Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 20(2010) s878−s882
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Prediction of shear-related defect locations in semi-solid casting using numerical flow models

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Received 13 May 2010; accepted 25 June 2010

Abstract: Contaminated surfaces of the feedstock materials in aluminum alloy casting processes often produce various types of defects which can affect the tensile properties of the final products as well as their fatigue reliabilities. Semi-solid processing takes advantage of a much higher apparent viscosity of the die cast materials by limiting the risk of oxides formed at the free surfaces to become incorporated into the casting when the material is injected into the die. Most of existing semi-solid processes that use billets as feedstock material are however tied up with a different type of contaminated surface. During the injection phase, the external-skin on the periphery of the billet, which has been in contact with air and lubricant during the transfer in the shot sleeve, can be incorporated into the casting. When subjected to a heat treatment, the lubricant is decomposed and produces lens shape porosities. This might be a cause of reject for most structural parts. To avoid this kind of defects, the paths along which the billet skin evolves must be controlled during filling. In order to investigate the possibility of skin inclusion into cast parts during injection of the billet, a two-phase finite element mixture model is employed to model the metal flow. The formation of a skin on the periphery of the billet is modeled by setting an initial solid phase concentration profile in the radial direction. Microscopic observations of the real castings show that the approach is able to model the shear layers and to predict the paths along which the "lens porosity" defects could be formed. An Arbitrary Eulerian-Lagangian (ALE) method is also investigated and appears to be very promising to follow the skin movement in the casting.

Key words: oxide skin defects; two-phase flow; finite element modeling; Arbitrary Eulerian-Lagangian (ALE) method

1 Introduction

Aluminum casting processes are highly adaptable to the requirement of mass production and are nowadays widely used for many commercial products. Certain advantages are inherent to these processes, eg. obtaining complex near net shape parts with specific requirements such as good surface finish and good mechanical properties.

Semi-solid casting processes are employed when high integrity parts are required. Indeed, semi-solid processes provide during filling more regular flow fronts compared with high pressure (liquid) die casting processes and thus reduce the possibility of entrapping oxide skins into the part. Nevertheless, oxide film related defects are difficult to avoid in metal injection processes. These defects may take different forms and originate either from the melt preparation or from the filling phase[1].

In many rheo-molding processes, the billet is obtained from liquid aluminum that partially solidifies before being injected into the cavity as a semi-solid material. During the billet preparation, the aluminum in contact with the container can form a skin around the semi-solid core. Meanwhile, the top circular surface of the billet remains in contact with air and is thus prone to oxidation. Oxides may also be introduced in the semi-solid billet when liquid aluminum is poured into the crucible but the latter case is not considered in this work.

The billet is next inserted horizontally into the shot sleeve. Because of gravity, there is contact between the bottom part of the billet and the shot sleeve wall. Consequently, the heat transfer is greater there and yields a "skin" that may be partially solidified. The "thickness" of the skin depends on the time spent in the shot sleeve before the injection. The lubricant in the injection chamber lies at the bottom of the shot sleeve and gets in contact with the skin. When injected into the cavity, the contaminated skin will probably enter into the part and

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yield undesired defects.

During heat treatment of the part, the lubricant that contaminated the surfaces that were injected in the part, is decomposed and produces “lens shape” porosities as depicted in Fig.1. In Fig.1 the defects are on the shearing plane, where they were formed, but they could also propagate downstream depending on the ensuing velocity field. These defects can have definitely detrimental effects on the part integrity. To limit any serious consequences, the distribution of the skin inside the casting must be controlled by properly directing the flow during the injection phase.

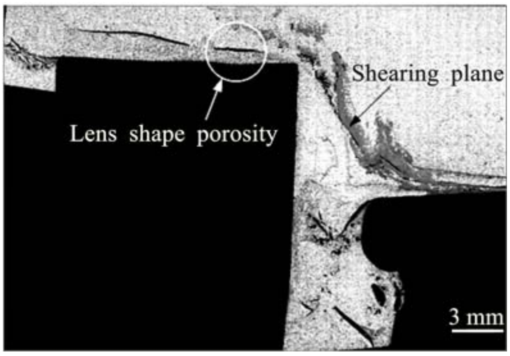

Fig.1 Porosity of lens defects along shearing plane

In this work, a method is presented to identify the paths followed by the contaminated skin in the semi-solid casting. This will provide a tool to predict potential defect locations and to design the gating systems accordingly.

2 Numerical simulation of problem statement

Different approaches have been employed in the past to track the oxide skins associated with die casting processes, e.g. Ref.[1]. A kinematic approach has often been employed to track selected points initially located on a free surface. This type of approach permits to follow air entrapments and free surface folding which are usually related to the occurrence of oxide formation and thus can identify potential defect locations into the part.

