Advances in Macro- and Micro-Modeling of Squeeze Casting Process

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Abstract: Squeeze casting is an advanced manufacturing process. The physics involved in squeeze casting is pressurized solidification, and it is important to understand the fundamental knowledge of pressurized solidification and to develop numerical models at macro and micro scales. This review presents the major challenge and novel research dedicated to macro- and micro-modeling on squeeze casting of aluminum and magnesium alloys, including metal displacement and free surface tracking, thermal-mechanical coupled simulation, casting-mold interfacial heat transfer model, pressurized solidification and microstructure modeling.

Keywords: squeeze casting, thermal-mechanical coupling, casting-mold interfacial heat transfer model, pressurized solidification, microstructure simulation

1 Introduction

Squeeze casting is an advanced near-net-shape forming process that offersmany remarkable advantages over conventional casting process. The combination of squeeze casting process with light alloys is an effective approach to produce lightweight components with excellent performance and precise geometry.

Squeeze casting process involves complicated physics at both macro and micro scales. Fig. 1 illustrates the essential physics at macro- and micro-scales and the major challenge in modeling and simulation of the squeeze casting process.

This article addresses the challenge in macro- and micro-modeling and simulation of squeeze casting process and reviews the major progress made in the past two decades.

2 The progress in macro-modeling and simulation of squeeze casting

Simulation of mold filling process

The major challenge in the simulation of mold filling process of squeeze casting is to deal with the movement of the punch, which means to solvethe fluid flow and track the free surface in a computational domain subject to a continuous change.Lewis and Han proposed a quasi-static Eulerian finite element method, where a velocity boundary condition was imposed at the interface between the punch and the molten metal to simulate the effect of the punch action (Fig. 2).

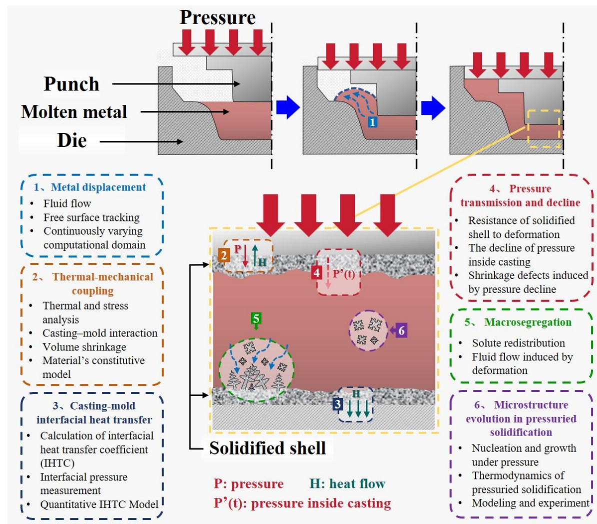


Fig. 1 The essential physics at macro- and micro-scales and the challenge in modeling and simulation of squeeze casting process.

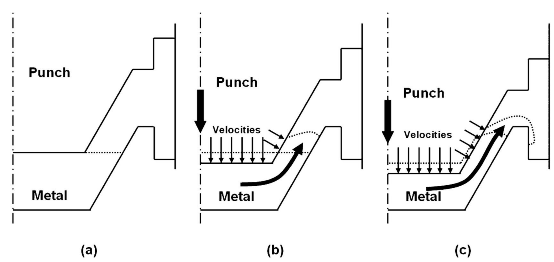


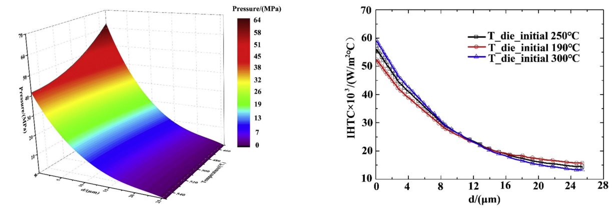
Fig. 2 The schematics of the metal displacement in direct squeeze casting process.

3 Thermal-mechanical coupled simulation

In squeeze casting, thermal and mechanical are inter-dependent, resulting in some important and complicated issues in the solidification process. In the work of Zhu and Tang et al., a three-dimensional thermal-mechanical coupled simulation method for squeeze casting components with complex geometry has been developed.

4 Casting-mold interfacial heat transfer model

In squeeze casting, the interfacial heat transfer coefficient (IHTC) depends upon the casting-mold interfacial contact status varying with time and location of the interface. Wang et al. established a quantitative model (Fig. 3) describing the intrinsic dependence of the IHTC on the interfacial pressure and temperature, providing a way to couple the thermal-mechanical inter-dependence.



