International Journal of Solids and Structures 99 (2016) 12–27

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Effect of coating material on the growth instability in solidification of pure metals on a coated planar mold of finite thickness

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ARTICLE INFO

Article history:
Received 28 December 2015
Revised 10 August 2016
Available online 23 August 2016

Keywords:
Solidification
Thermo-elastic stability analysis
Linear perturbation method
Mold coating
Metal casting

ABSTRACT

In this study, a theoretical basis of thermomechanical instability during the solidification of pure metals on a coated planar mold is presented. This study extends the previous works by taking into account the presence of a deformable coating layer on the inner mold surface. The thermal and mechanical problems are assumed to be coupled through the pressure dependent thermal contact resistances at the shell/coating and coating/mold interfaces. On the other hands, the thermal capacitance of solidified shell, coating layer and mold materials are neglected for the sake of simplicity. A linear perturbation method is used to reduce the spatial dimension of the problem. The model leads to two coupled differential equations for the shell thickness perturbation and residual stress which are solved numerically. The results document the variation of the perturbed solidification front as a function of ratio between the thermal conductivities of the shell and coating materials for combinations of other process parameters such as the combination of shell and mold materials, the values of coating thickness and coupling rates. In case of weak coupling, the maximum magnitude of this perturbation decreases regardless of the value of coating thickness and shell-mold material combinations when the thermal conductivity of the coating material is decreased. In case of strong couplings however, a critical thermal conductivity ratio between shell and coating materials which leads to a formation of greatest or lowest perturbation in the solidification front depending on the values of other process parameter has been found.

1. Introduction

The solidification of castings involves the extraction of heat by conduction across the interface between the casting and the mold. There will generally be some thermal resistance at this interface due to the effects of surface roughness and surface or contaminants films. Furthermore, this resistance will be pressure dependent, tending to fall when the contact pressure is increased. The contact pressure is in turn affected by the thermoelastic distortion of the casting and the mold during solidification due to the nonuniform temperature field that is an inevitable consequence of the cooling process. This process has the potential for instability, resulting in both surface and internal cracking of the cast product through nonuniform thermal distortions. This can also lead to an undesirable metallurgical structure within the cast product (Yigit and Barber, 1994).

The mold coating is one of the most important factors controlling the heat transfer rate and hence, it has very important role on the solidification rate and development of microstructure (Hamasaiid et al., 2007). Hamasaiid et al., (2007) worked on the influences of material and thickness of the mold coating and alloy composition on the extraction of heat at the shell/mold interface during solidification of Al alloys experimentally. They found that heat transfer coefficient decreases when the thickness of the coating layer is increased and the effect of coating material diminishes after air-gap nucleation at the shell/mold interface. Coating layer is also used to protect surface quality of the mold. Additionally, mold coating acts like a barrier between the shell and mold and promotes thermal properties. Additionally, it is used to get over the various operating needs such as low wettability, high hardness and good wear resistance (Sanz, 2001). Experimentalists have addressed the issue of mold coatings with different ways. Chen et al. used a thin Ga-In-Sn liquid coating layer for solidification of $Fe_{74}P_{21}C_5$ alloy to improve Cu mold casting method with higher cooling rates (Chen et al., 2015). They found that a Ga-In-Sn liquid alloy coating layer increases the cooling rate by reducing the interfacial thermal resistance and causes homogeneous nucleation in the casting on a copper mold. The effects of mold coating and sand grain size on the properties of thin wall ductile iron were investigated experimentally by Jafari et al., (2010).

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http://dx.doi.org/10.1016/j.ijsolstr.2016.08.010
0020-7683/

The results show that using fine sand grain size and applying graphite-based zircon containing coating on the mold cavity improves the fluidity and reduces hardness and strength of TWDI casting. Salas et al. proposed to design a coating to increase mold surface quality and mold life by comparing several coating materials (Salas et al., 2003). The wear resistance and the adhesion performance of the coating materials were analyzed. Kariman et al. studied on the effects of thickness of the coating pattern on imperfection and porosity of a lost foam Al-Su-Cu alloy casting (Karimian et al., 2012). They indicated that thinner pattern coating improves the mold filling and leads to higher quality casting with less porosity. Hsueh-Shang et al. and Borouni (Lu et al., 2006, Borouni et al., 2014) investigated the effects of the ceramic coatings on fluidity during the solidification of magnesium and aluminum alloys, respectively. Nwaogu and Tiedje, (2011) wrote a review paper about foundry coating, in which explanation of description, components, characteristics and mechanism of coating are discussed.

