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DEDICATED COMPUTER SYSTEM OF AIDED STEEL DEFORMATION TESTING PROCEDURE NEAR SOLIDUS TEMPERATURE

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Abstract

The paper presents the results of experimental and theoretical work leading to mathematical modelling of phenomena accompanying the deformation of steel which is still subjected to the last phase of the solidification process. Physical simulations of deformation at such extra high temperature performed with the aid of advanced testing machines (for example GLEEBLE 3800 simulator) are very expensive and extremely difficult due to simultaneous deformation and solidification of the metal and its very unstable behaviour. Application of dedicated computer simulation system with inverse method makes tests possible and results in lowering testing cost. The Authors present such a program taking into consideration the density changes and analytical form of the incompressibility condition. The primary aim of the simulation was the reconstruction of the temperature, strain and stress changes inside steel samples subjected to both deformation and final stage of solidification. The presented program enables the right interpretation of very high temperature testing.

Key words: deformation modelling, state of aggregation transformation, finite element method, inverse analysis

1. INTRODUCTION

In the course of experimental work carried out using GLEEBLE 3800 simulator a number of samples were subjected to the compression tests and underwent plastic deformation. The samples had regions where average temperature lays over the solidus line. The plastic behaviour of such specimens having mushy zone inside differs from the deformation of solid metal. During the successive drop in specimen temperature the thickness of the solid shell grows and the material becomes more and more stress resistant.

The material behaviour above the solidus line is strongly temperature-dependent. There are a few characteristic temperature values between solidus and liquidus (Hojny et al., 2003). The nil strength temperature (NST) is the temperature in which material strength drops to zero while the steel is being heated above the solidus temperature. Another, related to NST temperature, is the strength recovery temperature (SRT), which is characteristic for cooling process. At this temperature the material regains strength greater than 0,5 N/mm^2. Nil ductility temperature (NDT) represents the temperature at which the heated material losses it's ductility. The remaining, ductility recovery temperature (DRT), is the temperature at which the ductility of the material characterised by reduction of area reaches 5% while it is being cooled. Below this temperature plastic deformation of the material is allowed.

Very important for the plastic behaviour is also the material density. It varies with temperature and depends on the cooling rate. The solidification process causes non-uniform density distribution in the

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controlled volume. There are three main factors causing density changes: solid phase formation, thermal shrinkage and liquid movement inside the mushy zone. The density plays an important role in both mechanical and thermal solutions.

One of the most important relationships having crucial influence on the metal flow path is the strain-stress curve. It is not easy to construct the isothermal curves for a selected temperature range. Keeping constant temperature during the experiment is extremely difficult. There are some difficulties with interpretation of the results of measurements. Lack of good simulation models of metal flow and significant inhomogeneity in strain distribution in the deformation zone lead to weak accuracy of calculated strain and stress fields. The model presented in the current paper fills the gap in modelling of plastic deformation of semi-solid materials.

2. MATHEMATICAL MODEL

The finite element model of the compression tests has been developed. The solution is based on a thermal-mechanical approach with density changes described in (Głowacki et al., 2004).

The mechanical part of the model is an isotropic inelastic variational solution with analytical incompressibility constraining the velocity field. Both the strain and stress models are based on Levy-Mises flow criterion with density changes depending explicitly on temperature variations. In such kinds of models the fields of strain and deviatoric part of stress tensors are usually calculated by minimising the work functional:

$$J^*[v(r,z)] = W_\sigma + W_\lambda + W_t \qquad (1)$$

with respect to the velocity field components. In (1) W_σ is the plastic deformation power, W_λ denotes the penalty for the departure from the incompressibility or controlled compressibility conditions and W_t the friction power. In the presented solution the second part of functional (1) is missing and both incompressibility and controlled compressibility conditions are given in analytical form and constrain the velocity field components. The functional takes the following shape:

$$J^*[v(r,z)] = W_\sigma + W_t \qquad (2)$$

In (1) and (2) v describes the velocity field distribution in the deformation zone. The optimisation of functional (2) is much more effective than that of functional (1), because numerical form of incompressibility condition generates a lot of local minimums and leads to wide flat neighbourhood of the global optimum. The accuracy of the proposed solution is much better because of negligible volume lost. 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 described shortcoming. For solid regions of the sample the incompressibility condition in cylindrical coordinate system has been described with an equation:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0 \qquad (3)$$

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

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} - \frac{1}{\rho}\frac{\partial \rho}{\partial \tau} = 0 \qquad (4)$$

where ρ is the temporary material density and τ - the time variable. The mass conservation condition (4), which is more general than relationship (3), was used for the purpose of the proposed solution. The model is completed with numerical solution of Navier stress equilibrium equations.

