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SIMULATION OF THE THERMAL PROFILE OF A MUSHY METALLIC SAMPLE DURING TENSILE TESTS

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Abstract. *Strain measurement is a major challenge in tensile tests performed in a mushy state. While non-contact technique devices like the laser speckle extensometer remain the most reliable facility for this type of measurement, these devices are often not readily available. So the strain measurement is usually performed by determining the length of the ''hot zone'' of the sample. This is possible with the help of the thermal profile associated with the sample under heating. The purpose of our work is to develop a numerical model to predict the thermal profile of a A356 aluminum alloy sample at high temperature, taking into account the device geometry and characteristics.*

We simulate the joule heating effect using the FE software Abaqus. Our model takes into account the grips of a Gleeble machine, the thermal contact conductance and electrical contact resistance at the grip-sample interfaces, as well as the convection heat transfer on the free surfaces of the system. These thermo-physical properties have been determined by fitting the experimental thermal profile obtained at 545°C. The model was then used to simulate the temperature profile on the sample at higher temperatures (when the sample is in the mushy state).

The thermal profile predicted by our model is in excellent agreement with the profile obtained experimentally.

1 INTRODUCTION

The Digital Image Correlation is the most reliable technique for measuring the deformation on a mushy sample under tensile test. It consists in using a camera that follows the motion of a speckle printed on the sample surface. Non-contact measuring devices include laser speckle

Extensometer used by S. Dziallach [1] and laser dilatometer used in the work of AB Phillion [2]. However, these measuring devices are expensive and not available in our case.

When non-contact measuring devices are not available, deformation on a sample under tensile test is determined as the ratio between two amounts: the displacement of the testing machine grips and the change in length of the specimen hot zone. In a system with induction heating, the extent of the hot zone is known without difficulties: it corresponds to the length of the induction coil [3, 4]. In contrast, in the case of heating by Joule effect, the hot zone is not known *a priori*. In an experimental approach [4, 5], the hot zone length of a sample heated by Joule effect is obtained from the measured temperature profile along the specimen. This temperature profile has a parabolic shape along the test sample length, whose apex flattened which indicates the length of the hot zone.

However, the determination of the temperature profile on a mushy sample is very challenging. It is difficult to weld thermocouples on the semi-solid part of a joule effect-heated sample. In addition, holes made in the sample for thermocouples insertion induce current flow modification, and then, temperature increases around the region of the hole. For this reason, inserted thermocouples are not reliable for temperature measurement. A technique for controlling the temperature of the hot zone without having to set thermocouples was developed by Q. Han [6]. In his work, the author has established calibration curves giving the temperature of the hot zone of the specimen from the temperature of a point located outside it. These curves are drawn as long as it is possible to attach a thermocouple to the hot zone. When the temperature increases considerably and the hot zone becomes mushy, AB Phillion [2] suggests to extrapolate calibration curves to higher temperatures. This extrapolation is performed assuming a linear calibration curve. This assumption leads to an underestimation of the temperature of the hot zone.

Due to the experimental difficulties in measuring the temperature of the hot zone, numerical simulation is a useful alternative. This approach was proposed for the first time in the work of Changli Zhan et al [7] who study the thermal profile of ultra-resistant steels. This is the approach that we will deploy here to characterize the length of the hot zone of a A356 alloy sample heated by Joule effect via the Gleeble 3800 thermomechanical platform. The simulation is performed using the Abaqus software. First, we present the experimental setup consisting of the Gleeble machine and a cylindrical sample. Then the electrical transfer and heat exchange associated with the components of the experimental setup are presented. At the same time, the equations describing the electrical and thermal phenomena involved are given. Following this description, the experimental setup is modelled by assuming some geometric simplifications and some other assumptions are taken into account in order to reduce the number of simulation parameters. Finally, unknown parameters of the numerical model are identified by the inverse method.

2. Experimental setup

In this work, we used for heating tests the Gleeble 3800. This latter is a thermo-mechanical platform whose main characteristics are the high heating and cooling rates that may be reached during tests. Those characteristics allow to reproduce conditions encountered in foundry industry. The figure 1 shows the experimental setup with each component of the Gleeble indicated by a number: on each end of the specimen are located a pair of jaws (4), two pairs of grips (5) and some other metallic components. Through these components, electric current flows as indicated by the diagram of figure 2. Continuous lines indicate a significant current flow while dashed lines show a negligible one. Heat exchange between components takes place by conduction while free surfaces of these components are submitted to convection and radiation.

