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Numerical Modelling of Steel Deformation at Extra-High Temperatures

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1. Introduction

Due to the globalized energy crisis and high consciousness of environmental protection in last year's, more and more products and new technology that put stress on energy preservation and environmental protection are being developed. The integrated casting and rolling technologies are newest and very efficient ways of hot strip production. Only few companies all over the world are able to manage such processes. Among them one can mention the plant located in Cremona Italy which develops the Arvedi Steel Technologies – new methods of steel strip manufacturing. They are called ISP (Inline Strip Production) and AST (Arvedi Steel Technologies) processes and are characterized by very high temperature allowed at the mill entry. The instant rolling of slabs which leave the casting machine allows the utilization of the heat stored in the strips during inline casting.

The rolling equipment for the Inline Strip Production process consist of cast rolling machine, liquid core reduction equipment, high reduction mill, inductive heater, Cremona coiling station, descaler, traditional finishing mill and the cooling zone. The initial mould strip thickness is 74 mm and is reduced to 55 mm during liquid core reduction process. The region of maximum strip temperature for a high reduction mill is placed in the strip centre and varies from 1220^{o}C to 1375^{o}C depending on the casting speed. The main benefits of the technology are:

- very low investment costs,
- compact rolling equipment layout – total rolling line is only 170 m long,
- no need of tunnel furnace,
- good product quality – 1 mm strip with best shape and microstructure,
- very low level of heating energy consumption which drops to 0 when the casting speed is over around 0.14 m/s,
- up to 20 times lower water consumption,
- inverse (in comparison to traditional rolling) temperature gradient in the cross-section of the strip, which is very useful for the rolling process,
- low level of installed mill power in high reduction mill (3 rolling stands with 0.5, 0.6 and 0.8 MW) providing reduction from 55 to 12.5 mm by the strip width of 1300 mm.

The AST (Arvedi Steel Technologies) technology is a result of further development of ISP to a real endless process. The main difference between these two technologies is the absence of the heating equipment in case of AST. The whole reduction process is running in one rolling mill consisting of 5 or 7 stands, which can reduce the strip thickness from 55÷70 mm to 0.8 mm. AST is the most compact hot strip production process using oscillating mould technology with excellent efficiency and cost. The total equipment length is 70 to 80 m including casting machine at the front and final coolers at the rear end. The maximal temperature of the strip occurs in central region of its cross-section and varies from 1340^{o}C to 1420^{o}C according to the casting speed. It suggests that the central region of the strand subjected to the rolling is still mushy.

Both the technologies mentioned above ensure huge reduction of rolling forces, very high product quality and low investment costs and their details are usually classified. The main goal of the mentioned new technologies is to significantly lower the rolling forces and to reach very favourable temperature field inside the plate in comparison with traditional processes. However certain problems specific to such a metal treatment arise. The central part of the material is still mushy. This results in changes in material density and occurrence of characteristic temperatures, which have great influence on plastic behaviour of the material. A vital problem is also the lack of data regarding material's thermal and mechanical properties and significant changes of density.

The material behaviour above the solidus line is strongly temperature-dependent. There are a few characteristic temperature values between solidus and liquidus. The Nil Strength Temperature (NST) is the temperature level at which material strength drops to zero while the steel is being heated above the solidus temperature. Another temperature associated with NST is the Strength Recovery Temperature (SRT), which is specific to cooling. 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 steel loses its ductility. The 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. Over this temperature the plastic deformation is not allowed at any stress tensor configuration.

Very important for plastic behaviour of steel is also its density. It varies with temperature and depends on the cooling rate. The solidification process causes non-uniform density distribution in the controlled volume resulting in non-uniform deformation and heat conduction. There are three main factors causing density changes: solid phase formation, thermal shrinkage and movement of liquid particles inside the solid skeleton. The density plays an important role in both mechanical and thermal solutions.

The most important steel property having crucial influence on metal flow paths is the strain-stress relationship. It is not easy to run the isothermal tests that could be the source of the computation of yield stress function parameters for temperature range close to solidus line. Keeping constant temperature during the whole experiment course is difficult. There are also some difficulties with interpretation of tests results. Lack of good methods of particular metal flow simulation and significant inhomogeneity in strain distribution in the deformation zone lead to weak accuracy of standard FEM solutions.

The mathematical and experimental modelling of mushy steel deformation is an innovative topic regarding the very high temperature range deformation processes. Tracing the related papers published in the past ten years, one can find many papers regarding experimental results (Kang & Yoon, 1997; Koc et al., 1996; Kop et al., 2003) and modelling (Modigell et al., 2004; Hufschmidt et al., 2004) for non-ferrous metals tests. The papers deal mainly with tixotrophy. The first results regarding steel deformation at extra high temperature were presented in the past few years (Jing et al., 2005; Jin et al., 2002). The situation is caused by the very high level of steel liquidus and solidus temperatures in comparison with non-ferrous metals. The deformation tests for non-ferrous metals are much easier. The rising abilities of thermo-mechanical simulators enable steel sample testing and as a result both computer simulation and improvement of new rolling technologies, similar to ISP and AST processes.

The chapter sheds light on these problems. It focuses on the axial-symmetrical computer model, which ensures the possibility of its experimental verification with the help of physical simulation.

2. Thermo-mechanical model of steel deformation in semi-solid state

The numerical analysis of deformation of samples having liquid phase in their central parts shows extremely high strain inhomogeneity requiring application of hybrid analytical-numerical solution of the problem (Hojny & Glowacki, 2008, 2009, 2011). A coupled thermal-mechanical mathematical model was developed for simulation of plastic behaviour of such a species. The model is dedicated to modelling processes, which require high accuracy of resulting parameter fields. Analytical solutions of both incompressibility and mass conservation (for the mushy zone) conditions are important parts of the model. Analytical condition eliminates problems with unintentional specimen volume changes caused by application of numerical methods. The existing, physical changes of steel density in the mushy zone have influence on real variations of controlled volume. On the other hand numerical errors can be a source of volume loss which cause interference with real changes. This effect is very undesirable in modelling of thermal-mechanical behaviour of steel in temperature range characteristic for the transformation of state of aggregation.

The mathematical model of the process consists of two main parts – mechanical and thermal – both of them supported by density changes model. The mechanical part is responsible for the strain, strain rate and stress distribution in a controlled volume. The stress is substantial due to shrinkage and plastic deformation. It can cause cracks when the stress exceeds the ultimate tensile strength, which is very low within discussed temperature range.