In the present case, the skin is not a free surface. It is initially in contact with oil coating on the shot sleeve wall. Observations have shown that the skin will generally enter into the part along a shearing plane of the flow field. This very thin partially solid skin-fluid interaction is complex and not easy to deal with numerically. The skin must thus be followed to control inclusion defects into the part. An analysis of this complicated non-Newtonian flow that occurs during semi-solid injection casting can yield useful insights to resolve the difficulty.

In the next section, a model is presented to predict the displacement of the skin with the flow and evaluates where potential defects could be located. An arbitrary Lagrangian-Eulerian (ALE) approach is also presented. The latter approach has many interesting features that could be very helpful in a near future to accurately follow the oxide surface fragments and to optimize semi-solid gating systems.

3 Finite element model

As a first approximation, the flow resulting from the injection of a billet with a skin is modeled using a two-phase mixture approach. Three-dimensional modeling of the flow of a two-phase mixture is based on conservation of mass, momentum and solid volume fraction for an incompressible fluid. Derivation of the mixture conservation equations was detailed in Ref.[2]. The complete finite element model used in this work is described in Ref.[3]. The constitutive behaviour of the semi-solid material is given by a power-law relation from ORGEAS et al[4] which relates the local viscosity (μ_0) of the semi-solid material to the shear-rate ($\dot{\gamma}$) temperature:

$$\mu = \mu_0 \left(\frac{\dot{\gamma}}{\dot{\gamma}_c} \right)^{n-1} \quad (1)$$

In this work, the dependency of μ_0 and n to the solid fraction has been removed to prevent the freezing of high solid fraction areas such as the ones used to represent the skin (otherwise no movement is possible with the mixture formulation). The following constant parameters (Table 1) have been set in Eq.(1).

Table 1 Model parameters

μ_0/(Pa·s)	n	γ_c /s^{-1}
7.244 5	0.4955	1.0

To represent the “skin” on the billet surface, the solid fraction distribution is set along the billet radius as depicted in Fig.2. The solid fraction (mass fraction) is held constant (f_s=0.5) in the core and increases to 0.6 near the wall. To simulate the presence of an oil film at the wall, the solid fraction is reduced to 0.1 near the wall location.

The geometric model of the shot sleeve and the cast part used in this study is presented in Fig.3. The finite element mesh is shown in Fig.4 and consists of 444 142 four node tetrahedron elements (81447 nodes). The material is aluminum 357 (ρ=2 600 kg/m^3).

The boundary conditions are “full slip” for the shot sleeve wall and “no slip” for the cavity walls, including the oxide ring. These conditions better reflect the physics of the billet that is injected in the shot sleeve. Full slip

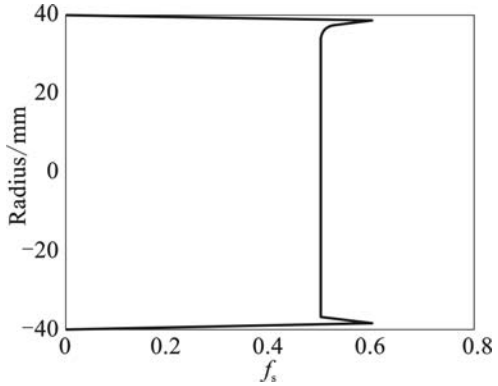

Fig.2 Initial solid fraction distribution along billet diameter

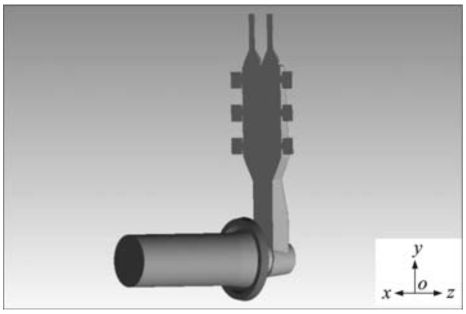

Fig.3 Geometrical model

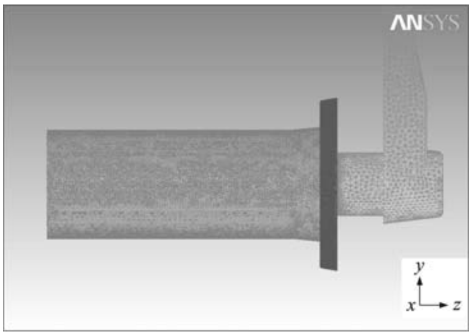

Fig.4 Finite element mesh of shot sleeve

conditions also prevent the skin from being stuck on the shot sleeve wall.

The inflow velocity (piston head velocity) is set to 300 mm/s. The movement of the piston is not accounted for, though this could certainly provide a better picture of the flow that is taking place. Instead, a constant feeding of the shot sleeve is set at the far end of the sleeve. The inflow solid fraction distribution is also set there and is similar to the initial solid fraction distribution inside the billet, except that it remains at 0.6 near the wall. This is used to better approximate the movement of the piston which somewhat pushes the “skin” along the walls. Isothermal conditions are assumed.