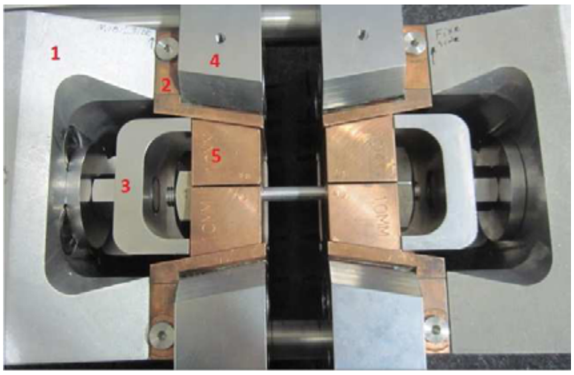

Figure 1 : experimental set up
Jaws (4), grips (5), copper plate (2)

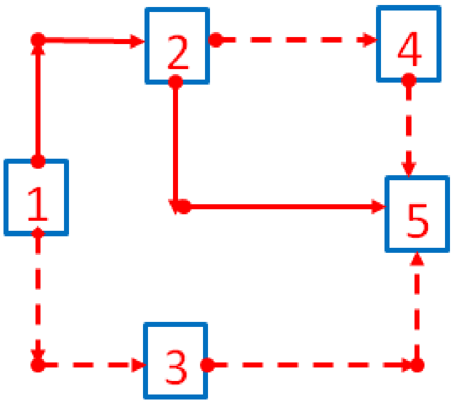

Figure 2 electrical flow

3 Electrical transfer and heat exchange balance

The Joule effect heating modeling passes through the review of the transfer electrical balance and heat exchange between the specimen and the various components of the Gleeble. In Joule heating problems, the main unknowns are electrical potential and temperature at each point of the experimental setup. These parameters are determined by solving Maxwell's equations related to electric charge and energy conservation.

3.1. Maxwell's equations

Electrical potential field in a conductor is governed by Maxwell's equations related to the conservation of electric charge. In steady state, direct current is given by the following equations:

$$\boldsymbol{J} = -\sigma_{elec}\boldsymbol{\nabla}\emptyset \qquad (1)$$

$$\boldsymbol{\nabla}.\boldsymbol{J} = 0 \qquad (2)$$

Where $\emptyset$ is electrical potential, σ_{elec} electrical conductivity, and $\boldsymbol{J}$ is the electrical current density vector.

The key of electrical problem then consists in solving the equation given by:

$$\boldsymbol{\nabla}.(\sigma_{elec}\boldsymbol{\nabla}\emptyset) = 0 \qquad (3)$$

The boundary conditions encountered in electrical problems are of two types: prescribed values of electric potential $\emptyset_{imp}$ (4a) and current density J_{imp} (4b). Those boundary conditions are applied on two distinct surfaces of the studied domain. In the case of two surfaces in contact, an effective electrical contact resistance h_{elec} is applied at interface (4c).

$$\emptyset_{imp} = 0 \qquad (4a)$$

$$-\boldsymbol{J}.\boldsymbol{n} = J_{imp} \qquad (4b)$$

$$-\boldsymbol{J}.\boldsymbol{n} = h_{elec}(\emptyset - \emptyset_{contact}) \qquad (4c)$$

In the above equations, **n** is the outward unit vector either normal to the electrical charge surface (4a) or normal to one of the surfaces of two bodies in contact (4c). $\emptyset_{contact}$ denotes the local electrical potential at the limit of the body.

3.2. Energy conservation equation

In thermoelectric problems, total energy includes energy created by Joule effect P_V^{elec} and heat associated with the power of deformation due to thermal expansion. The latter being neglected, the equation of energy conservation is written as follows:

$$\rho\frac{dH}{dt} - \boldsymbol{\nabla}.(\lambda\boldsymbol{\nabla}T) = P_V^{elec} \qquad (5)$$

Where ρ denotes the density, λ the thermal conductivity, T the temperature. The specific enthalpy H is defined as follows:

$$H = \int_{T_{ref}}^{T} c_p(\tau)\, d\tau + f_l L \tag{6}$$

With T_{ref} an arbitrary reference temperature, c_p the specific heat, f_l the mass fraction of liquid and L the specific latent heat of fusion.

