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BASICS OF THE NEW MULTISCALE METHODOLOGY 3D OF MECHANICAL PROPERTIES PREDICTION AT EXTRA-HIGH TEMPERATURES

PODSTAWY WIELOSKALOWEJ METODOLOGII 3D WYZNACZANIA WŁAŚCIWOŚCI MECHANICZNYCH W EKSTRA WYSOKICH TEMPERATURACH

A b s t r a c t

The paper presents example results leading to develop multiscale 3D methodology of mechanical properties prediction for steel deformed in the temperature range close to solidus line. Conducted experiments and simulations confirms the need to seek new methods to obtain precise characteristics in the context of detailed computer simulations.

Keywords: *physical simulation*, *finite element method*, *extra-high temperatures*

S t r e s z c z e n i e

W artykule przedstawiono wyniki prac zmierzających do opracowania wieloskalowej metodologii 3D wyznaczania własności mechanicznych stali odkształcanej w zakresach temperatur bliskich linii solidus. Przeprowadzone badania eksperymentalne i symulacyjne potwierdzają konieczność poszukiwania nowych metod w celu otrzymania precyzyjniejszych charakterystyk materiałowych w kontekście dokładniejszych symulacji komputerowych.

Słowa kluczowe: *symulacja fizyczna*, *metoda elementów skończonych*, *wysokie temperatury*

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1. Introduction

In the recent two decades, researchers have paid much attention to semi-solid forming (SSF). The reason of being under attention is higher production rate and lower energy consumption rather than conventional forming processes. 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 10–15 years, one can find many papers regarding experimental results [1] and modelling [2, 3] for non-ferrous metals tests, but the papers deal mainly with tixotrophy.

The first results regarding steel deformation at extra high temperature were presented in the past few years [4–7]. 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. Thixoforming or semi-solid metal forming offers many advantages in comparison with casting and conventional forging. However, because of the high-melting temperature and other related difficulties, there is relatively less amount of experimental data and investigations available on steels. The work [4] provide the basic deformation characteristics of stainless steel under semi-solid state, which was affected by the change in morphologies of microstructure at elevated temperature. Microstructural evolution and flow stress of semi-solid type 304 stainless steel using strain-induced melt activation method was investigated, and different morphologies of microstructure of type 304 steel was observed at different forming temperatures in the semi-solid state.

Hot compression tests for varied combination of deformation rate and deformation temperature around solidus temperature were conducted to obtain flow stress curves of type 304 stainless steel for two different semi-solid states and solid state. Flow stress curves around solidus temperature exhibit abrupt change according to the change in morphologies of microstructure, which was related to the phase change from delta-ferrite/austenite to liquid/delta-ferrite via liquid/delta-ferrite/austenite. The characteristics of deformation in two semi-solid states of type 304 stainless steel were discussed referring the change in flow stress and micrographs of quenched microstructure obtained by the experiments. The rising abilities of thermo-mechanical simulators such as a Gleeble® or Zwick Z250 machine enable steel sample testing at extra high temperatures. The material behaviour in temperature range above the solidus line is strongly temperature-dependent [8]. There are a few characteristic temperature values near the solidus line. 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 temperature associated with NST is the strength recovery temperature (SRT), which is specified during cooling. At this temperature the material regains strength greater than 0.5 N/mm2. Nil ductility temperature (NDT) represents the temperature at which the heated material loses its ductility. The ductility recovery temperature (DRT) is the temperature at which the ductility of the material (characterized by reduction of area) reaches 5% while it is being cooled. Above this temperature the plastic deformation, which is specific for traditional processes like rolling, is not allowed at any stress tensor configuration. Very important for plastic behaviour is the material's density. It varies with temperature and depends on the cooling rate. The solidification process causes non-uniform density distribution in the controlled volume. There are three main factors causing density changes: solid phase formation, thermal shrinkage and liquid phase flow inside the mushy zone. The density plays an important role in both mechanical and thermal solutions. Strain-stress relationship is extremely important and has crucial influence on the metal flow path. Special methods are usually applied for testing steel behaviour of steel in semi-solid state. An example method of strain-stress curve computation for steel in tixotropic state is presented in [6]. Keeping temperature constant during the whole experiment procedure is difficult. There are also some additional difficulties with interpretation of measurement results in case of samples with central mushy zone, which consist of dendritic skeleton of solid phase surrounding liquid phase. The solid phase may be subjected to the plastic deformation while liquid phase can flow through the porous solid phase. Lack of good methods of semi-solid steel simulation and significant inhomogeneity in strain distribution in the deformation zone lead to weak accuracy of the resulting stress field. On the other hand, the strain-stress curves, necessary for the mechanical model, can be constructed only on basis of a series of experiments conducted on physical simulators [8].

