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Prediction of hot tearing for a partially solidified bismuth bronze by using finite element method analysis

Akira Matsushita[1], Tomoaki Nakazawa[1,2], Toshimitsu Okane[3] and Makoto Yoshida[1,4]
[1] Department of Mechanical Engineering, Graduate School of Waseda University, 3-4-1 Shinjuku-ku Okubo, Tokyo 169-8555, Japan
[2] Toyota Motor Corporation, 1 Toyota-Cho, Toyota City, Aichi Prefecture 471-8571, Japan
[3] National Institute of Advanced Industrial Science and Technology, 1-1-1 Tsukuba Umezono, Ibaraki 305-8568, Japan
[4] Kagami Memorial Research Institute for Materials Science and Technology, Waseda University, 2-8-26 Shinjuku-ku Nishiwaseda, Tokyo 169-0051, Japan

The aim of this study is the prediction of solidification cracking, or hot tearing, for bismuth bronze by fluid flow, solidification, and thermal stress analysis. Constitutive equation required for the analysis was experimentally constructed as a viscoelastic equation by using tensile and relaxation test in the partially solidified state. For the purpose of predicting crack defects, some parameters were examined as cracking criteria, e.g. hot tearing indicator (HTI) which is the equivalent plastic strain during solidification [1]. The prediction results were compared with crack locations of the experimental castings by a copper mold in order to validate the analysis. As a result, there was a reasonable correlation between the distribution of HTI and cracking occurred during solidification.

Keywords: *semi-solid, solidification cracking, hot tearing, thermal stress analysis, viscoelastic*

1. Introduction

Recently, there is a strong need to predict cracking for increasing productivity of castings. Computer Aided Engineering (CAE) becomes an effective tool to predict these defects. In the crack prediction using CAE, the constitutive equation of solidifying alloy and the criteria for crack defects are required.

In this study, viscoelastic constitutive model was adopted for the crack prediction of partially solidified bismuth bronze. Firstly, Young's modulus and parameters of Norton's law in the partially solidified states were obtained as a function of fraction solid using tensile and relaxation tests during solidification. Secondly, casting tests of a water meter housing were executed using a copper mold. Thirdly, Analyses of fluid flow, solidification, and thermal-stress were performed. Lastly, crack locations of the obtained castings were compared with the analytical predictions by some criteria, such as HTI.

2. Experimental

The material used for this study is bismuth bronze. Its composition is given in Table 1.

Table 1 Composition of the test alloy (mass%).

Sn	Zn	Bi	Ni	Pb	P	S	Cu
6.3	4.3	1.63	0.12	0.08	0.03	0.002	Bal.

To validate analytical prediction of cracking, the copper mold casting was carried out [2]. The shape of the specimen is water meter housing as shown in Fig. 1. The pouring temperature was 1200 °C and the mold was held at 220 °C. The temperature of the casting was measured at the neck parts in Fig. 1.

3. Analysis

3.1 Constitutive equation

In this study, Maxwell constitutive model was used. The constitutive equations were as follows:

$$\varepsilon_{\mathrm{total}} = \varepsilon_{\mathrm{elastic}} + \varepsilon_{\mathrm{creep}} \tag{1}$$

$$\varepsilon_{\mathrm{elastic}} = \sigma / E \tag{2}$$

$$\dot{\varepsilon}_{\mathrm{creep}} = A\sigma^{n} \tag{3}$$

The total strain ($\varepsilon_{\mathrm{total}}$) was composed of the elastic ($\varepsilon_{\mathrm{elastic}}$) and the creep ($\varepsilon_{\mathrm{creep}}$) strain. In the partially solidified state, plastic strain which causes strain hardening was assumed to be negligible. For example, as to the Al-4.5%Cu alloy, Magnin et al. [3] showed that strain hardening coefficient in the partially solidified state had zero value. σ is stress, E is Young's modulus, n is stress exponent, and A is material constant. These mechanical properties of the bismuth bronze were obtained by unload, tensile, and stress relaxation tests during solidification as a function of temperature [4]. On copper alloys, there was no precedent for the experimental construction of the rate-dependent constitutive equation.

3.2 Finite element simulation

The experimental casting of water meter housing was simulated as shown in Fig. 1. A complete model was used in this work. The ProCAST 2013 software was used to perform fluid flow, solidification, and thermal stress analysis by finite element method (FEM). The simulated fields were computed with approximately 780,000 elements (mesh sizes range about 10 mm). Linear tetrahedral elements was chosen for the mesh.

The thermophysical properties of the cast and mold materials were calculated using JMatPro 8.0 software. Heat transfer coefficients were adjusted so that a temperature history of casting obtained by analysis should fit the experimental result.

4. Results and discussions

As shown in Fig. 1, the simulated distribution of HTI was found to be in reasonable agreement with the crack locations observed in the casting experiment. Consequently, in the copper alloy, HTI was capable of predicting hot tearing.

In the experiment, there was also external shrinkage on the upper surface part of the casting. Fig. 2 shows the relationships between HTI and upper surface deformation in z-direction, or external shrinkage displacement, in the analysis. The more external shrinkage occurred under the higher HTI condition.

Incidentally, the simulated distribution of maximum principal stress suggested only cracking at neck parts.

5. Conclusions

To predict the hot tearing for the bismuth bronze, fluid flow, solidification, and thermal stress analysis were performed by FEM. Viscoelastic constitutive equation was chosen for the analysis. The rate-dependent constitutive equation for the copper alloy was constructed by the experiment firstly in the world.

Comparing between simulated HTI and experimental result was suggested that HTI was able to predict the hot tearing and external shrinkage.

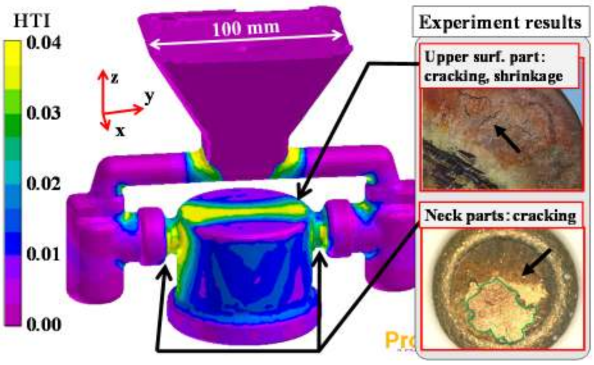

Fig. 1 Distribution of HTI and crack locations.

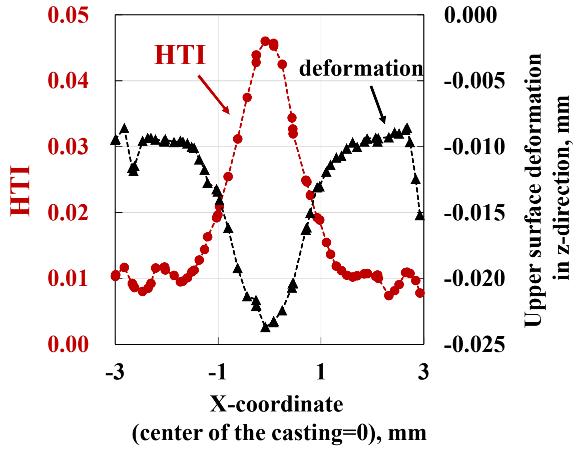

Fig. 2 Relationships between HTI and simulated external shrinkage displacement.

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