The heat generated by electrical resistance is given by Joule's law:

$$P_V^{elec} = \sigma_{elec}^{-1} \boldsymbol{J}.\boldsymbol{J} = \sigma_{elec} \boldsymbol{\nabla}\emptyset.\boldsymbol{\nabla}\emptyset \tag{7}$$

As in the case of electrical problem, boundary conditions in a heat flow problem are applied either at the border or at the interface of two bodies in contact. Regarding the boundary conditions at the border, it may be prescribed by a heat flux q_{imp} (8a) or a heat transfer with the surrounding environment through an equivalent exchange coefficient $h_{th_{eff}}$ (8c). At interfaces, heat transfer from one surface to another is provided via a thermal contact conductance h_c. Heat balance at the interfaces is given by equation (8b), with the interface energy denoted by $P_{interface}^{elec}$.

$$-\lambda \boldsymbol{\nabla T}.\boldsymbol{n} = q_{imp} \tag{8a}$$

$$-\lambda \boldsymbol{\nabla T}.\boldsymbol{n} = h_c(T - T_{contact}) + \frac{b}{b + b_{contact}} P_{interface}^{elec} \tag{8b}$$

$$-\lambda \boldsymbol{\nabla T}.\boldsymbol{n} = h_{th_{eff}}(T - T_{env}) \tag{8c}$$

Where $b = \sqrt{\lambda \rho c_p}$ denotes the thermal effusivity and the subscript "contact" refers to amounts at interfaces and the subscript "env" refers to amounts associated with the surrounding environment. The interface energy is given by $P_{interface}^{elec} = h_{elec}(\emptyset - \emptyset_{contact})^2$.

The review of thermo-electrical energy and equations governing the Joule heating shows several thermo-physical parameters involved in the problem. At interfaces, the parameters to be managed include electrical contact resistance, and thermal effusivity. On the free surfaces, the main parameters are the emissivity and convective heat transfer coefficient. In view of the relatively large number of interfaces identified in the experimental setup, and thermo-physical parameters involved in the problem, some simplifications are introduced in the numerical model, for obvious reasons of reduction of computation time.

4. Numerical model

The numerical model developed in this work includes only the specimen and the Gleeble grips. This simplification leads to postulate an equivalent heat transfer coefficient on the grips surfaces in order to take into account the components of the Gleeble omitted in the geometric model. In addition, the numerical model is only half of the experimental setup thanks to the horizontal symmetry plane (figure 3). Simplifying assumptions are also made to reduce the number of unknown thermo-physical parameters. First, we assume a perfect contact at grips-sample interfaces. That leads to no heat generation ($P_{interface}^{elec} = 0$) and a quasi-continuity of the electrical potential $\emptyset$. Also the electrical contact resistance h_{elec} is fixed to a low value. Secondly, the level of temperatures involved in the case of a A356 sample being relatively low, radiation is negligible compared to convection and conduction. This assumption leads to impose a zero value for emissivity.

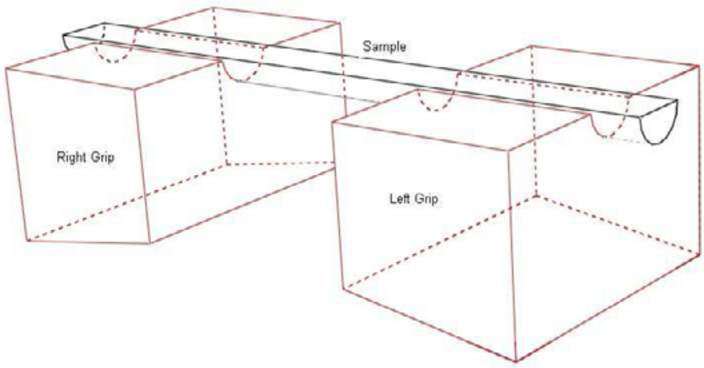

Figure 3: Gleeble Setup Modelisation on Abaqus/CAE 6.11-3: grips and sample (Section along an horizontal plane).

The thermo-physical parameters to be determined in this study are convection coefficient on the free surfaces of grips and sample, the thermal contact conductance at grips-sample interfaces and the equivalent heat transfer coefficient (defined on grips surfaces in contact with the rest of the experimental setup not shown in the model). The last two are obtained by inverse method based on calibration of the numerical model to the experimental data while the first parameter is derived from empirical relationships provided by the literature on heat transfer by convection.

Heat transfer through the free surfaces of the setup is natural convection type. Transfer coefficients are derived from the following empirical relations:

$$h = 1.32\left(\frac{T}{D}\right)^{1/4} \qquad (9a)$$

$$h = 1.42\left(\frac{T}{L}\right)^{1/4} \qquad (9b)$$

$$h = 1.33\left(\frac{T}{L}\right)^{1/4} \tag{9c}$$

In the above equations, T is the temperature in degree Celsius. Equation (9a) is valid for a horizontal tube of diameter D. It is employed to determine the coefficient of convection through the free surface of the sample. Relations (9b) and (9c) are valid respectively for a vertical plate and a upper surface of a horizontal plate of characteristic length L. They are used to determine the convection coefficient on the free surfaces of the grips.