The temperature field is a non stady-state solution of Fourier-Kirchhoff equation with convection. The combined Hankel's boundary conditions have been adapted for the presented model. The time discretisation was done according to Galerkin FEM scheme.

Density is one of the most important parameter of the solution. 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 (Mizukami, 2002). More details concerning the presented mathematical model changes were published in (Głowacki&Hojny, 2006; Hojny, 2006).

3. DEF_SEMI_SOLID SYSTEM

In aim to allow easy working with the presented models a user friendly system called *Def_Semi_Solid* was developed by the authors (Hojny&Głowacki, 2005; Głowacki&Hojny, 2006). Due to shape of testing samples (Figure 1) the numerical part of the program was developed for working with axial-symmetrical domains and was written in Fortran, which guaranties fast computation.

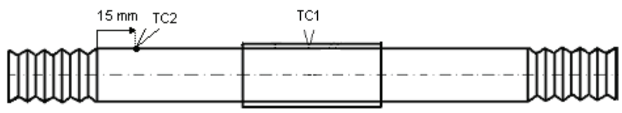

Fig. 1. *Samples used for the experiments. TC1 ÷ TC2 – thermocouples.*

Table 1. *The chemical composition of the investigated steel.*

Element content (in mass%)												
C	Mn	Si	P	S	Cr	Ni	Cu	Sn	Al	Ti	Ca	N
0.096	0.35	0.13	0.009	0.005	0.03	0.07	0.15	0.015	0.036	0.025	0.0026	0.008

The database and graphical interface were written using visual version of C++ language. This approach enables usability of the program both in Windows and Unix based systems. The latest version 2.0 of *Def_Semi_Solid* is equipped with fully automatic installation unit and new graphical interface (Figure 2). It allows the computer aided testing of mechanical properties of steels at very high temperature using GLEEBLE physical simulators avoiding problems which arise by traditional testing procedures.

Fig. 2. *View of DSS program setup window.*

The program consists of three units: DSS/Prep module, DSS/Solv module and DSS/Post module and additional tools e.g. inverse analysis module. The first of them allows the establishment of new projects or working with previously existing. Each project contains 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 dBASE IV and Paradox 7-8) and allows the implementation of material databases and procedures of automatic data verification. The next module gives the user the possibility of management with the working conditions of the solver. For example the inverse analysis can be turned off or on. The last module is dedicated to the visualisation of the numerical results and printing the final reports.

4. EXPERIMENTAL WORK

The experimental work was done in Institute for Ferrous Metallurgy in Gliwice, Poland. Figure 1 shows the shape of the testing samples and locations of thermocouples. The BW11 grade steel was investigated using GLEEBLE 3800 simulator. The chemical composition of the steel is presented in table 1.

The liquidus temperature of the BW11 grade steel is 1523°C. The average NST temperature 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:

1. Determination of the characteristic temperatures for investigated steel.
2. Computation of the temperature distribution along the heating zone for different variants of heating-holding-cooling processes and two different dies.
3. Optimisation of the stress-strain curve based on extension tests.
4. The compression tests were done for different variants. Based on results obtained from compression test, the inverse analyses were done.

Details concerning the physical simulations were published in (Hojny, 2006).

