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TEMPERATURE CHANGES DURING THE HEATING PART OF A SEMI-SOLID STEEL YIELD STRESS TESTING PROCEDURE ON GLEEBLE® SIMULATOR

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Abstract

The main objective of this work is experimental verification of resistance heating solver which is an integral part of a computer aided procedure of yield stress investigation of steels at very high temperature. The procedure of strain-stress curves investigation connect the possibility of the Gleeble® thermo-mechanical simulator with developed by authors dedicated FEM system (called Def_Semi_Solid v.5.0). Hence, the temperature distribution inside the tested samples should be mapped with a high level of accuracy. Due to the very high sensitivity of the material rheology to temperature changes, the testing procedure requires as uniformly distributed temperature as possible. The basic reason for non-uniform temperature distribution within the sample is its contact with copper jaws of the simulator during heating process. In the paper the influence cooper handles for temperature distribution inside the samples was analyzed. Finally, the comparison between experimental and theoretical results was accomplished in order to estimate the quality of developed solver.

Key words: computer aided engineering, mathematical modeling, finite element method, resistance heating

1. INTRODUCTION

Deformation processes of steels in semi-solid state and its resistance heating up to close solidus line are effectively supported using physical simulations (Hojny et al., 2009). One of the possible measuring machines that could be applied for analysis of such processes is the Gleeble® thermo-mechanical simulator (figure 1).

Material testing of semi-solid steel should be carried out in isothermal conditions (as isothermal as possible) due to the very high sensitivity of steel rheology to temperature changes. The resistance heating is the first stage of testing procedure. The current intensity is adjusted automatically by the Gleeble® equipment in response to the difference

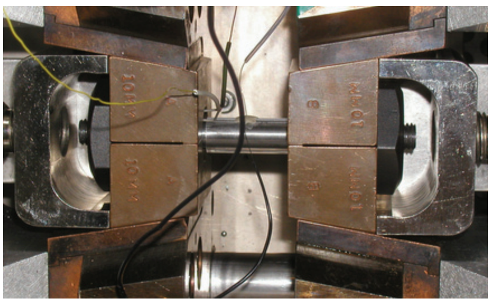

***Fig. 1.** The standard Gleeble® equipment allowing deformation is semi-solid state.*

between the required and measured temperature. The temperature is measured by a thermocouple welded to the sample surface in the middle of its height. After heating, the specimen is ready to mechanical test. In temperature range below so called Nil Ductility Temperature (NDT) the deformation of sam-

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ples subjected to the tension or compression is fairly homogenous temperature (Hojny & Głowacki, 2009; Hojny & Głowacki, 2008). In such a case application of standard testing procedure based on simple approximation of stress curve on the basis of recorded deformation and force is possible. For higher temperatures the inverse analysis was required due to strong strain inhomogeneity, which results in significant barreling of the sample. The inverse analysis is as good as the applied process simulation model (Hojny & Głowacki, 2009; Głowacki & Hojny, 2009). The core of the analysis is a dedicated hybrid numerical-analytical thermo-mechanical FEM system with variable density developed by the authors. The solver of the system allows simulation of both tension and compression of samples being in semi-solid state. Inverse solution model was developed in order to enable the study of mechanical properties of selected steels. Apart from modules enabling the computation of temperature, strain, stress and density fields, the system was equipped with supporting modules: an input/output data interface, a advanced module dedicated to visualization of numerical results, an approximation module and an inverse analysis subsystem. The proposed methodology of flow stress investigation can be divided into several steps. The general scheme of computer aided testing procedure is presented in figure 2.

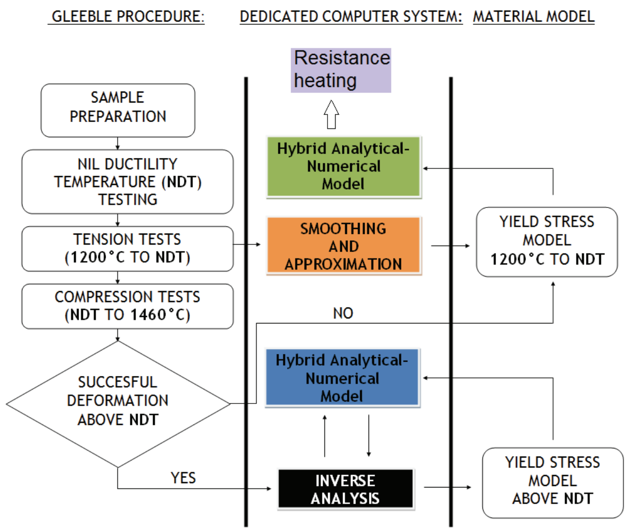

Fig. 2. The scheme of computer aided methodology of development of strain – stress curves with the help of the dedicated FEM system.