2.1 Thermal model

Thermal solution has crucial influence on simulation results, since the temperature has strong effect on remaining variables, especially if the specimen temperature is close to solidus line. Plastic flow of solid and mushy materials, stress distribution and density changes are relevant to the temperature field particularly for deformation of body which consist of both solid and semi-solid regions. The temperature field is a result of solution of Fourier-Kirchhoff equation. The combined Hankel's boundary conditions have been adopted for the model (Glowacki, 2005). The Fourier-Kirchhoff equation in cylindrical coordinate system is written as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\mathrm{k}_r\frac{\partial T}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{1}{r}\mathrm{k}_\theta\frac{\partial T}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right)+Q=\rho c_p\frac{\partial T}{\partial \tau} \tag{1}$$

where r, θ, z are cylindrical coordinate system, T is the temperature distribution in the controlled volume, τ is the time variable, k denotes the heat conduction coefficient (or coefficients matrix in case of thermal inhomogeneity), Q represents the rate of heat generation (or consumption) due to the transformation of the aggregation state, plastic work done and due to electric current flow in case of resistance heating of the sample. Finally, c_p describes the specific heat. The solution of equation (1) has to satisfy appropriate boundary conditions. The Hankel's boundary conditions can be written in form of differential equation (Glowacki, 2005):

$$k\frac{\partial T}{\partial n}+\alpha(T-T_0)+q=0 \tag{2}$$

In equation (2) T_0 is the distribution of the border temperature, q describes the heat flux through the boundary of the deformation zone, α is the heat transfer coefficient, n is a vector which is normal to the boundary surface.

2.2 Mechanical model with analytically controlled compressibility

As mentioned above the mechanical part is responsible for calculation of the strain, strain rate and stress distribution in the deformation zone which consist of solid and semi-solid regions. The analysis of mathematical models which can be applied for strain field calculations for semi-solid steel deformation process has proved good predictive ability of a rigid-plastic model of metal flow. The model is completed with numerical solution of Navier stress equilibrium equations in order to satisfy all the requirements leading to stress field. Rigid-plastic model was selected due to its very good accuracy with reference to strain field during the hot deformation and sufficient correctness of calculated deviatoric part of stress field. Moreover, the elastic part of stress tensor components is very low at temperatures close to solidus line and practically can be neglected in calculations of strain distribution. Classical rigid-plastic solutions are based on optimisation of following power functional:

$$J^*\left[v(r,z)\right]=W_\sigma+W_\lambda+W_t \tag{3}$$

where W_σ is the plastic deformation power, W_λ the penalty for the departure from either incompressibility or mass conservation conditions and W_t the friction power. In presented solution the second part of functional (3) is missing and both incompressibility and mass conservation conditions are given in analytical form constraining the velocity field components. The functional takes the following shape:

$$J^*\left[v(r,z)\right]=W_\sigma+W_t \tag{4}$$

where v describes the velocity field distribution in the deformation zone. In case of functional (4) the optimisation procedure is much more convergent than the one concerning functional (3), because numerical solution of both the mentioned conditions generates a lot of local minima and leads to wide flat neighbourhood of the global optimum. The accuracy of the proposed hybrid solution is also much better because of negligible volume loss caused by numerical errors which is very important for materials with changing density. Fully numerical solution shows lower accuracy contrary to the proposed analytical-numerical one. For solid regions of the sample the incompressibility condition is satisfactory and in cylindrical coordinate system it has been described with an equation:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} = 0 \tag{5}$$

where v_r and v_z are the radial and longitudinal velocity field components in cylindrical coordinate system r, θ, z. For the mushy zone equation (5) is replaced by the mass conservation condition, which takes a form:

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{\partial v_z}{\partial z} - \frac{1}{\rho}\frac{\partial \rho}{\partial \tau} = 0 \tag{6}$$

where ρ is the temporary material density and τ is the time variable.

2.3 Density changes

Density distribution is one of the most important properties of the mushy steel which undergo the deformation. Its changes have influence on both the mechanical and thermal parts of the presented model. The knowledge concerning effective density distribution is very important for modelling of deformation of porous and mushy materials. Density changes of liquid, solid-liquid and solid materials are ruled by three phenomena:

- solid phase formation,
- laminar liquid flow through porous material and
- thermal shrinkage.

Total density changes can be calculated according to the Darcy method which can be formulated in a form of differential equation:

$$\frac{\partial \rho}{\partial \tau} = \left(\rho_s X_s + \rho_l X_l\right)\left(\frac{\rho_s}{\rho_l} - 1\right)\frac{\partial X_l}{\partial \tau} + \rho_l X_l \,\mathrm{div}\, v + \left(\beta_s \rho_s X_s + \beta_l \rho_l X_l\right)\frac{\partial T}{\partial \tau} \tag{7}$$

where X and β are fraction and linear expansion coefficients, respectively. Indexes l and s denote the liquid and solid phases, τ is the time variable, T is the temperature distribution in the controlled volume. Solution of equation (7) requires further time and computer memory resources. Nevertheless another way of taking density into consideration is possible due to temperature dependency of this quantity. In order to avoid additional problems with solution of equation (7) density changes were calculated according to an empirical model taking into consideration the experimental data. The model is slightly less accurate but such a method makes the solution much easier. The density changes of the investigated steels were computed using commercial JMatPro software. Figure 1 presents an example graph of density versus temperature dependency drawn for steel having 0.41% carbon content.

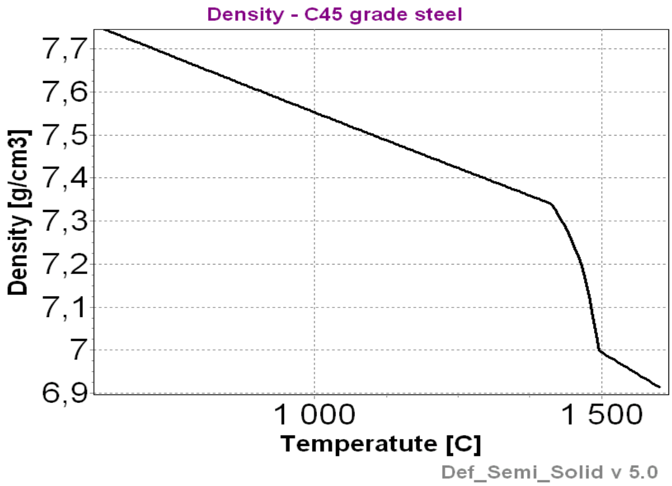


Fig. 1. The density versus temperature curve for C45 grade steel.

More details about presenting thermo-mechanical model, numerical methods and techniques will be described in the next chapter of this book.

