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Image-based modeling of viscoelastic properties of solidifying Al alloys and model validation

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ABSTRACT

The method to predict the viscoelastic properties of solidifying alloys is proposed and validated with experiments. The method consists of 2D image-based modeling and finite element analysis.Image-based modeling is based on the water-quenched solidification microstructure. FE analysis simulates uniaxial tensile testing, using the Eulerian-Lagrangian approach in the dynamic explicit procedure. The method enables the derivation of both Young's moduli and rheological properties of Norton's law without semi-solid tensile tests, which are technically demanding and costly, especially in the brittle temperature range. For the Al-5%Mg alloy, the differences between the numerical and experimental properties ranged from 10 to 40%.

1. Introduction

The casting process is indispensable in the manufacture of ingots and hollow articles with complex shapes; however, cast products sometimes have crack defects owing to solidification shrinkage and thermal contraction. Recently, cracks have become a more serious problem owing to the diversification of alloy composition and the increasing size of ingots. Against this background, crack prediction using thermal stress analysis (Monroe and Beckermann, 2005) is worthy of note. Consequently, the mechanical properties of the solidifying alloys are imperative, and are essential for the analysis. Magnin et al. (1996) obtained the stress-strain curves and the rheological properties of Norton's law for solidifying Al-4.5% Cu alloy. This means that solidifying alloys can be described as viscoelastic materials.

However, solidifying alloys, especially in the brittle temperature range (BTR), show both rheological and brittle behaviors. Owing to these contrary behaviors, reliable measurement of the viscoelastic properties in experiments is technically demanding and costly.

As a solution to the above, the authors focused on the numerical prediction of the properties by employing the finite element method using model-depicted material microstructure. Several studies using this approach for semi-solid alloys have been published. Sharifi and Larouche (2015) obtained the instantaneous Young's moduli of Al-Cu alloy during tensile analyses. They did not mention the inelastic properties. Phillion et al. (2008) and Sistaninia et al. (2012, 2013) compared the numerical and experimental stress-strain curves of aluminum alloys. Although the stress-strain curves were compared, derivation of the properties and their validation were not obtained.

In summary, none of the researchers both derived numerical viscoelastic properties and experimentally validated the properties. Hence, in this study, a numerical method based on image-based modeling by obtaining the elastic and rheological properties (Young's modulus and Norton's law parameters) was proposed and experimentally validated.

2. Outline of the proposed method

This method employs image-based finite element analysis (Hollister and Kikuchi, 1994), multi-scale analysis, and a method for obtaining rheological properties as described by Matsushita et al. (2017). The procedures are as follows:

1 The solidifying specimen is water-quenched to freeze its microstructures, and a two-dimensional micrograph is obtained.
2 The micrograph is binarized and imported into the solver (Abaqus ver. 6.14) as a two-phase model.
3 Mechanical properties of solid and liquid phases are input.
4 Boundary conditions to simulate the uniaxial tensile test are applied, and stress analysis is performed.

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5 The stress-strain curve is constructed regarding the above two-phase model as a homogeneous isotropic continuum.
6 Viscoelastic properties are derived from the stress-strain curve.

Only three types of information are required to carry out the above: a micrograph of the solidifying alloy, and the mechanical properties for both solid and liquid phases. The micrographs under various conditions are easily obtained from the water quench tests. When microstructures change in alloy compositions or during the casting process, this method can construct constitutive equations corresponding to each of the situations without the semi-solid tensile tests. This method should be generally applicable as long as the solidification structure is modeled as a solid-liquid two-phase process. Moreover, modeling of the two-dimensional micrograph requires less than one million elements. Both of the analyses, or procedures 4–6, can be completed within half a day, using a standard workstation (Intel® Core™ i7-6950X 3.0 GHz CPU with 128 GB of memory in this study). Therefore, it would be a practical method for many industrial companies. For a three-dimensional model, several billion elements are required.

In this study, the properties of the Al-5% Mg alloy were predicted under the various solid fractions *fs* and cooling rates. Section 3 describes the construction of the numerical models, and Section 4 describes the prediction of the viscoelastic properties by tensile analysis. In Section 5, the obtained stress-strain curves and viscoelastic properties are compared against the experimental results obtained by Takai et al. (2015, 2016) and Matsushita et al. (2017).

3. Image-based modeling

The numerical model was constructed using image-based modeling. In this modeling process, a micrograph was converted to the model data. Pixels and finite elements were in one-to-one correspondence.

The material used in this work was the Al-5%Mg alloy, whose composition is presented in Table 1. Although this alloy is widely used in the field of transportation, such as for railway vehicles, it has a high crack sensitivity.