2. Extra-High Temperature Solutions Platform

The Extra-High Temperature Solutions Platform (EHTS Platform) has been developed in order to support modelling of plastic deformation of materials at very high temperature levels (Fig. 1).

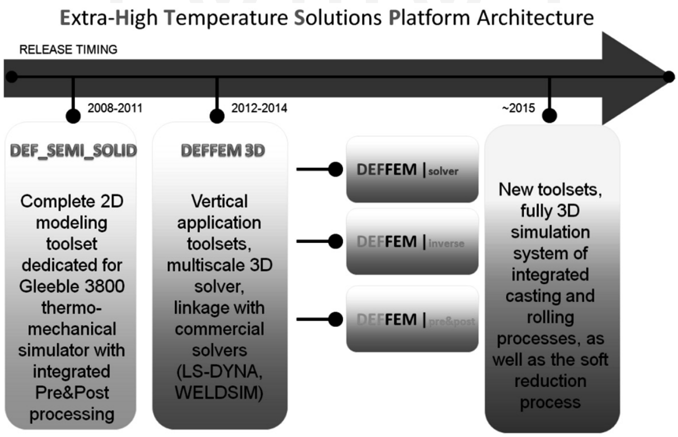


Fig. 1. Architecture of extra-high temperature solutions platform

Rys. 1. Architektura platformy obliczeń wysokotemperaturowych

The solutions platform consists of two independent tools: ***Def_Semi_Solid v.5.0*** – complete 2D modelling toolset dedicated for Gleeble® 3800 thermo-mechanical simulator with integrated Pre&Postprocessor and ***DEFFEM 3D*** – vertical application toolset including three modules: DEFFEM solver (still in development) full three dimensional multiscale thermo-mechanical solver for new methodology purposes, DEFFEM inverse and DEFFEM pre&postprocessor. The last two modules was tested in real industrial tests during modelling of TIG welding process of Inconel super alloy. Those modules supported of boundary condition identification as well as strain-stress curves based on industrial results of welding process. More details concerning modelling of TIG welding process with DEFFEM inverse module support can be found in [9].

In the current work experimental part was supported by using Def_Semi_Solid v.5.0 toolset. The main advantage of the main thermo-mechanical solver is the analytical form of mass conservation condition. The solution prevents usual unintentional specimen volume loss caused by numerical errors. Due to concurrent solidification and deformation the material is unstable. It results in strong inhomogeneity of strain distribution and difficulties in interpretation of results of deformation tests. Hence, the application of smart simulation system based on hybrid numerical-analytical model and inverse analysis is strongly recommended. The analytical part of the model was motivated by volume loss caused by numerical errors. In case of deformation of mushy materials the loss is comparable to volume changes related to the physical phenomenon of density evolution. Thus, the process requires solution with very accurate fulfillment of mass conservation condition. Because the numerical form of the condition is not satisfactory an analytical solution of the problem was proposed and a hybrid model was developed, avoiding problems with unintentional specimen volume changes, which is very important for modelling of thermal-mechanical behaviour of mushy steel. More details concerning mathematical model can be found in [10, 11].

3. Theoretical background of the new multiscale methodology – example results

The experimental work was done in Institute for Ferrous Metallurgy in Gliwice, Poland using Gleeble® 3800 thermo-mechanical simulator. The steel used for the experiments was the C45 grade steel with 0.45% carbon content. In all cases, experiments were performed according to the following schedule: initial stage: sample preparation divided into several sub stages (e.g. thermocouple assembly, die selection); stage 2: melting procedure; stage 3: deformation process. It is good practice to test materials in isothermal conditions [11]. Unfortunately, this is not possible for semi-solid steel. Nevertheless, the condition should be as close to isothermal as possible due to the very high sensitivity of material rheology to even small variations of temperature. The basic reason for uneven temperature distribution inside the sample body on the Gleeble® simulator is the contact with cold/warm copper handles [11]. The estimated liquidus and solidus temperature levels of the investigated steel are: 1495°C and 1410°C, respectively. Thermal solution of the theoretical model has crucial influence on simulation results, since the temperature has strong effect on remaining parameters. The resistance sample heating and contact of the sample with cooper handles cause non-uniform distribution of temperature inside heated material, especially along the sample. The semi-solid conditions in central parts of the sample cause even greater temperature gradient due to latent transformation heat. Such non-uniform temperature distribution is the source of significant differences in the microstructure and hence in material rheological properties.