3. Numerical systems – Def_Semi_Solid and JMatPro

In aim to allow easy working with the Gleeble® 3800 simulator a user friendly system called Def_Semi_Solid v.5.0 was developed in the Department of Computer Science and Modeling of the Faculty of Metals Engineering and Computer Science in Industry, AGH. The numerical part of the program was developed in FORTRAN/C++ language, which guaranties fast computation and the 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 Linux based systems. The newest version of Def_Semi_Solid system is equipped with full automatic installation unit (Figure 2) and new graphical interface. It allows the computer aided testing of mechanical properties of steels at very high temperature using Gleeble® 3800 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/tension test as well as the results of measurements and optimization. In the current version of the program the module permits application of a number of database engines (among other standard MSAcces, 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.

Fig. 2. View of DSS program setup window (local version).

The last module (DSS/Post module) is dedicated to the visualisation of the numerical results and printing the final reports. In the current version the possibility of visualization was significant improved. The main are: shading options using OpenGL mode (2D and 3D) and possibility make a full contour map (2D and 3D) as shown in Figure 3.

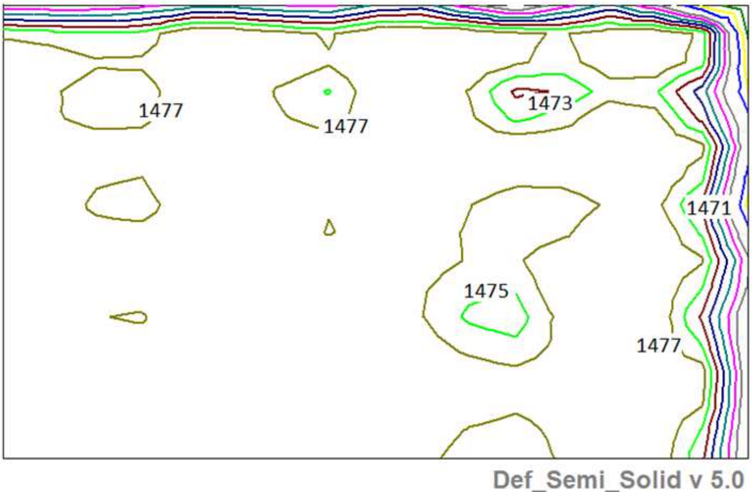


Fig. 3. The Post-processor of the newest version of Def_Semi_Solid system (contour option).

The less visible but powerful heart of the system is of course the solver. The finite element code dedicated to the axial-symmetrical compression/tension tests has been developed. The solution is based on the thermo-mechanical approach with density changes described in the previous section. The second software used during theoretical work was commercial code JMatPro. This program calculates a wide range of materials properties for alloys and steels. Using JMatPro we can make calculations for stable and metastable phase equilibrium, solidification behaviour and properties, thermo-physical and physical properties, phase transformations. JMatPro includes a Java based user interface, with calculation modules using C/C++, and will run under any Windows and under Linux system.

4. Computer aided experimental procedure

The steel grades subjected to series of experiments in Institute for Ferrous Metallurgy in Gliwice, Poland using Gleeble 3800® thermo-mechanical simulator (Figure 4) were the C45 (0.45% C) and S355J2G3So (0.11% C).

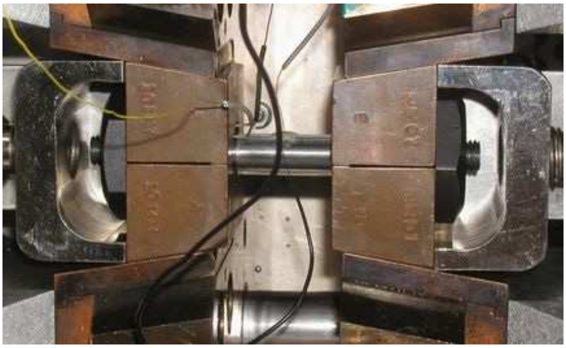


Fig. 4. The standard Gleeble® equipment allowing deformation is semi-solid state.

The essential aim of the investigation was reconstruction of both temperature changes and strain evolution on specimen exposed to simultaneous deformation and solidification. The analysis of metal flow in subsequent regions of the sample deformation zone requires adequate methods. Classical techniques of interpretation of results of compression testing procedures fail due to significant barrelling of the sample which is inevitable at any temperature close to solidus level. The developed user friendly dedicated FEM solution (Figure 5) with variable density based on the hybrid model described in previous sections is the core of strain-stress curves calculation system.

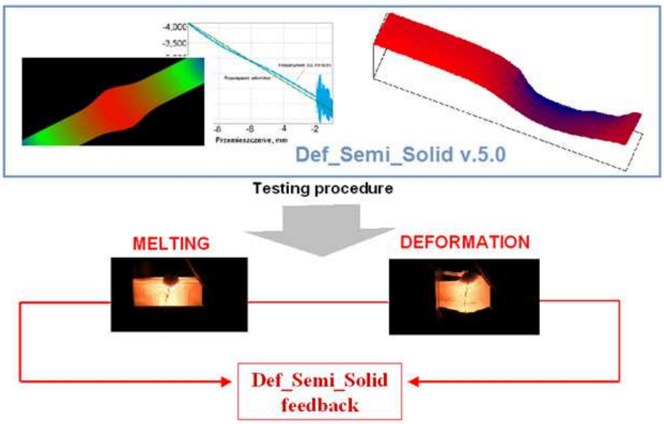


Fig. 5. The Def_Semi_Solid system as a feedback unit with Gleeble® 3800 simulator.

In all cases, experiments ran according to schedule:

stage 1: the sample was prepared (e.g. mounting thermocouples, die selection),
stage 2: melting procedure of the sample was realized,
stage 3: at the end the deformation process was done.

Figure 6 shows the shape of the testing samples and locations of thermocouples used during experiments.

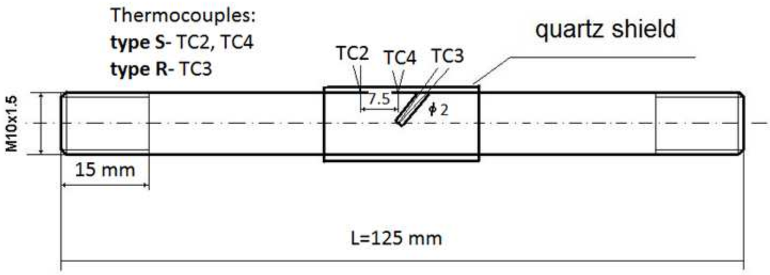


Fig. 6. Samples used for the experiments. TC2, TC3 and TC4 thermocouples.

Material tests in the semi-solid state should be carried out in as isothermal conditions as possible due to the very high sensitivity of material rheology on small changes of temperature (Hojny et al., 2009). The basic reason for uneven temperature distribution inside samples on the Gleeble® simulator is their contact with cooper handles during resistance heating (Figure 7).