4 Simulation results

Calculations were performed with the finite element code for mold filling applications developed at the Industrial Materials Institute[5]. Simulation results with the two phase mixture model are depicted in Fig.5 where the flow of the semi-solid material is shown at different times during the injection. The initial condition is depicted in Fig.5(a) where an approximation of the contaminated surface (oxide skin and lubricant) is represented by a layer of high solid fraction near the billet walls. This “skin” is then carried away by the flow. In the early stages, the skin material accumulates on the diaphragm wall, as shown in Fig.5(b). Part of the skin is caught by the oxide ring and most of the material near the wall remains in the shot sleeve as long as the oxide ring is not completely filled up, see Fig.5(c). Actually, some parts of the skin upstream may be swept along by the flow and get into the feeding channel due to some “surface instability” but this point has not been verified yet. When the oxide ring is filled up, the “high” solid fraction “skin” enters into the feeding channel along the shearing plane produced by the flow of semi-solid material through the constriction of the injection assembly, see Fig.5(d).

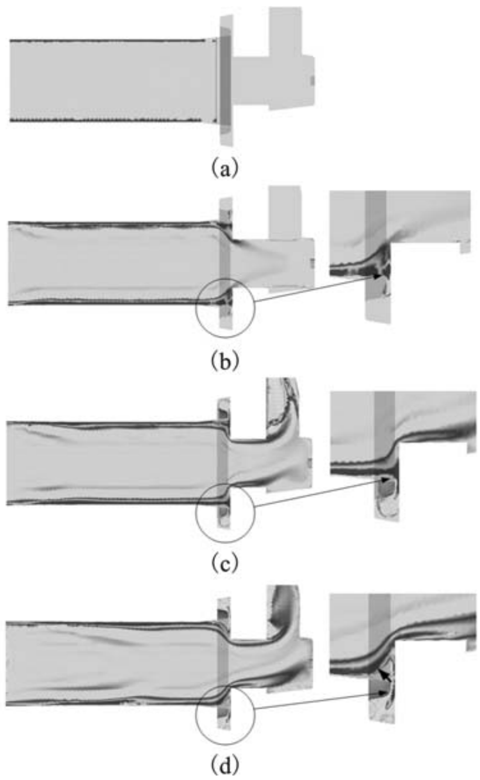

Fig.5 Material evolution near wall (solid fraction range is 0.6 near wall and decreases radically to 0.5)

Note that when the semi-solid material is sheared, bands of higher liquid fraction generally appear at the shearing plane location, which facilitates the inclusion of the skin into the casting, e.g. Ref.[6]. Evolution of the oxide skin further downstream will next depend on the channel geometry.

The low velocity region in the bottom portion of the “anvil” reservoir will generally trap the skins that come from the bottom part of the shot sleeve (when not trapped by the oxide ring), see Fig.6, “L” region.

However, skin fragments that come from the upper part of the sleeve may be caught by the flow and carried away downstream, see Fig.6, “H” region. In the latter case, oxide skin fragments do not have to follow a shearing plane once they have reached the channel and can show many different orientations in the part.

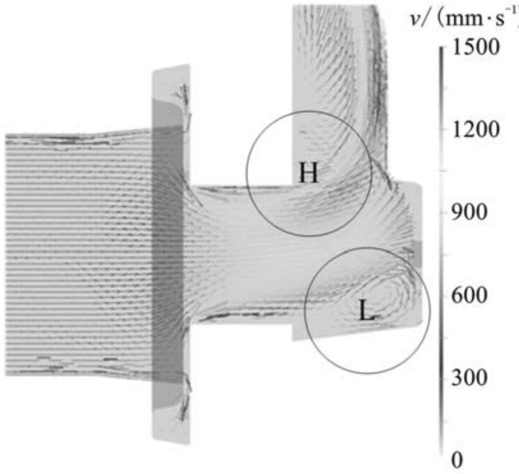

Fig.6 Velocity fields in feeding channel

Note also that skin fragments that come from the upper part of the billet are generally “less” contaminated by lubricants and will not necessarily yield a “lens” defect after heat treatment. They are thus more difficult to detect.

One of the problems with the mixture approach is that we follow a concentration field instead of a solid skin. The results are thus somewhat diffused and only give some information about the flow paths that are prone to be followed by oxide skins at the early time of the injection. Moreover, the latter approach assumes that the skin is continuous. In reality, it is not and it will be fragmented by the flow. Consequently, the mixture approach does not show exactly where defects could be located along those paths. To achieve that, an alternative method should be used. In the next section, we present an ALE approach, (Arbitrary Lagrangian-Eulerian), which could be further developed to follow and locate the contaminated skin fragments into the casting.