The micrographs were obtained during solidification by performing water quench tests. Solidifying specimens (40 mm in diameter by 40 mm in height) were rapidly quenched at various temperatures (440–590 °C) to freeze the microstructures. The temperature of the specimen was measured at 5 mm from the bottom and 15 mm from the center. The average cooling rate from the liquidus to the solidus was controlled to be approximately 0.46 or 0.24 K/s, the same conditions as in the tensile experiments (Matsushita et al., 2017; Takai et al., 2015, 2016). In the solidification condition, microstructures without porosities were obtained, which were suitable for binarization.

Fig. 1a is one of the obtained micrographs. The picture size was 602 × 800 pixels, and the pixel size was 2 μm. According to the binarization of the picture, all the pixels were classified into two phases: solid and liquid. The binarized image was converted to digital data and imported into the solver. The solid fractions of the micrographs were derived by dividing the number of solid pixels by the total number of pixels. The derived fractions were approximately 85–99% (cf. *fs* ~ 85% at zero strength temperature (ZST) in the tensile experiments (Takai et al., 2015)).

Table 1
Chemical composition of the Al-Mg alloy (mass %).

Mg	Si	Mn	Fe	Cu	Zn	Ti	Ni	Al
4.876	0.098	0.405	0.167	0.030	0.021	0.009	0.010	Bal.

4. FEM simulation to estimate viscoelastic properties

4.1. Numerical model

This section describes the construction of a model whose solutions converge and that is applicable for tensile analysis. The model described in Section 3 has jagged edges (see Fig. 1c). In the Lagrangian approach, the edges often prevent analysis from converging. As a countermeasure, the Eulerian–Lagrangian approach in a dynamic explicit FEM procedure was used.

In the Eulerian model, all individual Eulerian elements (8-node hexahedron) have material volume fractions. *Materials* refers to both solid and liquid in this study. As shown in Fig. 2, the numerical model consists of 700 × 900 Eulerian elements. The initial volume fractions of the 602 × 800 elements at the center were defined from the obtained digital data: (*fs*, *fl*) = (100%, 0%) or (0%, 100%). In the other elements, initial volume fractions were set to zero (*fs* = *fl* = 0%). In the Eulerian approach, the variations of the volume fractions of each element represent the deformation of the semi-solid region. The solid-liquid interfaces were described from the distributions of the fractions in the contour map, which were independent of element interfaces.

In Fig. 3 (enlarged view of Fig. 2), a gray part is found on the outer edge of the semi-solid region. This part consists of Lagrangian elements (hereafter, the Lagrangian shell). The Lagrangian shell makes it possible to set the boundary conditions described in Section 4.2.2. It is overlapped onto the Eulerian elements whose volume fractions are zero. To provide a close fit between the semi-solid material part and the Lagrangian shell, the conditions were set as follows:

- The Lagrangian shell is two elements wide and in solid phase (*fs* is constantly 100%).
- As shown in Fig. 4 (red area), the outer two elements of the initial semi-solid material part (602 × 800 elements) are in solid phase (hereafter, Eulerian shell). Their role is to prevent the leakage of the Euler liquid phase outside of the Lagrangian shell.
- The surface behavior of the interface between the Lagrangian and the Eulerian shell was set to "No separation."

Additionally, to simulate the two-dimensional plane-strain analysis, the following boundary conditions were also set:

- The Lagrangian shell had Z-symmetry $u_z = \varphi_x = \varphi_y = 0$.
- In the Z-direction of the Lagrangian shell, node displacements were synchronized to: $u_{x,(z=0)} = u_{x,(z=0.002)}$, $u_{y,(z=0)} = u_{y,(z=0.002)}$.
- The Eulerian model (700 × 900) was closed: no inflow or outflow of materials.

Here, u_i and φ_i are the *i*-axis translation and rotation, respectively.

4.2. Numerical conditions

4.2.1. Material properties

For the solid and liquid phases, the isotropic material properties were set as shown in Table 2 (Matsushita, 2017). The solid properties were based on the assumption of the viscoelastic properties for the Al-5% Mg alloy at a temperature just under the solidus temperature. A stress exponent and material constant from the literature (Kuchařová et al., 1974) were used. Due to the limitations of the solver, the viscoelastic properties were input as elastic perfectly plastic properties where yield stress σ_Y depended on plastic strain rate $\dot{\varepsilon}_{plastic}$. The sets of σ_Y and $\dot{\varepsilon}_{plastic}$ data were obtained by using Eq. (2) with the above literature data. Eq. (2) was derived by using Norton's law (Eq. (1)). The obtained datasets were input in a tabular format. The stress-strain behavior of these elastic perfectly plastic properties showed close agreement with the viscoelastic behavior (less than 1.5% difference in the