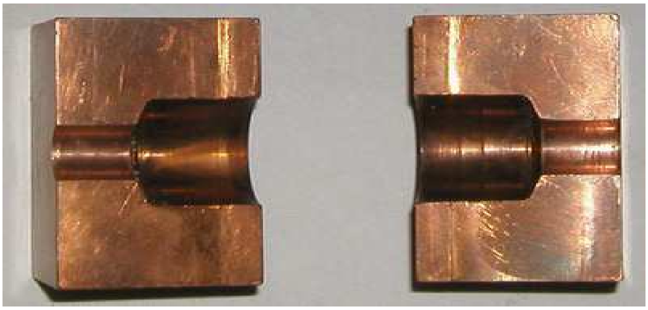


Fig. 7. The handle with short contact zone (sample - handle) used during experiments (called "hot handle").

The estimated liquidus and solidus temperature of the investigated steels are: 1495 °C and 1410 °C, respectively for C45, 1513 °C and 1464 °C, respectively for S355J2G3So. In the next section the example results of the melting and deformation procedure are presented.

4.1 Melting procedure

Thermal solution has crucial influence on simulation results, since the temperature has strong effect on remaining. The resistance heating processes cause non-uniform distribution of temperature inside heated materials especially in longitudinal section of the sample. In the case of the semi-solid steels, such distribution gives significant differences in the microstructure and rheology. The thermo-physical properties of this steel, necessary in calculations, were determined using *JMatPro* software. This software determines this properties on the basis of the chemical composition. The example main properties of C45 grade steel used in calculations are presented in Figure 8 and Figure 9.

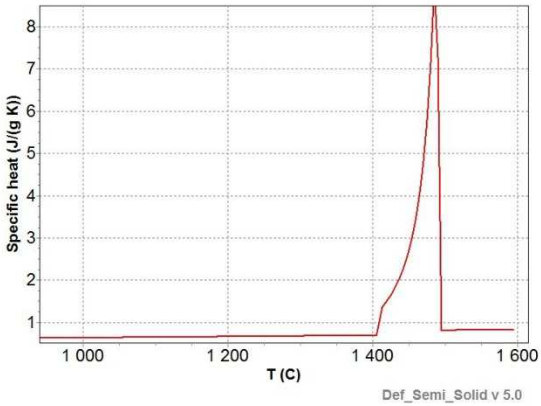


Fig. 8. Specific heat versus temperature for the investigated steel (C45).

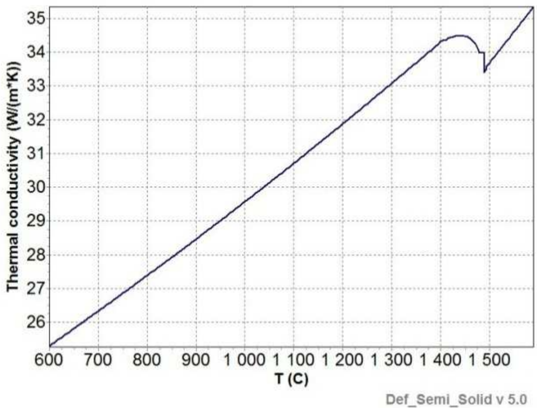


Fig. 9. Thermal conductivity versus temperature for the investigated steel (C45).

In case of each physical and computer simulation samples were heated to 1430 ^{o}C and after holding at constant temperature the sample was cooled to nominal deformation temperature. The heat generated (*Q*) due to direct current flow was calculated using inverse approach. The objective function (*F*) was defined as a norm of discrepancies between calculated (T_c) and measured (T_m) temperatures (only for indication steering thermocouples TC4) according to the following equation:

$$F(Q)=\int_{\tau_0}^{\tau_1}\left[\left(T_c(Q,r,z,T)-T_m(r,z,T)\right)^2\right]dT \tag{8}$$

where τ is the time variable.

In Figure 10 the comparison between experimental and theoretical temperature versus time curves is presented for steering thermocouple (mounting locations of thermocouples shown in Figure 6),

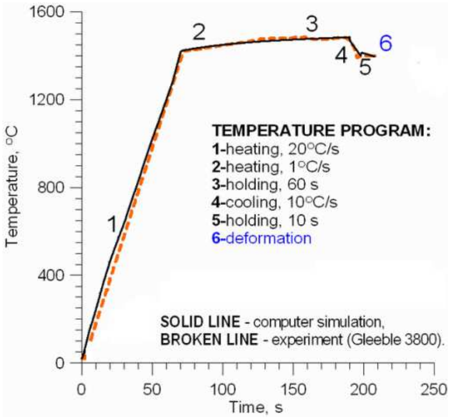


Fig. 10. Comparison between the experimental and theoretical time-temperature curves during initial heating and final compression at 1400°C.

In the final stage of physical simulation for different holding time, the temperature difference between core (TC3 thermocouple) of the sample and the surface (TC4 thermocouple) was analyzed. In all cases the core temperature was higher than surface temperature, for example, difference between core of the sample and surface was about 40 °C for test at 1380 °C (Figure 11).

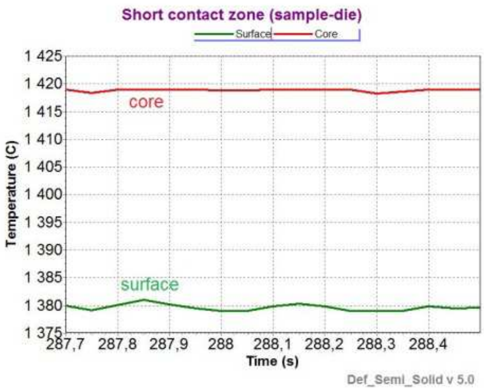


Fig. 11. The temperature change versus time for hot handle (final stage of physical simulation right before deformation at 1380 °C).

The numerical simulation confirmed results obtained during experimental parts. In the Figure 12 temperature distributions in the cross section of the sample tested at temperature 1380 °C are presented for 3 and 6 seconds of heating and final distribution right before deformation.