The various electrical and thermo-physical parameters listed above, whether the parameters set by assumption (electrical contact resistance) or settings determined by calculation (convection coefficient) or parameters to be determined by the inverse analysis (thermal contact conductance and equivalent heat transfer coefficient) will be assumed to be temperature independent for the numerical simulation. It is the same for thermo-physical properties of sample and grips materials, namely the A356 alloy and copper. Thermo-physical properties of the former are obtained from the database of Auburn University while the second properties are provided by the manufacturer of the Gleeble machine. These properties are summarized in the table 1.

Table 1: Thermophysical properties

Material	Density (Kg/m^3)	Thermal conductivity (W/m/K)	Electrical conductivity $(\Omega.m)^{-1}$	Spécific Heat (J/Kg/K)	Latent heat (J/Kg)
A356	2500	170	9803921	1315	437637
Copper	8900	350	20000000	450	176000

4.1. Loading and boundary conditions

During heating tests performed in this study, temperature was the controlled parameter defined in a given heat cycle. The current density that causes heating is adjusted via a PID controller so that heating is carried out at a prescribed rate. In numerical simulation, control is provided in the same way with the difference that the current density is controlled manually to achieve the desired temperature.

J_{imp} current density was imposed on the left grips of the Gleeble. It was associated with a zero potential $\emptyset_{imp} = 0$ applied on the right grips. At grips-sample interfaces, an electrical conductance (the inverse of electrical contact resistance) of the order of $10^8\ \Omega^{-1}m^2$ was applied for electrical current transfer. In addition to the boundary conditions related to the electrical problem, there are those related to thermal one. The free surfaces of the grips as well as those of the sample are submitted to heat exchange by convection. This heat transfer is ensured through the exchange coefficients derived from the relationships described in the previous paragraph (9a, 9b and 9c). At grips-sample interfaces heat transfer is ensured through the thermal contact conductance h_{theff}.

4.2. Identification of parameters

To determine the two unknown parameters of this simulation (namely thermal contact conductance at grips/sample interfaces and the equivalent heat transfer coefficient), the numerical model was calibrated on the experimental data from heating tests achieved via the Gleeble machine. The identification is performed for a test temperature of 500°C. The approach used to determine these parameters consists in varying the value of the unknown parameters in the numerical model until the experimental temperature profile coincides with the thermal profile resulting from the numerical simulation. During heating, temperature of grips and sample are recorded. The locations of thermocouples welded on the sample and grips are shown in figure 4. Giving the temperature at the middle, TCc, and at the extremity of the sample, TC_E, the numerical value of the thermal contact conductance at the grips/sample interface is chosen such that the numerical couple (TCc, TC_E) is closed to the experimental values. Once the thermal contact conductance was determined, the equivalent coefficient of heat transfer is selected such that the numerical grips temperature is close to that recorded experimentally.

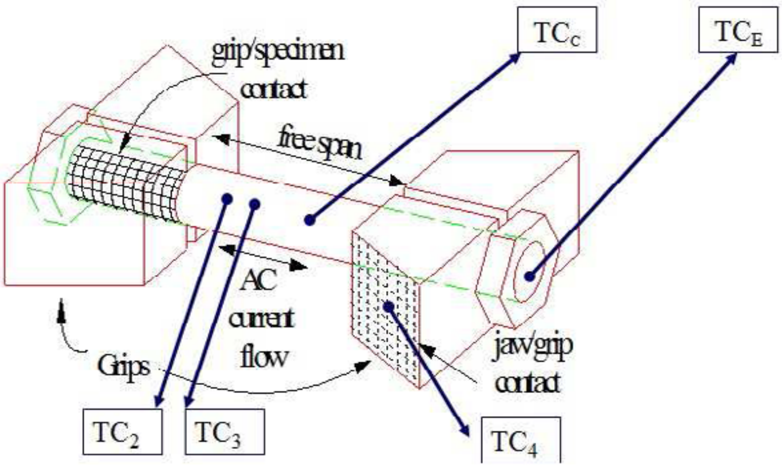

Figure 4: thermocouples location during heating test

5. DISCUSSION

With the values of thermal contact conductance (*3500 W.* $m^{-2}K^{-1}$) and equivalent heat transfer coefficient (*1000 W.* $m^{-2}K^{-1}$) thus determined by inverse method based on the experimental results performed with 545°C temperature at the center of the sample, simulations are performed for set points of 200, 300, 400°C and 500°C at the center of the sample. Also, new heating tests were performed with the same set points at the center of the sample (the thermocouples are still located as shown in figure 4). Figure 5 shows the agreement between the experimental data and the numerical model, regarding thermal profile in the axial direction. This agreement is particularly good in the central part of the sample. That validates our numerical model.