As was mentioned, 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. This is why temperature distribution inside the tested samples should be analyzed. The basic reason for non-uniform temperature distribution inside samples on the Gleeble® simulator is their contact with cooper handles during resistance heating (figure 3 and figure 4).

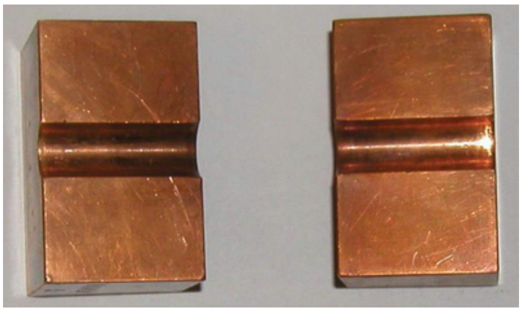

Fig. 3. The handle with long contact zone with sample (so-called "cold handle").

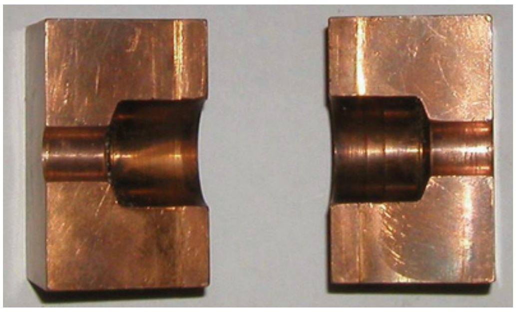

Fig. 4. The handle with short contact zone with sample (so-called "warm handle").

2. NUMERICAL MODEL OF THE RESISTANCE HEATING

The samples in the Gleeble® system are heated by direct resistance Joule heating when an alternating current is passed into the samples through the system anvils. The level of current is regulated automatically in response to the difference between the prescribed temperature and the real temperature measured by a thermocouple welded to the surface of the samples at the middle of their heights. The temperature field is a solution of Fourier-Kirchhoff's equation with convection. The most general form of this equation can be written as:

$$\nabla^T (k\nabla)T + \left[Q - c\rho\left(\frac{\partial T}{\partial \tau} + v \circ \nabla T \right) \right] = 0 \quad (1)$$

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 (2) has to satisfy the boundary conditions. The combined Hankel's boundary conditions have been adopted for the presented model.

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

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 and n is the normal to the boundary surface.

The testing procedure requires the sample to be melted down as a result of its resistance heating. The heat generated due to direct current flow was calculated using the Joul-Lenz law according to following equation:

$$Q=I^2R\tau \qquad (3)$$

where I is the current intensity, R is the electrical resistance and τ is the time variable. The resistance was calculated using following formula:

$$R=\rho_w\frac{l}{A} \qquad (4)$$

In equation (4) l, A and ρ_w are the sample: length, area of the cross-section and specific resistance, respectively. It has to be mentioned that the temperature changes have influence on the specific resistance. In the presented solutions the empirical equation was used to calculate the specific resistance at a desired temperature:

$$\rho_w=\rho_0\left[1+\overline{\alpha}(t-t_0)\right] \qquad (5)$$

In equation (5) ρ_0 is the specific resistance at the temperature t_0 = 20°C, t is the current temperature and $\overline{\alpha}$ is a coefficient.

3. EXAMPLE RESULTS

The experiments were done in Institute for Ferrous Metallurgy in Gliwice, Poland. The shape of the testing samples and locations of thermocouples using during experimental part are shown in figure 5.

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
0.44	0.72	0.25	0.021	0.012	0.1	0.08	0.21	0.017	0.015	0.002	0.002	0.011

The C45 grade steel was investigated using Gleeble® simulator. The chemical composition of the investigated steel is presented in table 1.

