A numerical model of the resistance heating system for material tests on a Gleeble simulator

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Abstract

A three-dimensional finite element model has been used to simulate the thermal behaviour of the resistance heating system of aluminium alloy specimens tested on a Gleeble thermomechanical simulator. The objective was to adapt the simulator to investigate the rheology of the aluminium alloys in a semi-solid state. The resistance heating system was optimized in order to obtain a uniform distribution of temperature in the tested material. The simulations of heating were carried out using ADINA software.

Keywords: Resistance heating; Joule effect; Numerical simulation; Finite element method; Material tests; Semi-solid state

1. Introduction

Investigations concerning the rheology of materials are connected with material tests that may be carried out on thermomechanical simulators. However, the determination of the properties of the alloys in a semi-solid state requires obtaining a uniform distribution of temperature in a specimen before a test [1]. This necessity results from the narrow solidification range. A special heating system satisfying conditions required was constructed by us (Fig. 1). This system consists of two copper grips and a steel chamber. A specimen is located inside the steel chamber. This set-up is heated by direct resistance Joule heating when an alternating current of 50 Hz is passed into the chamber through the grips. The level of current is regulated automatically in response to the difference between the prescribed temperature and the real temperature measured by a thermocouple welded to the surface of the specimen at a selected point (Fig. 1). The temperature sampling is synchronized to intervals when the current is momentarily switched off. The intersections of the copper grips and the steel chamber are especially matched to obtain in the steel chamber the maximal value of the released heat. A photograph of the whole experimental set-up is shown in Fig. 2. After heating, the specimens can be tested mechanically using a servo-hydraulic system. In our experiments, aluminium alloy A356 was used.

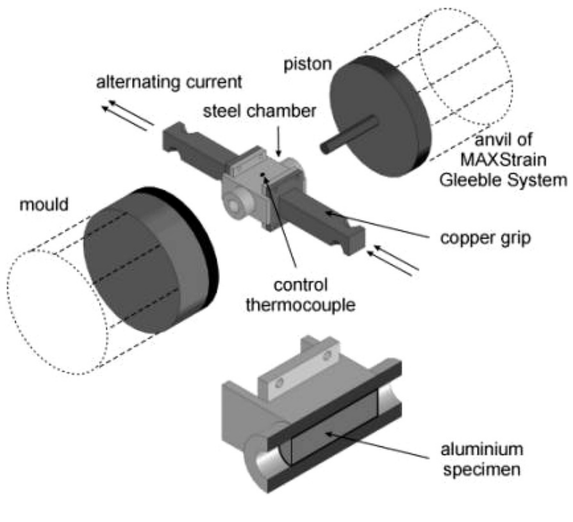

Fig. 1. The experimental set-up used to test the aluminium specimen.

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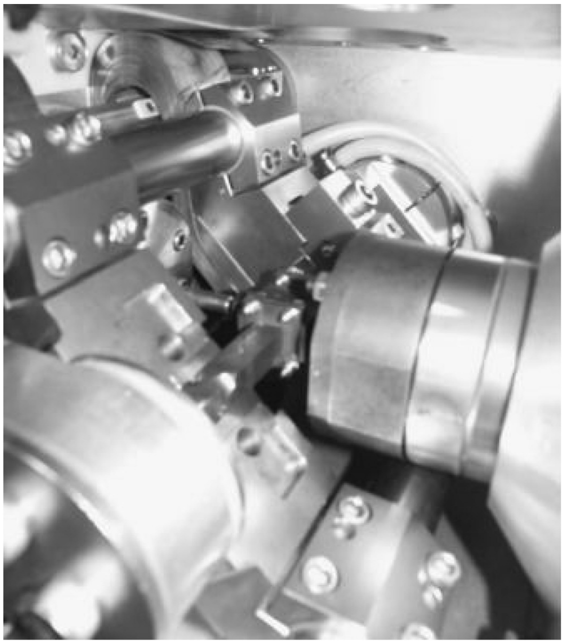

Fig. 2. Photograph of experimental set-up used to test the aluminium specimen.

2. The numerical model of the resistance heating

The simulations of the heating were carried out using ADINA software [2]. The generation of the heat Q can be described as follows:

$$Q = \mathbf{J}^2 \sigma^{-1} \tag{1}$$

where $\mathbf{J}$ is the current density, which can be determined from the relation:

$$\mathbf{J} = -\sigma \nabla \phi \tag{2}$$

Furthermore, σ is the electrical conductivity and ϕ is the electrical potential. One may evaluate ϕ using Laplace's equation [3]:

$$\nabla(\sigma \nabla \phi) = 0. \tag{3}$$

Eq. (3) is solved using the finite element method [2]. The variational form of Laplace's equation is:

$$\int_V \left(\sigma \nabla \phi \cdot \nabla h^{\phi}\right) \mathrm{d}V = -\oint h^{\phi} \mathbf{J} \cdot \mathrm{d}\mathbf{S} \tag{4}$$

where h^{ϕ} is the virtual quantity. Laplace's equation is solved for the potential ϕ at each time step and then the Joule heat Q is calculated and added to the right-hand side of the energy equation:

$$\rho c_P^{eff} \frac{\partial T}{\partial t} = \nabla(k \nabla T) + Q. \tag{5}$$