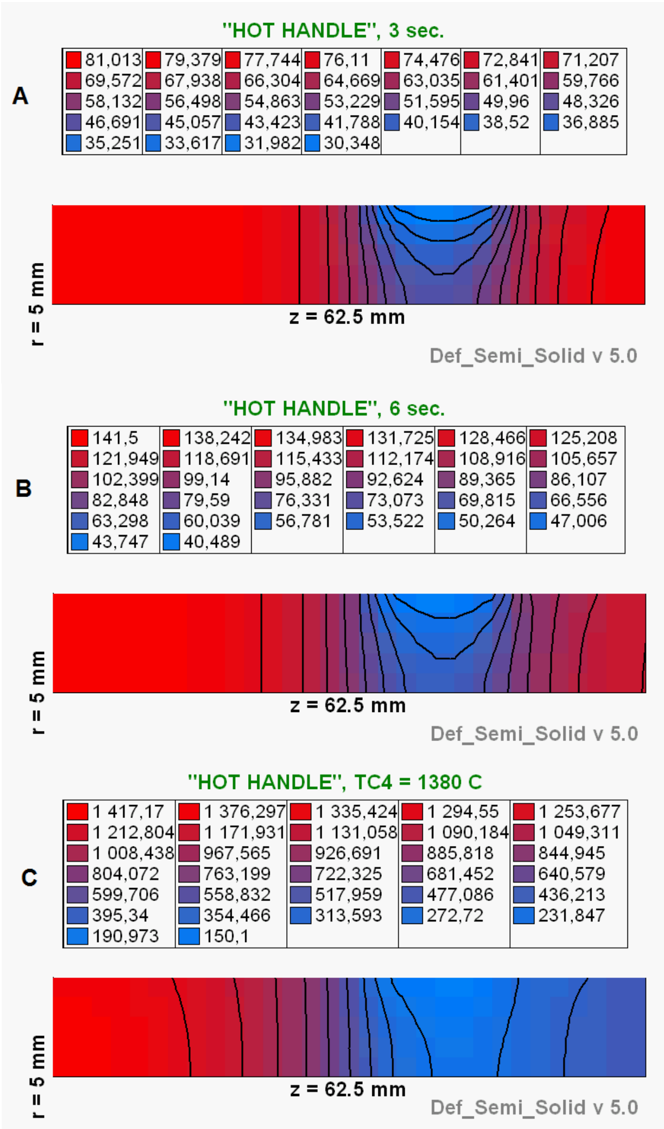


Fig. 12. Distribution of temperature in the cross section of the sample tested at temperature 1380 °C after time heating a) 3 seconds, b) 6 seconds, c) right before deformation.

The one can observe, major temperature gradient between contact surface die-sample. The difference between experimental and theoretical core temperatures for hot handles was 3°C (calculated core temperature equal 1417^{o}C, measured core temperature equal 1420^{o}C.) Finally, the micro and macrostructure of the tested samples was investigated. Figure 13 show example microstructure of the tested samples right before deformation for middle and border of the heating zone.

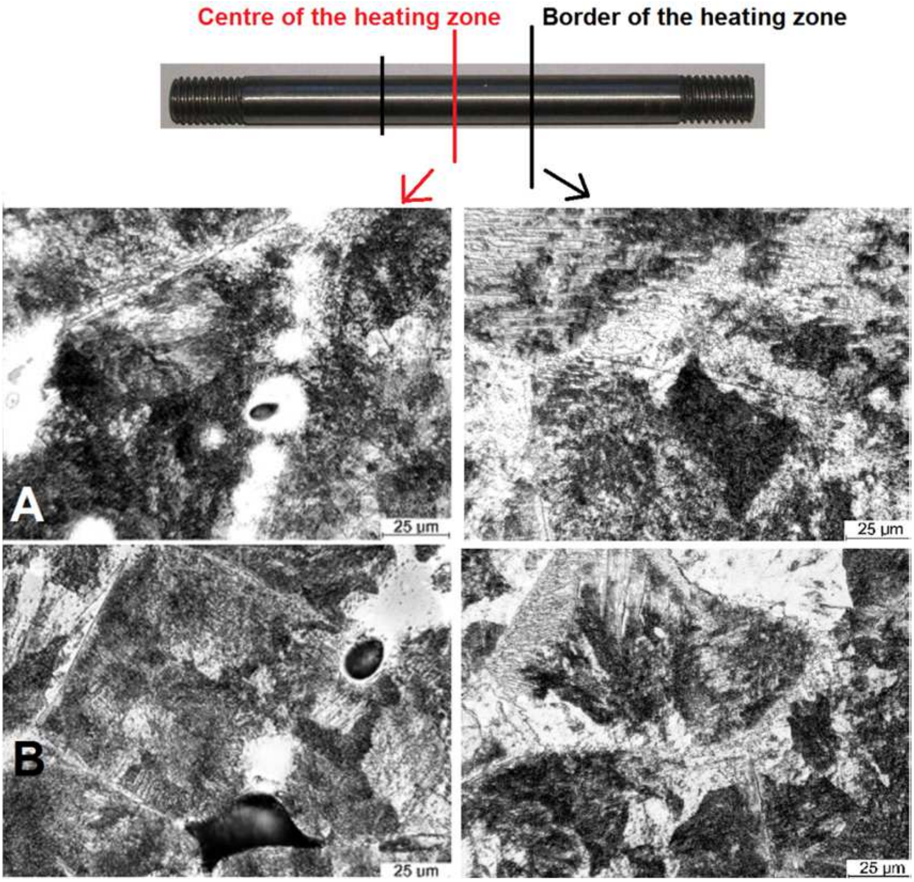
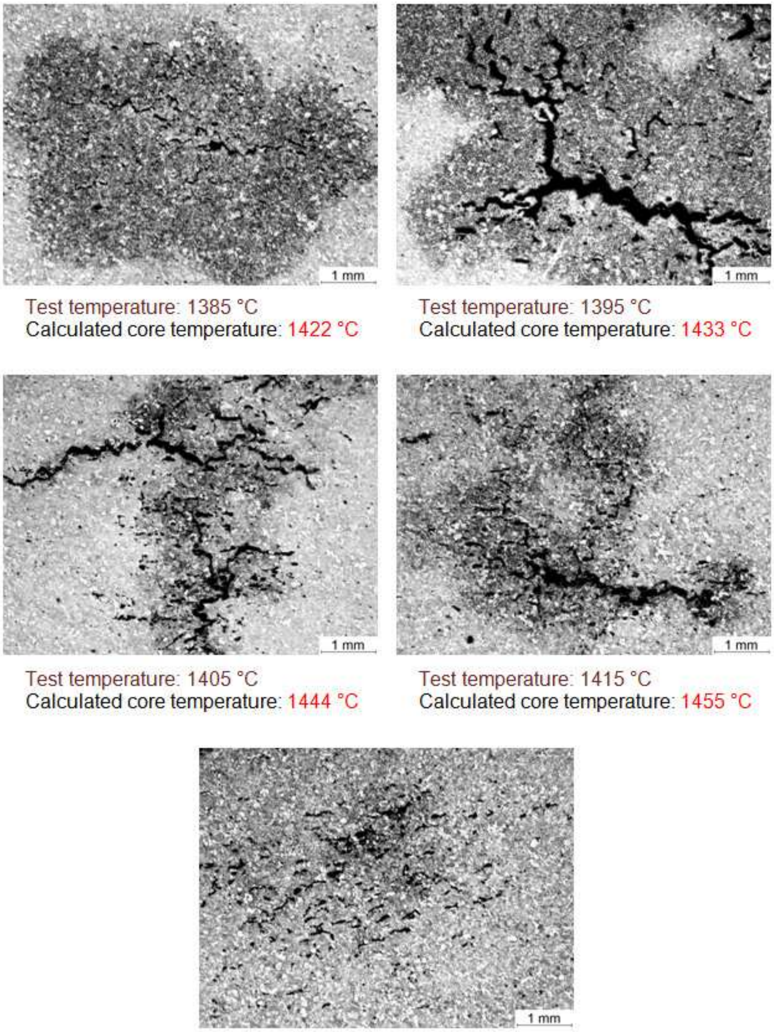


Fig. 13. Microstructure of the middle/border of the sample right before deformation. Variant with hot handle. Magnification: 400x.

