DEVELOPMENT OF A COMPUTER SYSTEM FOR HIGH TEMPERATURE STEEL DEFORMATION TESTING PROCEDURE

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Abstract

The subject of the presented paper is the development of a computer aided engineering (CAE) system dedicated to the numerical simulation of plastic deformation of steel at very high temperatures. The paper reports the results of theoretical work leading to the construction of a FEM oriented code allowing the computer simulation of physical phenomena accompanying the steel deformation at temperatures which are characteristic for direct rolling of continuously cast charge, as well as the graphical and database oriented pre- and post-processing modules completing the system and making it user-friendly. A coupled thermal-mechanical model including inverse analysis technique was adopted for the solver. The sophisticated mathematical model has been developed for the processes requiring high optimisation accuracy. A coupled analytically-numerical approach was proposed. The advantage of the solution was the analytical form of both incompressibility and mass conservation conditions. This can prevent usual FEM variational solution problems concerning unintentional specimen volume loss caused by the numerical errors. It is very important for the discussed modelling because the deformation process is running in temperature range that is characteristic for the last stage of transformation of steel aggregation state. Existing density changes of the material which is partially mushy can cause volume variations close to those which have source in numerical errors. In the proposed work the possibilities of adaptation of the model to simulation of plastic behaviour of axial-symmetrical steel samples are presented. The paper focuses on computer aided testing procedure leading to determination of mechanical properties of steels at temperatures which are very close to solidus line. Example results of the developed system in application to the testing procedure are presented as well.
1. INTRODUCTION

Modern engineering science requires computer techniques and methods. Application of CAE systems results in lowering production costs, shortening manufacturing and technology preparation times etc. Finite Element Method is the most efficient and popular among methods dedicated to numerical engineering systems. Physical simulations of deformation of metals at extra high temperatures performed with the aid of advanced testing machines (for example GLEEBLE 3800 simulator) are very expensive. Proper setting of testing process parameters and good interpretation of obtained results are sometimes problematic due to lack of good traditional methods. The results of steel deformation at extra high temperature cannot be analysed without numerical support. As a consequence, a system of computer aided physical simulations of deformation of metals at extra high temperatures has been developed. The aim of the program is making possible both: the prediction of the deformation zone shape and size and the mechanical material properties investigation. The implementation of inverse analysis was necessary for tests conducted at extremely high temperatures, i.e. 1420°C and higher.

2. THE COMPUTER SYSTEM

The only well known machine allowing tests in the discussed temperature range is the GLEEBLE physical simulator. In aim to allow easy working with the machine a user friendly system called Def_Semi_Solid was developed in the Department of Computer Science in Industry of the Faculty of Metals Engineering and Computer Science in Industry AGH. The numerical part of the program was developed in FORTRAN, which guaranties fast computation and the database oriented graphical interface was written using visual version of C++ language, taking advantage of its object oriented character. This approach has sufficient usability both in Windows and Unix based systems. The latest PC version 3.0 of Def_Semi_Solid is equipped with full automatic installation unit and new graphical interface (Figure 1). It allows the computer aided testing of mechanical properties of steels at very high temperature using GLEEBLE physical simulators to avoid problems which arise by traditional testing procedures.

The first module allows the establishment of new projects or working with previously existing ones. The integral parts of each project are: input data for a specific compression test as well as the results of measurements and optimisation. In the current version of the program the module permits application of a number of database engines (among other standard MS Acces, dBASE IV and Paradox 7-8 for PC-based systems) and allows the implementation of material databases and procedures of automatic data verification. The next module (the solver) gives user the possibility of managing the working conditions of the simulation process. The inverse analysis can be turned off or on using this part of the system.
The program consists of three main units: DSS/Prep module, DSS/Solv module (Figure 2) and DSS/Post module and additional tools included in auxiliary inverse analysis module (Figure 3).

The last module is dedicated to the visualisation of the numerical results and printing the final reports.
Figure 3. An example window of DSS/Opti_curves module

3. SOLVER

The less visible but powerful heart of the system is of course the solver. The finite element code dedicated to the axial-symmetrical compression tests has been developed. The solution is based on the thermal-mechanical approach with density changes described in [2]. Most of the rigid-plastic FEM systems apply a variational approach, which allow the calculation of strain field and deviatoric part of stress tensor distribution according to subsequent functional:

\[ J^*[v(r, z)] = W_\sigma + W_\lambda + W_f \]  

where \( W_\sigma \) is the plastic deformation power, \( W_\lambda \) the penalty for the departure from the incompressibility or mass conservation conditions and \( W_f \) the friction power. The main idea of the presented solution is the lack of the second part of functional (1). Both the incompressibility and mass conservation conditions are given in an analytical form and constrain the velocity field components. The functional takes the following shape:

\[ J^*[v(r, z)] = W_\sigma + W_f \]  

