INTRODUCTION

Fundamental understanding of the relationship between solidification variables and the resulting microstructure is essential for the development of optimum methods for quality casting. The microstructures of casting product consist of columnar grains formed around the wall and equiaxed grains formed in the middle of the mold. Generally, the equiaxed grains have more dominant effect on the mechanical properties of the product than the columnar grains. Therefore, it is crucial for industrial applications to understand the formation mechanism of equiaxed grain structure. Although the mechanical fragmentation of columnar dendrite due to melt flow and gravity is thought to be a possible nucleation mechanism of equiaxed grains, it has not been clarified yet.

In this study, we investigate stress concentration, which is the indicator of mechanical fragmentation, occurred at dendrite neck due to gravity applying to the vertical direction of dendrite growth direction. The coupling simulations by phase-field method and finite element method are performed.

NUMERICAL MODELS

The dendrite growth from undercooled pure Ni is simulated by a quantitative phase-field model. Then, the calculated dendritic morphologies are transformed to the finite element simulation and the mechanical stress due to gravity are simulated.

<Phase-field method>

Evolution equations of phase-field variable \( \phi \) and temperature \( T \)

\[
\frac{\partial \phi}{\partial t} = M \left[ \Delta \nabla^2 \phi - \frac{\partial}{\partial \theta} \left( \frac{\partial \phi}{\partial \theta} \right) \right] + \frac{1}{4} W(1-\phi^2) \left( 15 \frac{LT}{T_m} - T \right) T_m
\]

Here, \( \phi \): phase-field variable \( (\phi = 1 \text{ in solid, } \phi = -1 \text{ in liquid}) \)
\( \theta \): melting temperature
\( L \): latent heat
\( T \): temperature
\( \Delta \nabla^2 \phi \): thermal diffusivity
\( \partial \phi / \partial \theta \): specific heat
\( \partial \phi / \partial T \): latent heat

Surface anisotropy

\[
a(\theta) = a_0 [1 + \zeta \cos(k\delta)]
\]

Phase-field parameters \( a \), \( M \) and \( \zeta \) can be related to the material parameters by following equations.

\[
a = \frac{3.8 \delta y}{b}, \quad W = 6 \delta y, \quad M = \frac{4\sqrt{2} \gamma T L \kappa}{3$, $ \zeta \delta yL$,
\]

<Finite element method>

Finite element simulations are performed as linear elastic plane stress problem.

NUMERICAL CONDITIONS

Phase-field simulation

Finite element simulation

CONCLUSIONS

The stress concentration occurred at the neck of dendrite that grows to the vertical direction for gravity was investigated by coupling phase-field method and finite element method. As a result, it was clearly shown that the maximum stress at dendrite neck increase with dendrite growth and the increasing ratio is higher for high undercooling condition than lower one. Furthermore, to evaluate the maximum stress in the dendrite with high accuracy, the simple cantilever model was concluded to be not enough and finite element method which can directly treat the dendrite morphology is much more powerful.

The developed coupling model of phase-field method and finite element method is anticipated to be applied to the study of mechanical dendrite fragmentation due to the gravity and melt flow.

FUTURE WORK

We will try to develop coupling model of phase-field method, finite element method and Navier-Stokes equation, and to estimate stress distribution in dendrite due to melt flow and gravity force.