Based on this numerical model, temperature of the hot zone can be predicted giving the measured temperature at any point of the sample located outside the central part. This avoids overloading the hot zone with inserted or welded thermocouples and thus improving the stress measuring during tensile test. Moreover, the extent of the hot zone can be determined more precisely and more easily without many heating tests. The knowledge of the hot zone length leads to a better calculation of strain.

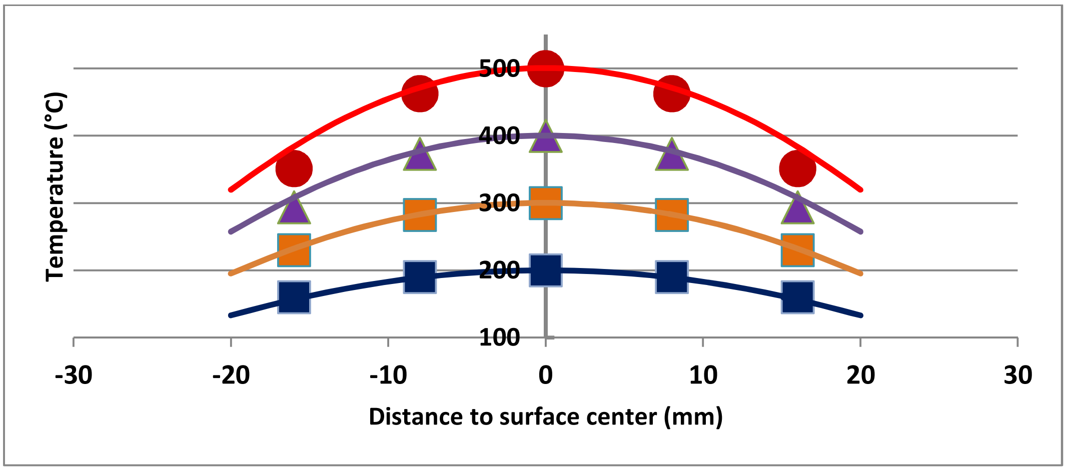

Figure 5. Thermal profile along the sample axial direction: experimental data vs numerical model for various set points temperatures(●500°C, ▲400°C, ■ 300°C, ■ 200°C).

6. CONCLUSIONS

In this work, we have developed a model intended to characterize the length of the hot zone formed on a sample heated by the Joule effect. The model determines the thermal profile in the axial direction of the sample set on the Gleeble machine. The modeling of the experimental setup included only the grips and the sample. Morever, due to the existence of a plane of symmetry, we were able to make a geometric simplification that led to a half grips-sample assembling. To take into account the rest of the set up not represented in the model, we assumed an equivalent heat transfer coefficient at the grips/jaws interfaces.

For the simulation, some assumptions have been made, including perfect contact at grips/sample interfaces and negligible radiation losses on the free surfaces of the setup. This led to a low value for the first parameter while the second was set to zero. As far as the heat transfer along the free surfaces of the model is concerned, the convective coefficients were computed using empirical relations. The inverse method has been used to determine the equivalent heat transfer coefficient assumed at the grips/jaws interfaces as well as the thermal conductance at grips/sample interfaces. The procedure consisted of finding a couple of both parameters which allowed us to fit the numerical thermal profile to the experimental one for a set point temperature of 500°C. To validate the model, simulations and heating tests were conducted for set points of 200°C, 300°C and 400°C. The good agreement between numerical and experimental thermal profile validated our model.

In this study, the thermo-physical properties are assumed to be temperature independent. The agreement between experimental data and numerical simulation suggests that the identified parameters do not vary much in the temperature interval considered. Indeed, for the temperature of the hot zone varying between 100°C and 500°C, the temperature at grips/sample interface did not vary much (between 25°C and 290°C) while the temperature of the grips did not exceed 40°C. For temperatures outside the set point interval considered, the variation of thermo-physical properties at grips/sample interfaces would probably need to be taken into account.

Non-contact techniques being often expensive or difficult to implement, numerical simulation has proved to be an alternative for characterization of the hot zone length. In the development of the numerical model, the identification of heat flow parameters was the main challenge. This study presented the inverse method as an alternative for the identification of parameters such as thermal contact conductance. This depends on so many factors such as the clearance between the contact surfaces as well as the average temperature and pressure at the interface that experimental techniques are not feasible.

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