5. EXAMPLE RESULTS

Strain-stress curve is one of the most important relationships having crucial influence on the metal flow path. The strain-stress curves, which are necessary for the mechanical model, were constructed on basis of a series of experiments conducted on GLEEBLE simulator, as well (Hojny, 2003). For the temperature range under 1350°C traditional testing methods give good results. Figure 3 shows the relationship at 1300°C and die velocity equal to 1 mm/s. The usual testing procedure was applied for the discussed temperature. The curves were described by following Voce'a equation:

$$\sigma_p = w_4 + w_5\left[1-\exp(-w_2\varepsilon)\right]^n - w_1\left[1-\exp\left(-w_3\frac{\varepsilon-\varepsilon_c}{\varepsilon_p}\right)\right]^m$$
$$\varepsilon_c = w_6 w_7^{w_8} Z^{w_9}$$
$$\varepsilon_p = w_{10}\varepsilon_c \tag{5}$$

where w_i ($i = 1, ..., 10$), n and m are the coefficients calculated by way of approximation of experimental data, ε is the logarithmic strain and Z is the Zener-Holomon parameter defined as:

$$Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right) \tag{6}$$

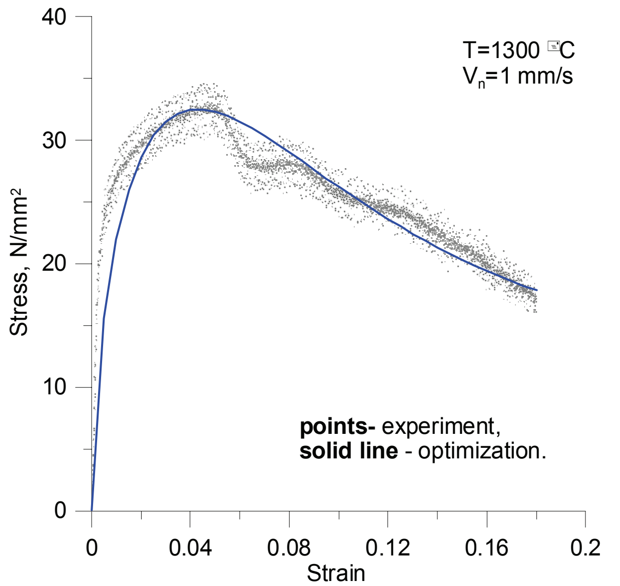

Fig. 3. Stress – strain relationship at temperature of 1300°C and tool velocity 1 mm/s obtained in usual testing manner.

In equation (6) R is the gas constant, T - temperature, Q - activation energy, $\dot{\varepsilon}$ - strain rate. In table 2 the coefficients obtained during optimization are collected.

The presented methodology is applicable in the temperature range between 1200°C and 1420°C. It is not easy to construct isothermal experiments for temperatures higher than 1420°C. Several serious experimental problems arise. First of all, keeping so high temperature constant during the whole experimental procedure is extremely difficult. There are also 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 (Głowacki&Hojny, 2004). The only possibility to have good coefficients of formula (5) for temperature higher than 1420°C is the inverse analysis. Figure 4 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 4, showing good agreement between both loads. The coefficients obtained during inverse analysis allow the construction of stress-strain curve, which is presented in figure 5.

Table 2. *The coefficients of the strain-stress curve (optimization).*

n	m	w_1	w_2	w_3	w_4
0.707742	1.569899	182.2723	18.00453	4.390496	73.39844
w_5	w_6	w_7	w_8	w_9	w_{10}
120.3222	0.0004	93.67933	4.390496	0.15	1.23

Using previously presented curves, example simulations of compression of cylindrical samples with mushy zone have been performed. The results of the tests demonstrate the possibilities of the mathematical model. For all series of tests the simulations were done using short contact zone between the sample (Fig. 1) and simulator 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 6 the comparison between experimental and theoretical temperature versus time curves is presented for two different locations (mounting places of two thermocouples).

