simulation shows how solutes are redistributed through the central mushy zone of the ingot under the effect of the compression of the solid phase and the induced fluid flow resulting from the punching of the solid shell. By comparison with measurements of macrosegregation operated on two ingots of same initial composition but punched under different conditions, the simulation proves its capacity to reproduce the main experimental trends. However the predicted intensity of macrosegregation is lower than the one measured. Through discussion and analysis of different numerical sensitivity tests, critical material parameters and model improvements are identified in view of attaining better quantitative predictions in the future.

1. Introduction

The paper focuses on a major defect encountered during secondary cooling in steel Continuous Casting (CC): macrosegregation. This critical defect is observed at the center of continuously cast semi-products, such as slabs and billets. Like in any solidification process, macrosegregation results from the concurrent effect of microsegregation on the one hand, and the relative movement of the liquid phase with respect to the solid phase on the other. Microsegregation consists of the enrichment or depletion of the liquid phase in solutes at the scale of the dendritic microstructure. As analyzed in the pioneer work by Flemings and Nereo [1], the differential liquid motion with respect to the solid may have different causes: i) the solidification shrinkage and the thermal contraction of the solid phase, ii) the convection flow of liquid arising from its local variations of density with temperature and chemical composition, iii) the movement of equiaxed solid grains transported by the liquid flow, and iv) the deformation of the solid phase within the mushy zone. In steel ingot casting, all coupled phenomena are present and play a part in the formation of macrosegregation, but the last one (iv) can often be neglected. Regarding numerical modeling, one can refer to Wu and Ludwig, Li et al. [2,3] and Zaloznik and Combeau [4] who developed the more advanced numerical models at the present time, in the context of the finite volume method. The latter authors have also worked with two authors of the present paper to demonstrate the feasibility of finite element (FE) formulation [5].

Conversely to ingot casting, the deformation of the solid phase within the mushy zone plays a major role in continuous casting of steel. This deformation is created by the bulging of the solid shell

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between support rolls of the CC machine, which is due to the metallostatic pressure, the possible bending and unbending of the strand, and by the possible so-called “soft reduction” consisting of a mechanically applied thickness reduction of the strand operated close to the end of solidification. Such a thickness reduction of the cast product generates deformations of the underlying solid phase within the mushy zone and, as a consequence, macrosegregation. Several researchers studied these phenomena in the context of CC process with numerical modeling. Miyazawa and Schwerdtfeger [6] modelled solidification and macrosegregation, considering bulging between support rolls and the associated mushy zone deformation. In their model, mass, liquid phase momentum, solute and energy conservation equations are described in a fully Eulerian approach. The solid phase momentum equation is not solved so the velocity fields of the solid shell and of the solid phase in the central mushy region are arbitrarily given. The numerical simulation shows the formation of a center line with positive macrosegregation due to bulging. Kajitani et al. [7] studied the so-called soft reduction process using the same approach and discussed the quantitative impact of the soft reduction technique to reduce the intensity of the central macrosegregation. In a more recent contribution, Domitner et al. [8] developed a two-dimensional (2D) model covering the whole length (25 m) of the product in the caster, but still with a predefined motion of the solid phase, like in Refs. [6,7]. Fachinotti et al. [10] developed a different approach to model the mushy zone in the context of CC, using an arbitrary Lagrangian-Eulerian approach in which solid and liquid velocity fields are concurrently solved for, avoiding then the strong hypothesis over the solid velocity field which was present in previous works. With this model, the authors simulated continuous casting and similarly retrieved the effect of bulging on the formation of central macrosegregation [11]. More recently, Rivaux [12] developed an alternative approach to model the deformation of the solid phase and its Darcy-type interaction with the liquid phase in the mushy state, through a staggered scheme in which the two fields are separately and successively solved for at each time increment. However, in the end and despite lots of efforts made in developing those numerical models, none of them has been successfully applied up to the scale of a three-dimensional (3D) simulation representative of the complexity of the industrial process. This is certainly due to the considerable amount of computational power required to run the models encompassing a significant part of the secondary cooling section of an industrial caster.