Microstructure of the cooled samples consist of pearlite (the darkest phase), bainit (grey phase mainly near the borders of grains) and the bright ferrite (Figure 13). It is result of such phase composition the wide zone of melting and almost twice smaller speed of cooling in the case of samples warmed in „hot" handles. Figure 14 show example macrostructure in the cross-sections of the tested samples right before deformation and calculated core temperature. One can observe that for analyzed temperatures liquid phase particle exist in the central part of the sample. The comparison between experimental results and numerical show that mathematical model of resistance heating right reflect back the physical simulation of resistance heating of samples using Gleeble® 3800 physical simulator.



Test temperature: 1425 °C
Calculated core temperature: 1464 °C

Fig. 14. Macrostructure of the middle of the sample right before deformation. Variant with hot handle. Magnification: 10x.

4.2 Deformation procedure

In the next stage of the experimental part the compression tests were done. During experiments die displacement, force and temperature changes in the heating zone are recorded. Parallel, the computer simulations were realized in order to obtain optimal value parameters of process. The strain-stress curves were described by following equation:

$$\sigma_p = A\varepsilon^n \dot{\varepsilon}^m \exp(-BT) \tag{9}$$

where A, B, n, m are material constant, T - temperature, ε - strain and $\dot{\varepsilon}$ - strain rate. It is not easy to construct isothermal experiments for temperatures higher than 1300°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. The only possibility to have good coefficients of strain-stress formula is the inverse method (Glowacki & Hojny, 2009). The long calculation time, which is usual by this kind of analysis requires sometimes parallel computation. The application such a method is considered for the future application.

The objective function was defined as a norm of discrepancies between calculated (F_c) and measured (F_m) loads in a number of subsequent stages of the compression according to the following equation:

$$\varphi(x) = \sum_{i=1}^{n}\left[F_i^c - F_i^m\right]^2 \tag{10}$$

The theoretical forces F_c were calculated with the help of sophisticated FEM solver facilitating accurate computation of strain, stress and temperature fields for materials with variable density. The example comparison between the calculated and measured loads are presented in Figure 15-17, showing quite good agreement between both loads.

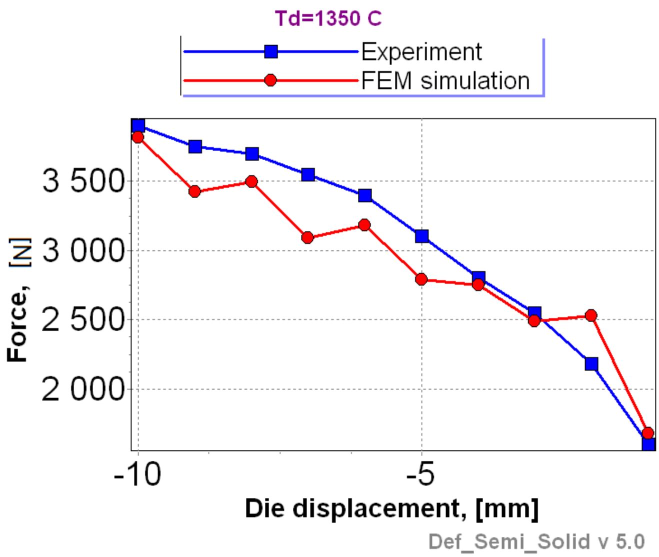


Fig. 15. Comparison between measured and predicted loads at temperature 1350°C.

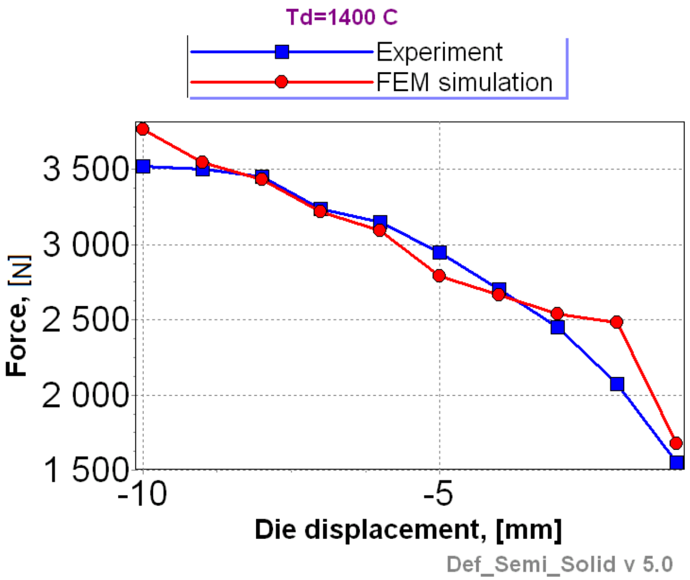


Fig. 16. Comparison between measured and predicted loads at temperature 1400°C.

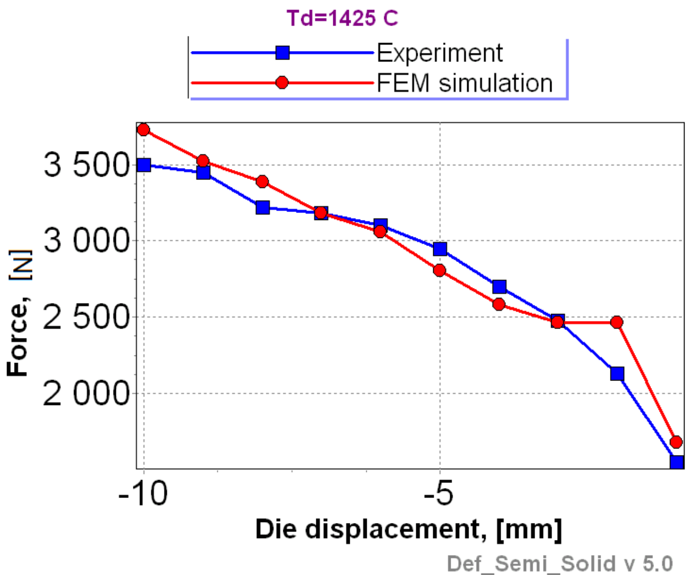


Fig. 17. Comparison between measured and predicted loads at temperature 1425°C.