In (1) and (2) \( v \) describes the velocity field distribution function in the deformation zone. The optimisation of functional (2) is much more effective than the functional (1) because numerical form of incompressibility condition generates a lot of local minimaums and leads to wide flat neighbourhood of the global optimum. The accuracy of the proposed solution is much better because of negligible volume loss.
This is important for materials with changing density. In classical solutions the numerical errors which are caused by volume loss can be comparable to those coming from real density changes. All that leads to solution with low accuracy. The model with analytical incompressibility condition is free from the described shortcoming. For solid regions of the sample the incompressibility condition has been described in cylindrical coordinate system with an equation:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0$$

where $v_r$ and $v_z$ are the velocity field components in cylindrical coordinate system $r, \theta, z$. For the mushy zone equation (3) must be replaced by the mass conservation condition, which takes a form:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} - \frac{1}{\rho} \frac{\partial \rho}{\partial \tau} = 0$$

where $\rho$ is the temporary material density and $\tau$ - the time variable. Both the strain and stress models are based on Levy-Mises flow criterion. Condition (4), which is more general than relationship (3), was used for the purpose of the model. The model is completed with numerical solution of Navier stress equilibrium equations.

The temperature field is a solution of Fourier-Kirchhoff equation with convection. The most general form of this equation can be written as:

$$\nabla \cdot (k \nabla T) + \left[ Q - c \rho \left( \frac{\partial T}{\partial \tau} + \nu \cdot \nabla T \right) \right] = 0$$

where $T$ is the temperature distribution inside the controlled volume, $k$ denotes the isotropic heat conduction coefficient, $Q$ represents the rate of heat generation due to the plastic work done and $c$ describes the specific heat. The solution of equation (6) has to satisfy the boundary conditions. The combined Hankel’s boundary conditions have been adopted for the presented model.

$$k \frac{\partial T}{\partial n} + \alpha (T - T_0) + q = 0$$

In equation (6) $T_0$ is the distribution of the border temperature, $q$ describes the heat flux through the boundary of the deformation zone, $\alpha$ is the heat transfer coefficient and $n$ is the normal to the boundary surface.
During the testing procedure the sample is melted down as a result of its resistance heating. The heat generated due to direct current flow was calculated using the Joule-Lenz law according to following equation:

\[ Q = I^2 R \tau \]  \hspace{1cm} (7)

where \( I \) is the current intensity, \( R \) is the electrical resistance and \( \tau \) is the time. The resistance was predicted using the following formula:

\[ R = \rho_w \frac{l}{A} \]  \hspace{1cm} (8)

In equation (8) \( l \), \( A \) and \( \rho_w \) are the sample: length, area of the cross-section and specific resistance, respectively. The temperature changes have influence on the specific resistance. In the presented solutions the empirical equation was used to predict the specific resistance at a desire temperature:

\[ \rho_w = \rho_0 \left[ 1 + \alpha(t - t_0) \right] \]  \hspace{1cm} (9)

In equation (9) \( \rho_0 \) is the specific resistance at the temperature \( t_0 = 20^\circ C \), \( t \) is the current temperature and dashed \( \alpha \) is a coefficient.

One of the most important parameters of the solution is also the density. Its changes have influence on the mechanical part of the presented model and strongly depend on the temperature. The knowledge of effective density distribution is very important for modelling the deformation of porous materials. Description of the density changes has been presented in details in [3]. More details concerning the presented mathematical model were published in [4].

4. COMPUTER AIDED TESTING PROCEDURE

The computer aided experiments were done in Institute for Ferrous Metallurgy in Gliwice, Poland for BW11 grade steel using GLEE Ble 3800 simulator. Figure 4 shows the shape of the testing sample with locations of thermocouples.

The liquidus temperature of the BW11 grade steel is 1523°C. Some other temperature levels, important from the physical point of view, were investigated. The average nil strength temperature (NST) for the selected steel was 1447°C. In aim to determine the nil ductility temperature (NDT) a number of experiments were done. All the tests lead to a common temperature of 1420°C.
The estimated ductility recovery temperature was 1385°C. At this temperature the sample’s reduction of area was around 5% and rose very fast with the temperature drop.

- The experimental work was divided into four stages:
- Determination of the characteristic temperatures
- Computation of the temperature distribution along the heating zone for different variants of heating-holding-cooling processes and two different dies.
- Optimisation of the stress-strain curve based on tensile tests.
- Several compression tests done for different variants. The inverse analyses was done on the basis of compression test results.