One of the first reported studies about the growth instability during the casting process is done by Neymark, (1955). The growth instabilities in cast metal plates were investigated by using a vacuum crystallization device in this study and it is observed that air gaps tended to nucleate beneath minima on the freezing fronts of metals. Other earlier experimental works about periodic undulation of the casting microstructure are listed in Sigutani et al., (1992), Singh and Blazek, (1974), Wray, (1981) and they observed that undulatory growth in the solidified shell causes severe faults in the final casting product such as cracks in the casting. Theoretical works on thermoelastic instability during solidification firstly investigated by Richmond and Huang, (1977), Richmond et al., (1990). They found that air gaps are formed where the contact pressure falls zero at the shell/mold interface and the thinnest region of the shell is observed above the air gaps. Li and Barber modelled the thermomechanical coupled process by neglecting the mold properties (Li and Barber, 1991). Yigit investigated Li's coupled model by considering effects of the deformable mold of finite thickness under the assumption that the thermal capacity of mold is zero (Yigit, 1998).

Unstable growth of the solidified shell may also be eliminated or minimized by controlling the heat transfer at the shell/mold interface. One of the most frequently used technique for this purpose is to use specific mold surface topographies. Murakami et al. investigated the solidification process on the periodic grooved mold surface experimentally (Murakami et al., 1992). They found that grooved mold provides more uniform contact along the mold-shell interface, and reduces crack nucleation in the casting due to more uniform heat extraction. Hector et al. developed theoretical models for solidification of pure metals on a sinusoidal mold without interfacial coupling and neglecting thermal capacities of the shell and mold. In their study, two models have been developed: In the first model, the mold surface temperature is held constant; while in the second model, the heat flux through the mold-shell interface is held constant (Hector et al., 1999). Hector et al. presented a coupled model to determine the time and location of gap nucleation and investigated the effect of the groove wavelength of the mold on them (Hector et al., 2000). Yigit and Hector extended this coupled model for a sinusoidal deformable mold of finite thickness F. Yigit and Hector, (2000a, 2000b). The effect of mold surface topographies is investigated and a critical wavelength band for unstable growth is determined by using different material combinations as mold-shell materials. The effects of the mold properties such as groove wavelength and mold thickness on solidification of pure metals on a sinusoidal mold is investigated by neglecting thermal capacities of the shell and mold material without interfacial coupling effect (Yigit et al., 2002). Yigit studied combined

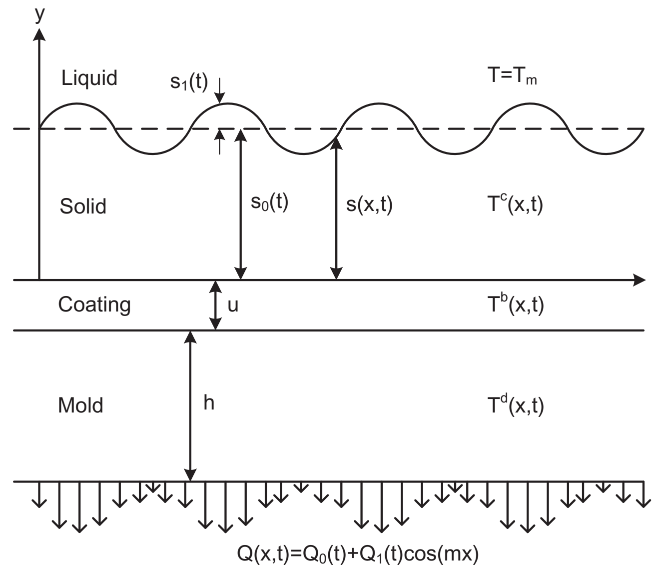

Fig. 1. Geometry of the system.

effects of interfacial coupling and thermal capacity of the solidified shell in solidification of pure metals on a sinusoidal rigid mold (Yigit, 2004).

On the other hand, Howarth and Hector (2001a, 2001b) investigated the different techniques for mitigating the heat extraction during the solidification instead of perfectly sinusoidal mold surface roughness. In their studies, they modelled the solidification process in which pure metals solidifies on a moving rigid mold with constant and on a plane wall with single asperity of Gaussian, triangular and trapezoidal profiles, respectively. They found that the movement of the mold diminishes the magnitude of the contact pressure at both the trough and crest regions on the surface and the contact pressure is a minimum at positions of maximum positive curvature and gap nucleation occurs unless the hydrostatic pressure is sufficiently large. Developed models in above studies are valid before the air gap formation at the shell/mold interface. After the nucleation of air gaps, the dynamics of the problem changes.

All of the preceding theoretical works on the growth instability problem have assumed that the mold surface is in contact with the solidified shell. In light of existing experimental work on the mold coating, we present a theoretical model to determine the required properties of the coating layer to minimize the growth instability. For this purpose, we reconsidered the work of Yigit, (1998) to include a coating layer on the mold inner surface in his model. We use the Yigit, (1998) methodology to reformulate the problem to examine the effect of mold coating on the growth instability. The effects of the coating layer material on the growth instability are examined when the other system parameters such as coating layer thickness, coupling rates, materials of mold and solidified shell are changed.

2. Mathematical formulation

The physical model of the solidification process depicted in Fig. 1 consists of three solid layers such as the solidified shell, coating layer and mold. We assumed that the temperature of the liquid metal is constant in every point in the melt and equal to the melting temperature, T_m. Thus, the temperature at the moving interface between the solid and liquid phases is always equal to the melting temperature of the molten metal during the solidification.