The coefficients obtained during inverse analysis allow the construction of stress-strain curves, which are presented in Figure 18.

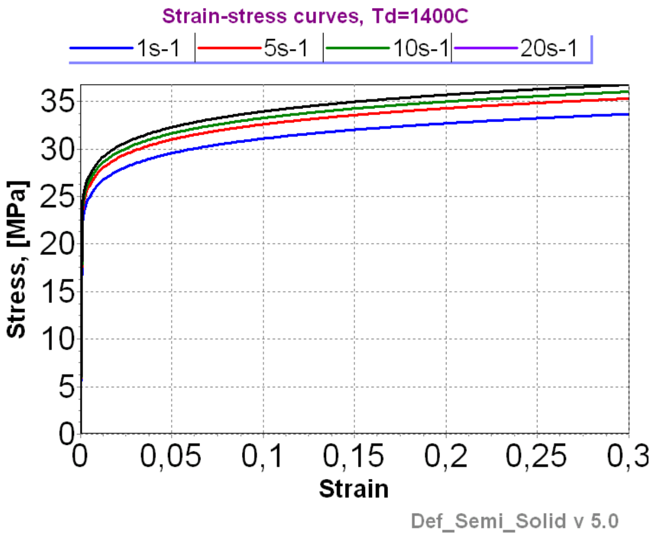


Fig. 18. Stress-strain curves at several strain rate levels for temperature 1400°C.

4.3 Verification of the computer system – Example results

Using previously developed curves, example simulations of compression of cylindrical samples with mushy zone have been performed. The results of the tests demonstrate the possibilities of the computer system. For all series of tests the simulations were done using short contact zone between the sample and simulator jaws. The deformation zone had the initial height of 62.5 mm. The radius of the sample was 5 mm. An example specimen was melted at 1430°C, and then after cooling temperature deformed at demanding temperature. The first variant at 1430°C, the second variant at 1425°C. During the tests each sample was subjected to 10 mm reduction of height. The final temperature for variant no. 1 and no. 2 is shown in Figure 19. The temperature distribution for the both variants is similar. Taking into account the value of core temperature for variant no. 2 one can state the existence of the mushy zone in the sample centre. The analysis of the effective strain fields for specimens no. 1 and no. 2, which are presented in Figure 20 show that influence of density variations on the metal flow scheme is not very significant, although small differences are clearly visible. The analysis of the strain shows maximal values of strain in the central region of the sample. In Figure 21 mean stress distribution is presented. The initial temperature distribution has great influence on the stress field in the deformation zone. The inhomogeneity of the strain field also leads to stress generation. The analysis of the mean stress (Figure 21) shows the stress concentration near the upper surface and in the centre of the sample. In accordance with the earlier conjectures for sample no. 1 the stress level is significantly higher than for sample no. 2. The material properties which have been used in the model are not very accurate because of difficulties in experiment. The existing inhomogeneity of deformation causes problems concerning the calculation of right stress values. The good analysis of the results of experiments needs computer programs to simulate plastic deformation of steel samples. The created model, which takes into account the variable density, can be helpful for the discussed purposes.

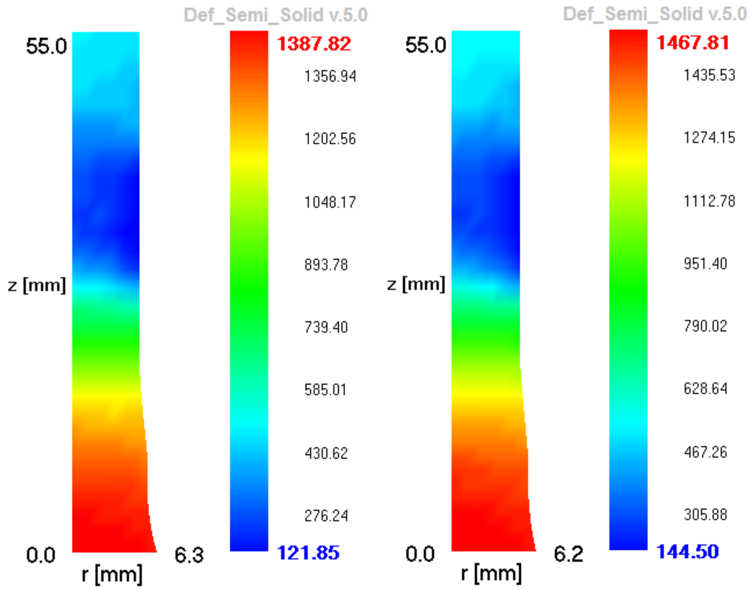


Fig. 19. Example results of computer simulation of deformation at 1350°C (left) and 1425°C (right): final temperature distribution in the cross-section of the sample.

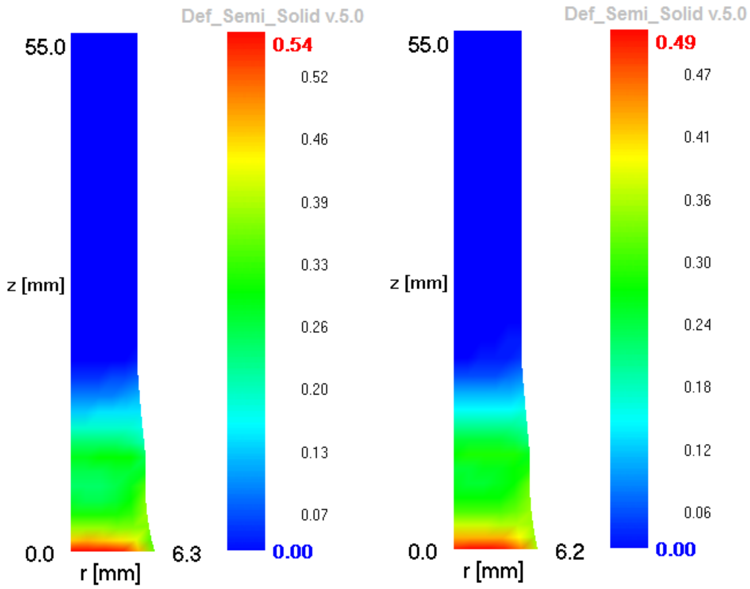


Fig. 20. Example results of computer simulation of deformation at 1350°C (left) and 1425°C (right): final strain distribution in the cross-section of the sample.