The effective specific heat c_p^{eff} is defined as follows:

$$c_P^{eff} = c_P \qquad T \le T_{sol}$$

$$c_P^{eff} = c_P - \frac{\mathrm{d}f_s}{\mathrm{d}T} L \qquad T_{sol} \le T \le T_{liq} \tag{6}$$

where c_p is the specific heat, f_s is the solid fraction, T_{sol} and T_{liq} are the solidus and liquidus temperatures, respectively, L is the latent heat, ρ is the density and k is the thermal conductivity.

3. Results of the simulations

To carry out simulations, we used a PC-based version of ADINA software. We employed a three-dimensional (3D) finite element code allowing the generation of grids with up to 100 000 elements within 500 MB of random access memory (RAM). We attempted to mimic the prescribed sequence of heating, holding at a prescribed temperature and cooling of the specimens. The actual physical and thermal properties of the materials of the heating set-up were taken in the simulations. The distribution of the temperature after reaching the temperature of 575 °C, at the control point for a thermocouple, is shown in Fig. 3. The shape of the steel chamber ensured a relatively uniform distribution of the temperature in the aluminium alloy specimen. This situation is illustrated in Figs 4 and 5. The maximal difference in the temperature values is smaller than 5 °C, which can be considered a satisfactory result.

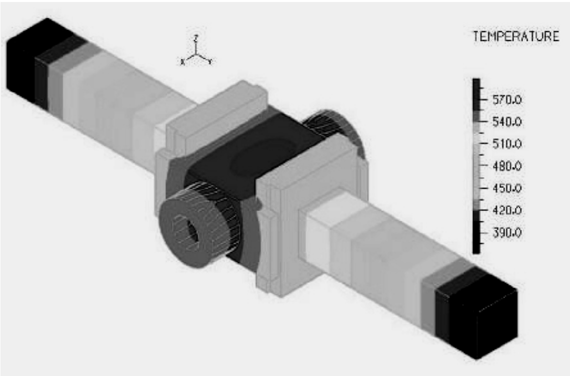

Fig. 3. The distribution of the temperature (°C) in the set-up after heating.

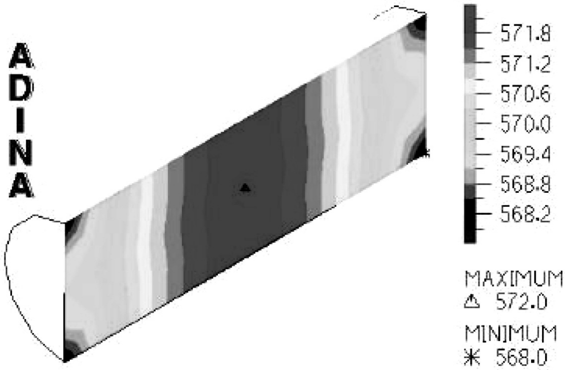

Fig. 4. The distribution of the temperature (°C) on the intersection of the specimen before the forming process.

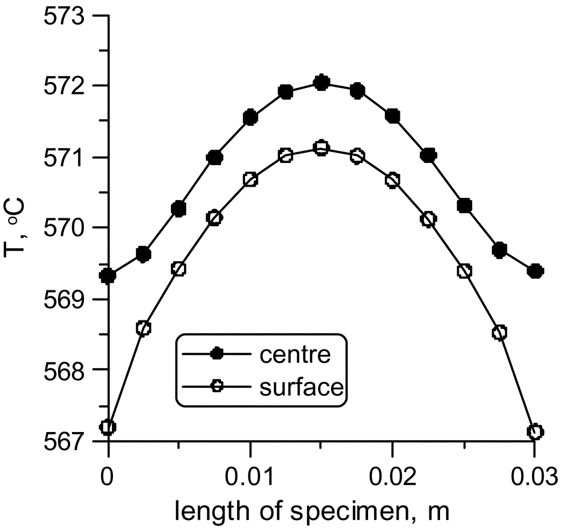

Fig. 5. The distribution of the temperature (°C) in the centre and on the surface of the specimen before the forming process.

4. Conclusions

Knowledge of the strain rate deformation behaviour in the solidification range is particularly important for the solidification modelling of processes such as shaped casting, continuous casting, welding and thixoforming. A number of recent papers have reported models that attempt to predict some of the processes aforementioned and that emphasize the need for inputting correct mechanical data. A Gleeble machine can be used for collecting such data. In this paper, we analysed the preparation of specimens. The simulations of specimen heating were shown. It was demonstrated that such simulations can be carried out successfully with the help of ADINA software. In our work, ADINA software was employed to serve several functions, including the design of the heating set-up (materials, geometry, cooling arrangements), the prediction of the temperature distributions within the specimens and the prediction of cooling rates after current switch-off.

Acknowledgements

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