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A verification of the thermal stress analysis, including the furan sand mold, used to predict the thermal stress in castings

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ABSTRACT

The restraint exerted on a casting by a furan sand mold on the casting and the contraction of the casting during cooling was dynamically and simultaneously measured using a device that we developed. The measurements were compared during cooling with thermal stress analyses. The thermal stress analyses were based on the representative mechanical models for the furan sand mold, i.e., the elastic and elasto-plastic models used in previous studies. The comparison demonstrated that the elasto-plastic model simulates the restraint force more accurately than the elastic model. In the thermal stress analysis, it was important to describe the development of inelastic deformation and the fracture of the sand mold. However, the simulated restraint force was still twice as large as the measured force even in the elasto-plastic model. This error is most likely attributable to using the temperature-independent mechanical properties of the furan sand mold and the mechanical model of the casting alloy, which neglected the viscoplasticity at high temperature in the thermal stress analysis.

1. Introduction

The residual stress and distortion in a casting are very crucial issues in the sand casting process. Casting simulation software has been developed by several researchers to predict and control these issues. In these analyses, several researchers have tried to incorporate the effect of the restraint force of sand molds into the thermal stress analysis. Although the mechanical properties of the sand mold are necessary for simulating the restraint force of the sand mold in the thermal stress analysis, few studies have investigated the mechanical properties of the sand mold. The details of the above-mentioned studies are described in the following.

i. *Previous studies on thermal stress analysis including sand molds*

Monroe et al. (2009) calculated the deformation of a steel casting in a sand mold during cooling with MAGMA soft. They showed that the predicted stresses and distortions in the castings were sensitive to the stiffness of the sand mold. Kang et al. (2008) conducted a thermal mechanical analysis of a cylinder block casting and a hydro turbine blade casting. In their study, the restraint force of the sand mold had a significant effect on thermal stress development during cooling. Daniel et al. (2001) and Chang and Dantzig (2004) developed and improved a sand surface element for the efficient prediction of residual stress in castings.

Ahmed and Chandra (1997) simulated the residual stress and the casting deformation of a Ni–Al–bronze casting in a sand mold. They used the elasto-plastic model and temperature-independent mechanical properties for the bonded sand. Their results showed that the mold rigidity affects the results of the simulated residual stress and deformation in the casting.

Sato et al. (2005) studied a method for predicting porosity defects in cast iron using numerical stress analysis in which the furan mold strength effects was taken into account. In their analyses, the furan sand mold was modeled as a linear elastic model.

Inoue et al. (2013) compared the measured and simulated values of the restraint force of a green sand mold during cooling. They tested the various mechanical models and mechanical properties of the green sand mold. Their results showed that it is necessary to use the mechanical properties of the sand mold used rather than that of the literature for an accurate prediction.

ii. *Studies measuring the mechanical properties and developing mechanical models for sand molds*

Ami Saada et al. (1996) measured the mechanical properties of a green sand mold using an independently developed triaxial apparatus, and developed an elasto-plastic model for green sand molds.

Thole and Beckermann (2010) conducted high-temperature three-point bending experiments and measured the elastic modulus of phenolic urethane no-bake bonded sand (PUNB) as a

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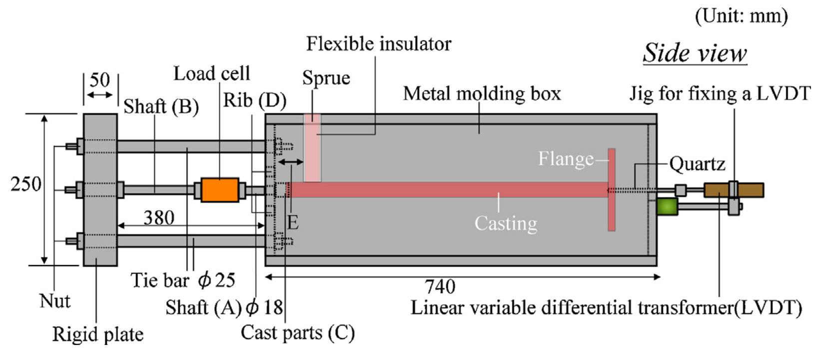

Fig. 1. The measuring apparatus used for the restraint force of the sand mold and the casting contraction.

function of specimen temperature, heating rate, holding time, etc. Their study revealed that the elastic modulus of PUNB was significantly affected by the above-mentioned parameters.