During the experiments samples were heated to 1430°C and after maintaining at constant temperature were cooled down to the required deformation temperature. The temperature distribution model requires solutions of Fourier-Kirchhoff's equation. One of its parameters is the rate of heat generation (or consumption) due to different physical phenomena accompanying the deformation i.e.: phase transformation, plastic work done and – in case of electric heating – electric current flow. The last one is usually not known because the Gleeble® equipment uses an adaptive procedure for resistive heating controlled by temperature instead of current flow. Hence, the actual heat generated by direct current flow (in fact the rate of heat generation Q) which is required for the theoretical model, has to be calculated using inverse procedure. In this case the objective function (F) was again defined as a norm of discrepancies between calculated (T_c) and measured (T_m) temperatures at a checkpoint (steering thermocouple position: TC4 in Fig. 2).

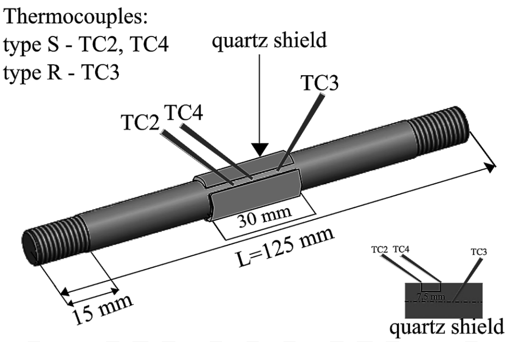


Fig. 2. Samples used for the experiments. TC2, TC3 and TC4 thermocouples

Rys. 2. Schemat próbki wraz z rozmieszczeniem termoelementów TC2,TC3,TC4

In the final stage of physical test the temperature difference between core (TC3 thermocouple position) of the sample and the surface (TC4 thermocouple position) can be significant. In all cases the core temperature was higher than surface temperature. Difference between these two was around 30°C for cold handle and about 40°C for hot handle (handle with short contact zone) for tests at 1380°C. The numerical simulation results are in agreement with results obtained during experiments. Fig. 3 presents the temperature distributions in the

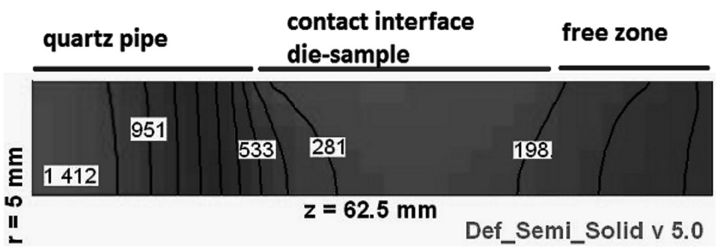


Fig. 3. Distribution of temperature in the cross section of sample tested at temperature 1380°C right before deformation (variant with cold handle)

Rys. 3. Rozkład temperatury na przekroju próbki dla próby realizowanej w temperaturze 1380°C (wariant dla uchwytów zimnych) cross section of sample tested at 1380°C right before deformation (variant with cold handle). One can observe major temperature gradient between die-sample contact surface. However, difference between experimental and theoretical core temperatures for cold handles was only 2°C (calculated core temperature was equal to 1412°C and measured one was equal to 1410°C.)

The micro and macrostructure of the tested samples were investigated as well. Fig. 4 shows macrostructure of the central part/ transitory zone/boundary of cross-sections of samples right before deformation and calculated core temperature (measurement of the core temperature is not always possible). Liquid phase particles were observed in the central part of the sample. Experimental and numerical results can be compared taking into consideration the temperature gradient within the sample. This shows that the mathematical model of resistance heating is consistent with the experimental data.

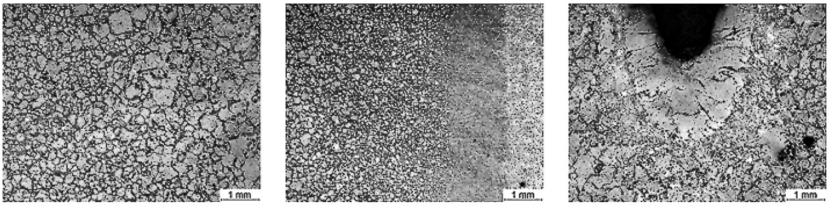
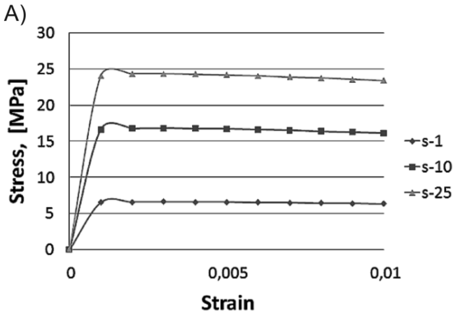