(a) (b)

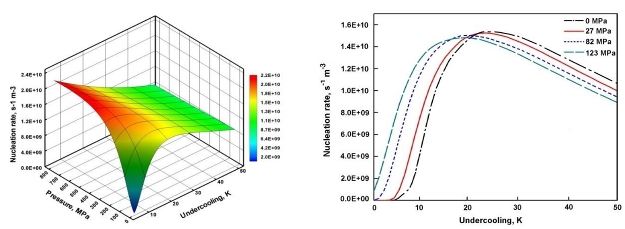
Fig. 3 (a) The dependence of mean plane separationon pressure and temperature; (b) The relationship between IHTC and the mean plane separation.

5 The progress in micro-modeling and simulation of squeeze casting

Nucleation model of pressurized solidification

Squeeze casting is essentially a pressurized solidification process. Pressuresignificantly affects the nucleation in solidification.Huang et al. developed a quantitative model (Eq. 1) for describing the heterogeneous nucleation in pressurized solidification.Fig. 4 shows the dependence of nucleation rate on the undercooling and pressure.

$$ {}^{v}I_{\mathrm{he}} = 10^{42} K_{\mathrm{he}} \exp\left[-\frac{\mathrm{b}f(\theta)\frac{\sigma^3}{(\Delta G_V+\varepsilon P)^2}+\Delta G_{\mathrm{d0}}+\Delta VP}{\mathrm{k_B}T}\right] \qquad (1) $$



(a) (b)

Fig. 4 The effects of pressure and undercooling on the heterogeneous nucleation in squeeze casting.

Microstructure simulation of squeeze casting

For the simulation of the microstructure evolution in squeeze casting, it is essential to appropriately incorporate the effects of pressure on the thermodynamics and kinetics of growth. Huang et al. developed a mathematical expression of the solid-liquid interface equilibrium of a binary system during its pressurized solidification:

$$ C^* - C_0 = \left(\frac{\partial C}{\partial T}\right)_{\mathrm{P}}(T^* - T_{\mathrm{L}}^{\mathrm{eq}}) + \left(\frac{\partial C}{\partial P}\right)_{\mathrm{T}}(P^* - P_0) + \left(\frac{\partial C}{\partial T}\right)_{\mathrm{P}}\Gamma K f(\varphi,\theta) \qquad (2) $$

This work provided an approach to calculate the growth dynamics in cellular automaton simulation of the pressurized solidification of binary systems.

Shang et al. developed a phase field model incorporating the effect of pressure on solidification of multi-component system. As an example, Fig. 5 demonstrates a pressure-effect-embedded calculation of phase diagram, which was used to simulate the dendritic growth of a Mg-Al-Sn ternary alloy solidified under pressure (Fig. 6).

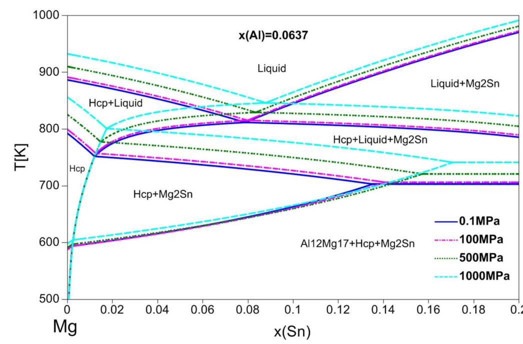


Fig. 5 The vertical section of the Mg-Al-Sn ternary phase diagram at 6.37 at.% Al.

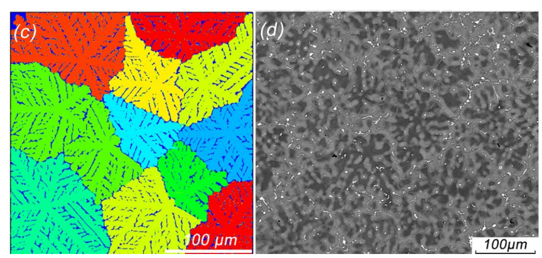


Fig. 6 The simulated and observed microstructure of a Mg-Al-Sn alloy under 85 MPa.

Summary and prospect

The major challenge and progress in modeling and simulation of metal displacement, thermal-mechanical coupled phenomenon, casting-mold interfacial heat transfer, and microstructure formation during pressurized solidification of squeeze casting are addressed, and a prospect for future work is provided.

Acknowledgments

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