Although experimental and analytical studies have been conducted for a thermal stress analysis that includes the sand mold, as mentioned above, few previous studies have compared the simulated restraint force of the sand mold and the casting contraction with experimental values. In particular, no study has been conducted on a furan sand mold. Therefore, it is not clear whether the analyses presented in the previous studies that included sand molds were able to simulate accurately the restraint force of the sand mold, in addition to the residual stress and the deformation in the castings.

This issue motivated the study presented here, in which we attempt to verify how a thermal stress analysis that includes the sand mold is quantitatively able to predict the experiments. In this study, it was our aim to provide the necessary insights for the mechanical model and the mechanical properties of the furan sand mold used in the experiment, which is primarily used in sand casting. To achieve these aims, a flange casting was cast in the furan sand mold. The restraint force of the sand mold occurring in the flange casting and its casting contraction were measured during cooling with a device developed in our lab (Motoyama et al., 2012, 2013). Additionally, the permanent deformation that developed in the casting during cooling was measured after shake-out. Next, uniaxial compressive tests were conducted to obtain the mechanical properties of the furan sand mold for the thermal stress analyses. The thermal stress analyses were conducted based on the casting experiment. Finally, this study compared the simulated restraint force, the casting contraction, and the permanent deformation with the experimental values.

2. Experimental procedures

2.1. Measurements collected during casting experiment

2.1.1. The restraint force of the furan sand mold and the casting contraction

Our originally developed device (Fig. 1) was used to measure the restraint force of the flange casting dynamically and simultaneously in addition to its contraction during cooling. The methods used to obtain the aforementioned parameters were explained in detail in our previous papers (Motoyama et al., 2012, 2013); for this reason, we only explain the methods briefly in the present work. The dimension of the flange casting used in this investigation is shown in Fig. 2. The end of the casting opposite of the casting flange was fixed in position. Using a load cell, it was possible to dynamically measure the load on the casting due to the reaction force between the flange and the sand mold from the end of the solidification

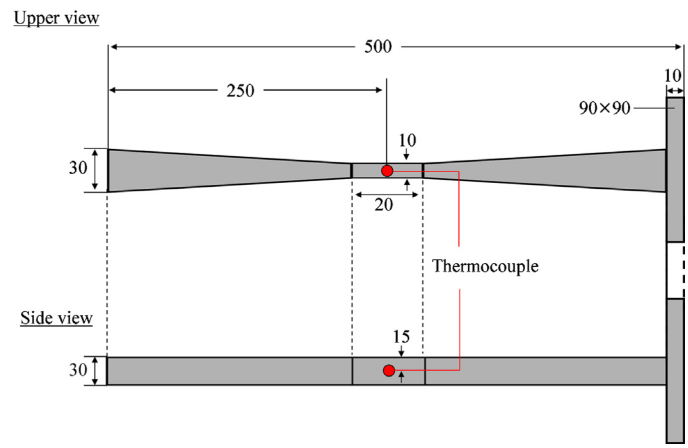

Fig. 2. The dimensions of the casting used in the experiments.

process until shake-out (50 °C). Simultaneously, the longitudinal contraction of the casting was dynamically obtained by measuring the displacement of a quartz glass rod cast-in at the flange. The castings were made using an Al–Si–Cu aluminum alloy, JIS AD12.1 (the chemical composition is shown in Table 1); the liquidus and solidus temperatures of the aluminum alloy were 572 °C and 494 °C, respectively. These values were obtained by thermal analysis. The pouring temperature of the casting was 780 °C. In the experiments with the furan sand mold, the molten alloy was poured 240 min after molding, such that the degree of sand mold hardening corresponded with that of the compressive test specimen used to obtain the mechanical properties of the furan sand mold.

2.1.2. Measuring of the permanent deformation in the casting

When the casting was cooled and shaken out, the permanent deformation of the flange casting was measured by subtracting the casting contraction from the free contraction (6.25 mm) as mentioned in our previous studies.

2.1.3. Temperature measurements of the casting and sand mold

Ungrounded type N thermocouples (the outer diameter of the stainless steel thermocouple probe was 2.3 mm) were installed in the casting and the sand mold to measure the temperatures during cooling as shown in Fig. 2 and Fig. 3.

Table 1
The chemical composition (wt%) of the JIS AD12.1 aluminum alloy.

Si	Fe	Cu	Mn	Mg	Zn	Ni	Sn	Al
11.12	0.81	1.61	0.15	0.22	0.41	0.04	0.01	Balance