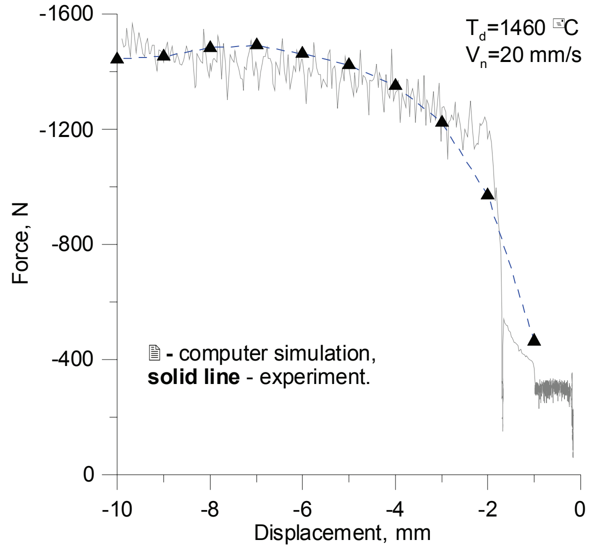

Fig. 4. Comparison between measured and predicted loads at temperature 1460°C for tool velocity 20 mm/s.

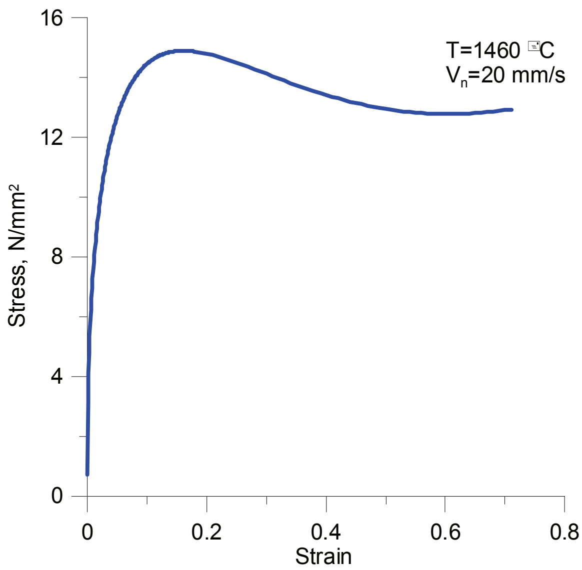

Fig. 5. Flow stress vs strain at temperature 1460°C for tool velocity 20 mm/s.

In the figure 7 the initial temperature distribution in the cross-section of the sample deformed at 1460°C is presented. Taking into account the values of characteristic temperatures one can state the existence of mushy zone in the sample centre. 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 (Fig. 8).

In figure 9 the comparison between the measured and calculated shapes of the sample cross-section is presented showing good agreement between theoretical and experimental data.

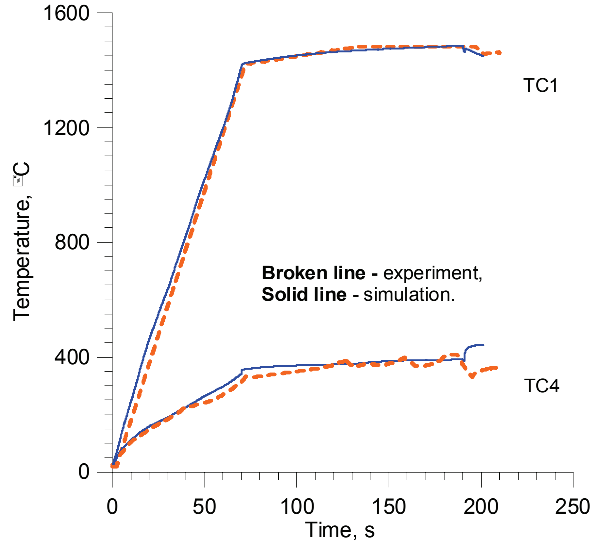

Fig. 6. Comparison between the experimental and theoretical time-temperature curves. Situation during initial heating and final compression at 1460°C.

6. 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 lost due to numerical form of incompressibility condition, which causes problems concerning optimization of the velocity field.

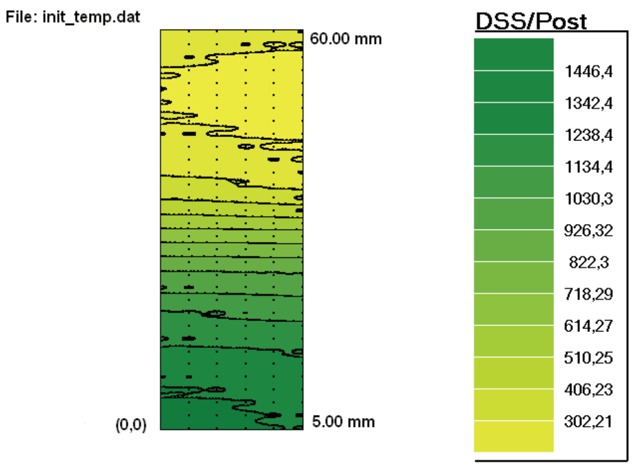

Fig. 7. Initial temperature distribution in the cross-section of the sample deformed at 1460°C.