Details concerning the physical simulations were published in [4, 5]. Strain-stress curve is one of the most important relationships having crucial influence on the metal flow path. The investigation of the curves, which are necessary for the mechanical model, was done on basis of a series of experiments conducted on GLEEBLE simulator [1]. For the temperatures under 1350°C traditional testing methods give fairly good results. However, it is not easy to construct isothermal experiments for temperatures higher than 1420°C. Several serious experimental problems arise. First of all, keeping such high temperature constant during the whole experimental procedure is extremely difficult. There are also other severe difficulties concerning interpretation of the measurement results. The significant inhomogeneity in the strain distribution in the deformation zone and distortion of the central part of the sample lead to poor accuracy of the stress field calculated using traditional methods, which are good for lower temperatures. Figures 5-6 show example microstructure in the cross-sections of two samples deformed at 1400°C and 1425°C, respectively. One can state that for temperatures higher than 1420°C liquid phase particle exist in the central part of the sample (Figure 5).

At temperature 1400°C and lower the lack of the liquid phase has been observed. Conclusion – the results of tests conducted at temperatures higher than 1420°C require inverse analysis. For the purpose of the analysis the curves were described by following Voce’a equation:
Figure 5. Sample etched with Oberhoffer reagent – deformation at 1400°C.

Figure 6. Sample etched with Oberhoffer reagent – deformation at 1425°C.

\[
\begin{align*}
\sigma_p &= w_4 + w_5 \left[1 - \exp\left(-w_2 \varepsilon \right)\right]^n - w_i \left[1 - \exp\left(-w_3 \frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)\right]^m \\
\varepsilon_c &= w_6 w_7 Z^{w_9} \\
\varepsilon_p &= w_{10} \varepsilon_c
\end{align*}
\]

where \( w_i \ (i=1,...,10) \), \( n \) and \( m \) are the coefficients being the components optimisation vector of the inverse analysis, \( \varepsilon \) is the logarithmic strain and \( Z \) is the Zenner-Holomon parameter defined as:

\[
Z = \varepsilon \exp\left(\frac{Q}{RT}\right)
\]

In equation (11) \( R \) is the gas constant, \( T \) - temperature, \( Q \) - activation energy, \( \varepsilon \) - strain rate. The objective function of the analysis is the mean relative difference between measured and calculated values of deformation force at subsequent stages of the deformation process.

Figure 7 summarises the results of an example inverse procedure applied to the identification of stress-strain curve parameters for an example test conducted at 1460 °C with the tool velocity of 20 mm/s. The comparison between the calculated and measured loads is presented in figure 7, showing good agreement between both
loads. The coefficients obtained during inverse analysis allow the construction of stress-strain curve, which is presented in figure 8 together with two other curves (for 1425°C and 1450°C).

Using previously presented curves, example simulations of compression of cylindrical samples with mushy zone have been performed. The results of the tests demonstrate the advantages of the mathematical model. For all series of tests the simulations were done using short contact zone between the sample and simulator short jaws. The deformation zone had the initial height of 67 mm. The diameter of the sample was 10 mm. An example specimen was melted at 1480°C and then deformed at 1460°C. During the tests each sample was subjected to 10 mm reduction of height. In figure 9 the comparison between experimental and theoretical temperature versus time curves is presented for two different locations (mounting places of two thermocouples).

Figure 7. Comparison between measured and predicted loads at temperature 1460°C for tool velocity 20 mm/s.

Figure 8. Flow stress vs strain at temperature 1425°C, 1450°C and 1460°C for tool velocity 20 mm/s.

In figure 10 the initial temperature distribution in the cross-section of the sample deformed at 1460°C is presented. The initial temperature distribution has great influence on the stress field in the deformation zone. The inhomogeneity of the strain field leads to inhomogeneous stress distribution. The analysis of the strain shows maximal values of strain in the central region of the sample (Figure 11).

In figure 12 the comparison between the measured and calculated shapes of the sample cross-section is presented showing good agreement between theoretical and experimental data.
5. CONCLUSIONS

Modelling and simulations of deformation of steel samples with mushy zone requires resolving a number of problems for the discussed temperature range:

- the difficulties in calculation of material constants,
- the necessity of determination of characteristic temperatures,
- avoiding the volume loss due to numerical form of incompressibility condition, which causes problems concerning optimization of the velocity field.

Figure 9. Comparison between the experimental and theoretical time-temperature curves. Situation during initial heating and final compression at 1450°C.

Figure 10. Initial temperature distribution in the cross-section of the sample deformed at 1450°C.
The presented model with incompressibility condition in analytical form allows the simulation of the deformation of material with mushy zone avoiding volume loss, which cause problems with density.

Figure 11. Strain distribution in the cross-section of the sample deformed at 1450°C.

Figure 12. The comparison of the measured (broken line) and calculated (solid line) shapes of the central part of the sample deformed at 1450°C.
The presented dedicated Def_Semi_Solid system can be very helpful and may enable the right interpretation of results of very high temperature tests. It has shown good predictive ability of the computation regarding both shape and size of the deformation zone and mechanical properties of steels. It is possible with the help of developed CAE system thanks to computer aided testing, application of right model and implementation of the inverse analysis.

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