Fig. 4. Macrostructure of the sample central/transitory zone/boundary part right before deformation. Variant with cold handle. Magnification: 10×

Rys. 4. Makrostruktura rdzenia/strefy przejściowej/brzegu próbki tuż przed procesem odkształcenia. (wariant dla uchwytów zimnych). Powiększenie: 10×

Compression tests were performed, according to the methodology described detailed in [11]. The old version of steel examination methodology, denoted as variant no. 1, was based on both tension and compression tests. The temperature range was divided into two sub-ranges: lower – below NDT – and higher – above this temperature. The usual experimental procedure based on tensile tests, which is valid for cold and low-level hot deformation was applied for the lower temperature range. The resulting yield curves were described by modified Voce formula using approximation of experimental data.

A special technique of testing was developed for temperatures higher than NDT due to several serious experimental problems. The deformation process has been divided into two main stages. The first one – a very small preliminary compression and the second one – the ultimate compression. The preliminary deformation was designed to eliminate clearances in the testing equipment. The coefficients of the Voce formula were calculated using inverse solutions. This was the only acceptable method due to strong strain inhomogeneity of semi-sold steel. This approach allowed to compute strain-stress curves depending on only one additional parameter – the temperature. The newly modified developed methodology (denoted as variant no. 2) allows the computation of curves depending on both temperature and strain rate. The tension has been replaced by compression and the Voce formula was replaced by more adequate equation. During experiments die displacement, force and temperature changes in the deformation zone were recorded. The computer simulations were performed in order to obtain optimal process parameters. All series of tests and computer simulations were done using long contact zone between samples and simulator jaws (cold handle). The deformation zone had the initial height of 62.5 mm. The sample diameter was 10 mm. The samples were melted at 1430°C, and then cooled to deformation temperature. During the tests each sample was subjected to 10 mm reduction of height. Results of each test were used for inverse analysis to compute yield stress curve parameters. In Fig. 5 strain-stress curves at several strain rate levels for temperature 1380°C as well as comparison between calculated and measured forces, are shown (for methodology variant no. 2). Comparison between the calculated and measured loads showing quite good agreement.



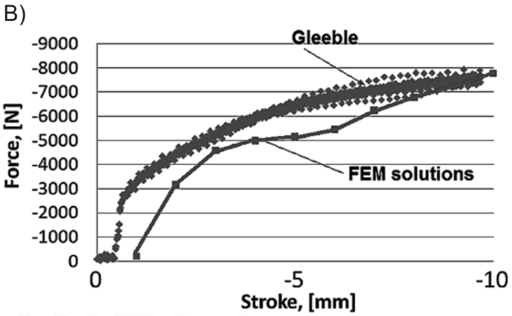


Fig. 5. A) Stress-strain curves at several strain rate levels for temperature 1380°C, B) Comparison between measured and predicted loads at temperature 1380°C

Rys. 5. A) Krzywe umocnienia dla temperatury 1380°C i trzech prędkości odkształcenia, B) Porównanie przebiegu sił zmierzonych i obliczonych dla próby w temperaturze 1380°C

Calculated and experimental shapes of the sample allow a rough verification of methodology. For verification two comparative criteria were used: comparison between the maximum measured and calculated diameters of the sample and comparison between the measured and calculated lengths of the deformation zone. The mean error for earlier methodology (variant no. 1) is greater than its equivalent for methodology denoted as a variant no. 2. The main reason for that is the lack of strain rate dependency of yield stress relationships in case of variant no. 1. Considering the strain rate as a parameter of the flow curve one can obtain more accurate results for extra high temperature range.

4. Conclusions

The investigations presented in the current paper has shown, that temperature distribution inside the controlled semi-solid volume is strongly heterogeneous and non-uniform. Axial--symmetrical model does not take into account all the physical phenomena accompanying the deformation. Finally, the error of the predicted strain-stress curves can still be improved. The proposed solution of the presented problem is application of both fully three-dimensional solution and more adequate solidification model taking into consideration evolution of forming steel microstructure. Therefore, the study of multiscale modelling of mechanical properties is the main target of the future work. Contrary to the current model the new approach should allow to better capture the physical principles of semi-solid steel deformation in micro-scale. Additionally, the methodology should allow to transfer the characteristics of the material behaviour between the micro- and macro-scale. As a consequence the final results should be more precise and accurate.

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