The presented Def_Semi_Solid program is very helpful and may enable the right interpretation of results of very high temperature tests. It has shown its predictive ability regarding both shape and size of the deformation zone and mechanical properties of steels. It was possible due to application of right models and implementation of the inverse analysis.

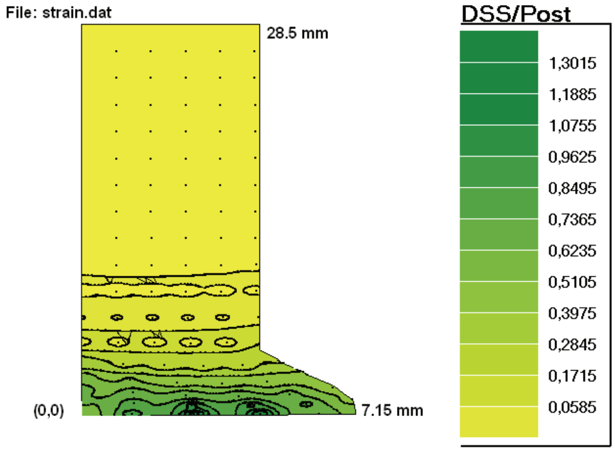

Fig. 8. Strain distribution in the cross-section of the sample deformed at 1460°C.

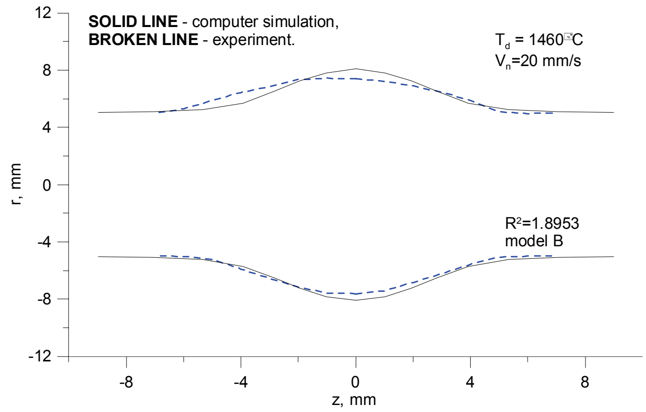

***Fig. 9.** The comparison of the measured (broken line) and calculated (solid line) shapes of the central part of the sample deformed at 1460°C.*

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DEDYKOWANY KOMPUTEROWY SYSTEM WSPOMAGANIA PROCESU ODKSZTAŁCANIA STALI W POBLIŻU TEMPERATURY SOLIDUS

Streszczenie

W parcy zaprezentowano wynki prac teoretycznych i doświadczalnych prowadzących do modelowania zjawisk towarzyszących odkształcaniu stali w ostatniej fazie procesu krzepnięcia. Symulacje fizyczne odkształcania w takich warunkach z wykorzystaniem nowoczesnych urządzeń (np. symulator GLEEBLE 3800) są kosztowne i bardzo trudne ze względu na równoczesne odkształcenie i krzepnięcie metalu i jego nietabilne zachowanie. Zastosowanie dedykowanego systemu symulacji komputerowej wykorzystującego analizę odwrotną umożliwia procedurę testową i obniża koszty eksperymentu. Autorzy zaprezentowali taki właśnie system uwzględniający zmienną gęstość i warunek nieściśliwości w postaci analitycznej. Podstawowym celem symulacji jest odtworzenie zmian temperatury, odkształceń i naprężeń w próbkach stalowych poddawanych odkształceniu w końcowej fazie krzepnięcia. Zaprezentowany program umożliwia prawidłową interpretację odkształcania w bardzo wysokich temperaturach.

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