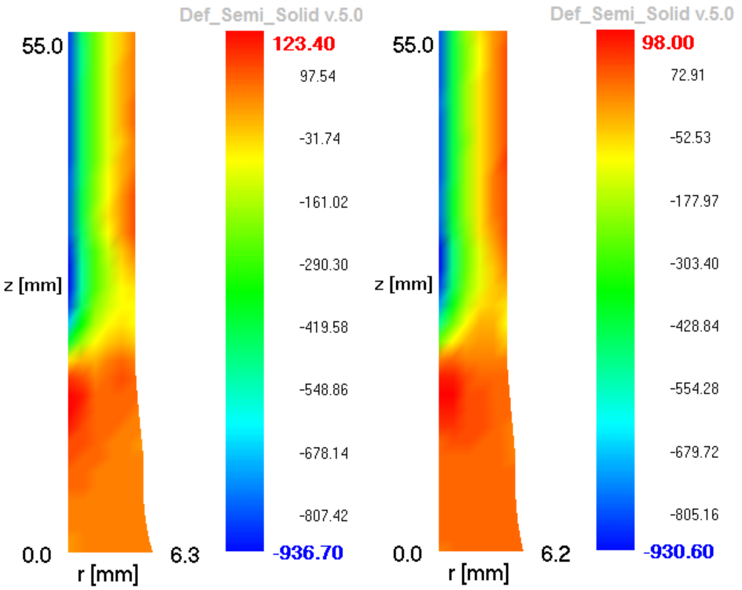


Fig. 21. Example results of computer simulation of deformation at 1350°C (left) and 1425°C (right): final mean stress distribution in the cross-section of the sample.

The calculated and experimental (Figure 22) shapes of the sample allow a rough verification of rheological model. For verification of the computer system two comparative criteria were used:

- comparison of the maximum measured and calculated diameters of the sample,
- comparison between the measured and calculated lengths of zone which was not subjected to the deformation.

Figures 23 and 24 show example application of the 1st and 2nd criterion, respectively. The figures confirm quite good agreement between theoretical and experimental results.

Fig. 22. Final shape of the sample after deformation at 1350°C, 1400°C and 1425°C.

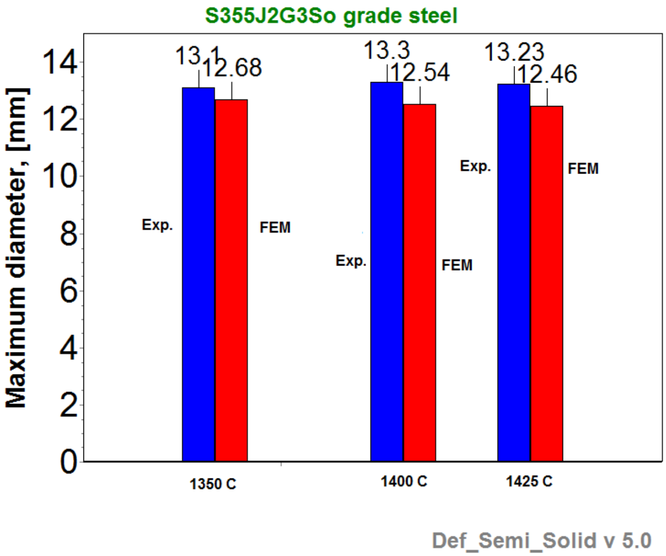


Fig. 23. The comparison of the measured and calculated maximal diameters of the sample – experiments between 1350°C and 1425°C.

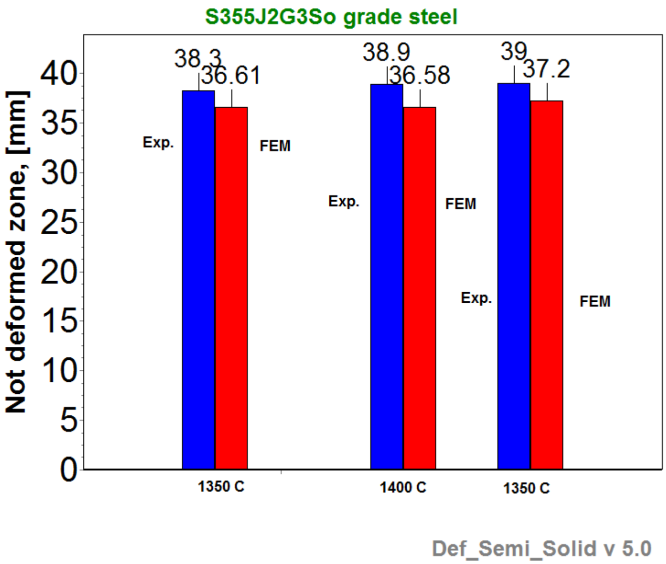


Fig. 24. The comparison between the measured and calculated length of zone which was not subjected to the deformation – Experiments between 1350°C and 1425°C.

5. Conclusions

Computer aided testing of steel samples deformation at coexistence liquid and solid phase requires resolving a number of problems. One of them is the difficulty in determination of material thermal and mechanical properties, such as: coefficients of heat transfer and other thermal properties, diagrams of density changes, which is dependent on temperature, etc. The main problem is the interpretation of compression tests results leading to strain – stress curves. 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. The presented Def_Semi_Solid program is a unique tool, which can be very helpful and may enable the right interpretation of results of very high temperature tests. The paper has shown its predictive ability regarding: temperature, shape and size of the deformation zone. The focus of attention were mechanical properties of investigated steel and specific character of theoretical model applied to the analysis. One can observe that the compression tests interpretation was possible only due to application of right model and implementation of the inverse analysis.

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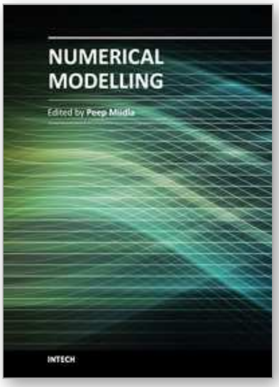

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This book demonstrates applications and case studies performed by experts for professionals and students in the field of technology, engineering, materials, decision making management and other industries in which mathematical modelling plays a role. Each chapter discusses an example and these are ranging from well-known standards to novelty applications. Models are developed and analysed in details, authors carefully consider the procedure for constructing a mathematical replacement of phenomenon under consideration. For most of the cases this leads to the partial differential equations, for the solution of which numerical methods are necessary to use. The term Model is mainly understood as an ensemble of equations which describe the variables and interrelations of a physical system or process. Developments in computer technology and related software have provided numerous tools of increasing power for specialists in mathematical modelling. One finds a variety of these used to obtain the numerical results of the book.

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