5 Aribitrary Lagrangian-Eulerian calculations

The following calculations have been carried out with the commercial software LS-DYNA. The latter has been originally designed to solve dynamics problems using Lagrangian formulations[7]. LS-DYNA, incorporates Eulerian formulations as well for fluid flow analyses. Moreover, Lagrangian problems can interact with Eulerian problems inside the same model to treat fluid-structure interactions[8]. The complete ALE formulation is presented in Ref.[9]. An application of LS-DYNA to casting problems has been performed in Ref.[10]. In this work, the software is used to evaluate the feasibility of the ALE approach to predict skin related defects in parts produced with semi-solid processing. These initial tests are carried out on a 2-D model. The problem is again isothermal. The skins are 0.25 mm in thickness and are modeled as an elastoplastic material with corresponding mechanical properties.

Fig.7 shows the mold geometry with initial positions of the skins near the wall of the shot sleeve and in front of the billet. The semi-solid billet is modeled as a fluid-like material with a non-Newtonian type behavior. Velocity boundary conditions are set at the inflow plane.

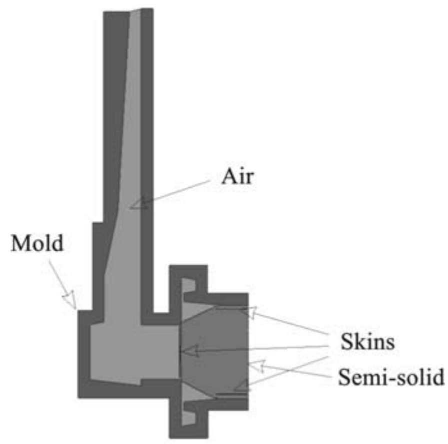

Fig.7 LS-DYNA SSM casting model

Sequences of filling with skin tracking are depicted in Fig.8. In Fig.8(a), the semi-solid material hits the bottom of the “anvil” reservoir. The skin associated with the front of the billet impinges the “left” wall and remains there. Parts of the skin that were on the billet periphery enter in the channel section. As suggested by the mixture model, the bottom skin is carried by the vortex and remains there. The top skin is carried into the part by the flow, Figs.8(b) and (c) and can yield potential defects in the part.

6 Conclusions

1) A finite element mixture model has been used to investigate the flow of a semi-solid billet “coated” with an “oxide skin”. The model can provide valuable information on the flow that takes place in the shot sleeve and can predict the paths by which the contaminated surfaces enter into the feeding channel.

2) The model reproduces the shear layers that seem to facilitate skin inclusions in the casting. However, the mixture model is diffusive and the skin which is approximated

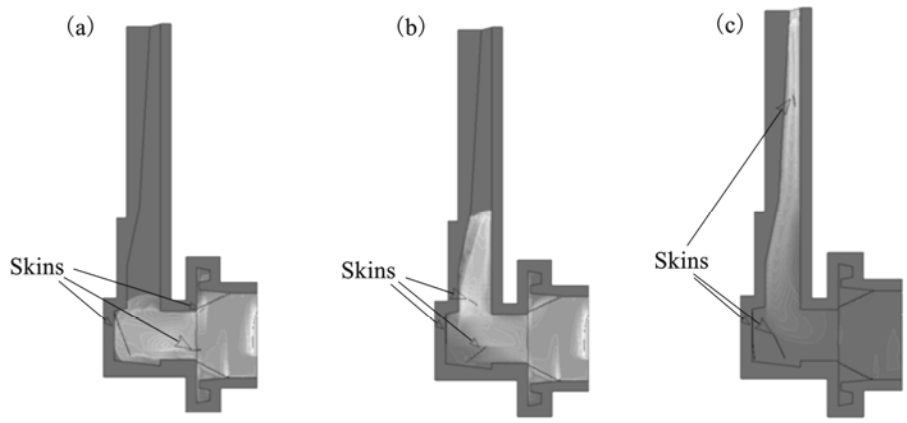

Fig.8 LS-DYNA SSM skin flow casting model

by a layer of higher solid fraction tends to be diluted during the flow and disappears. Consequently, the model can be employed to indicate locations where shear type defects could be formed and propagate into the flow, as long as there is a shear layer. To overcome these limits, another approach has been investigated and used: The ALE method of LS-DYNA. In this model, the skin is represented as a solid entity with distinctive dimensions and mechanical properties. It can be transported, torn and folded according to the velocity field.

3) Preliminary tests on a 2-D slice show that the model is very promising and could eventually be used to predict shear defect locations in the casting. The mold and gating system could then be designed to avoid these defects.

4) Further work is required to characterize properly the skin mechanical properties in addition of the semi-solid flow properties.

Acknowledgements

The authors want to express special thanks to their colleagues Marie-Ève Larouche and Dany Drolet for their help given in this work.

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(Edited by YANG Hua)