This is one of the reasons why, in order to study and better understand the origin of the defect, experiments such as ingot bending or ingot punch pressing, have been developed by several researchers for many years [13–18]. The objective of these experiments is to analyze macrosegregation phenomena when they arise essentially from the deformation of the solid phase, and to do this in a configuration a priori simpler than continuous casting: ingot casting. This is obtained by deforming the external solid shell of an ingot during its solidification. The present study reports on an ingot punch pressing test which has been designed and operated by Nippon Steel & Sumitomo Metal Corporation (Tokyo, Japan). In order to analyze the test, especially from the macrosegregation point of view, a FE numerical simulation has been developed using the research code R2SOL previously developed at MINES ParisTech CEMEF [10,11]. The paper presents the test and its application to two steel ingot of similar initial composition but punched at different times (that is for different degrees of solidification progress). Then, FE modeling of thermomechanics and solute transport is introduced. Finally, results are presented and the predicted occurrence, location, and intensity of macrosegregation are explained and discussed in the light of experimental measurements.

2. Ingot punch pressing test

The schematic of the ingot punch pressing test, as developed at Nippon Steel & Sumitomo Metal Corporation, is shown in Fig. 1. It has been designed to mimic the thermomechanical loads taking place during CC process; for instance, with respect to the evolution of the cooling rate and deformation. The procedure of the experiment is as follows: the molten metal is prepared in an electric ladle furnace and the temperature is maintained at 1640 °C before pouring. The molten metal is poured into the mold from the top through a tundish. The filling duration is about 70 s. After filling, powder is added at the top of the ingot to limit heat exchanges with air. The mass of metal is approximately 450 kg. The size of the ingot is 0.16 m in thickness, 0.5 m in width and 0.75 m in height. In practice, a fibrous thermal insulator of thickness 5 mm covers the inner walls of the lowest part of the mold up to 0.2 m from the bottom of the ingot in order to avoid molten metal sticking. At a precise time after filling, the upper part of one of the two large faces of the mold is removed, as illustrated in the right part of Fig. 1(b). The ingot is then deformed during solidification by pushing a horizontal cylindrical tool perpendicularly to the surface of the ingot, its longitudinal axis being located 0.45 m from the bottom of the ingot. The tool velocity and displacement are controlled by means of a hydraulic system and measured during the test. The reaction force is also measured using the time evolution of the hydraulic system pressure.

For the alloy targeted in the present work, a total of 9 experiments, labelled N-1 to N-9 were performed. They belong to a series that aims at studying both macrosegregation and hot tearing sensitivity as these defects are frequently found to form concomitantly [19]. However, due to very demanding efforts to analyze and present the trials with respect to macrosegregation, only the test conditions referred to as N-1 and N-9 are considered in the present work. Parameters are summarized in Table 1, together with measured nominal compositions in the ladle before filling. Note that a unique alloy composition was targeted for the experimental results reported hereafter. The two tests differ first by the time at which the punching starts. For N-1 punching starts earlier on a central mushy zone richer in liquid. Conversely, for N-9, solidification is more advanced at the beginning of punching. Tests show also differences in punch displacement, the maximum punch force being limited to 450 kN for the protection of the bending equipment. In case N-9, this limiting punch force is obtained for a displacement of 9 mm, after which the punch stops. In case N-1, which is a priori less resistant, due to a less advanced solidification, the limiting force is obtained for a larger displacement of 13 mm. The temperature evolution during the test is recorded by a B-type thermocouple positioned in the ingot cavity, as shown in Fig. 1(a). For the thermocouple setting, a hole along horizontal direction, of diameter 5 mm, is pierced through the fixed large face of the mold. A thermocouple is inserted into the hole from outside and is placed at the desired position. For sealing purpose, a thermal insulator is put into the hole after setting of the thermocouple.

After the experiment, ingots were cut along their central transverse symmetry plane and micrographs were carried out after appropriate etching. Fig. 2 shows micrographs for both trials N-1 and N-9. The punching tool moves from the right to the left and the surface deformation due to punching appears clearly. Concerning microstructure, one can see a dendritic columnar microstructure which has grown from the ingot surface toward the center. Note that the primary trunk of the dendritic structure is slightly oriented upward. This is expected when considering liquid melt thermal convection oriented downward in front of the growing dendrites. Because the direction of dendrite trunks and arms correspond to ⟨100⟩ crystallographic directions in the present system, a texture of