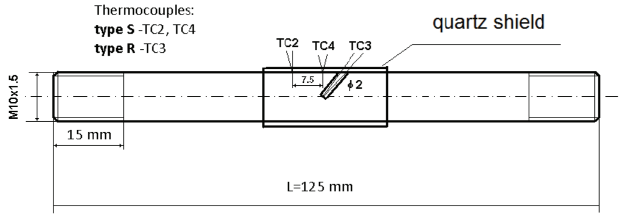

***Fig. 5.** Samples used for the experiments. TC2, TC3 and TC4 – thermocouples.*

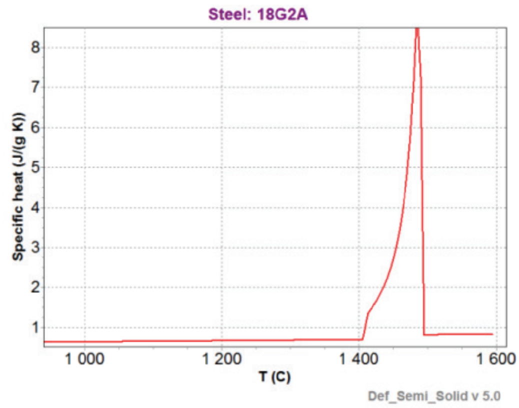

***Fig. 6.** Specific heat versus temperature for the investigated steel.*

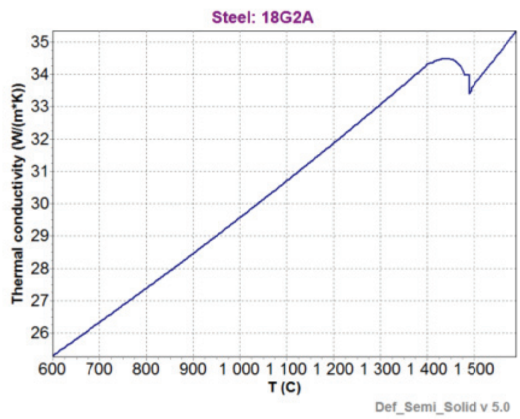

***Fig. 7.** Thermal conductivity versus temperature for the investigated steel.*

The liquidus and solidus temperature of the C45 grade steel are 1490°C and 1410°C, respectively. 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 (figure 6-8) . This software determines this properties on the basis of the chemical composition.

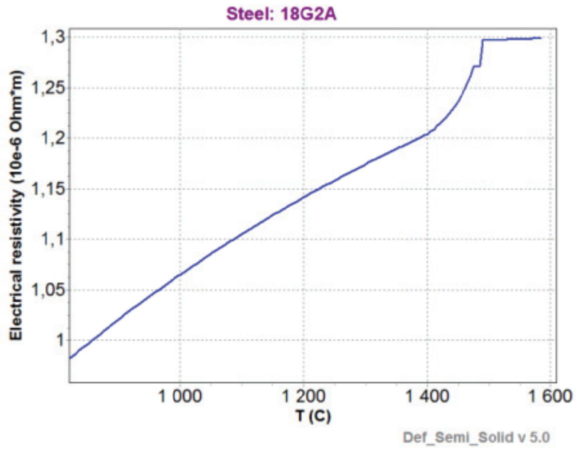

Fig. 8. *Electrical resistivity versus temperature for the investigated steel.*

In case of each physical and computer simulation samples were heated to 1430°C and after holding at constant temperature the sample was cooled to nominal deformation temperature. In the final stage of physical simulation for different holding time, the temperature difference between core (indication of TC3 thermocouple) of the sample and the surface (indication of TC4 thermocouple) was analyzed. In all cases the temperature difference between core of the sample and surface was about 25°C for variant with cold handles (figure 9) and about 40°C for variant with hot handles (figure 10). The numerical simulation confirmed results obtained during experimental parts. In the figure 11-13 temperature distributions in the longitudinal section of the sample tested at temperature 1385°C are presented for 3 and 5 seconds of heating and final distribution 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 5°C. The similar situation was observed in case of using cold handles - 7°C. The comparison between experimental results and numerical show that developed module of resistance heating right reflect back the physical simulation of resistance heating of samples using Gleeble® 3800 physical simulator.

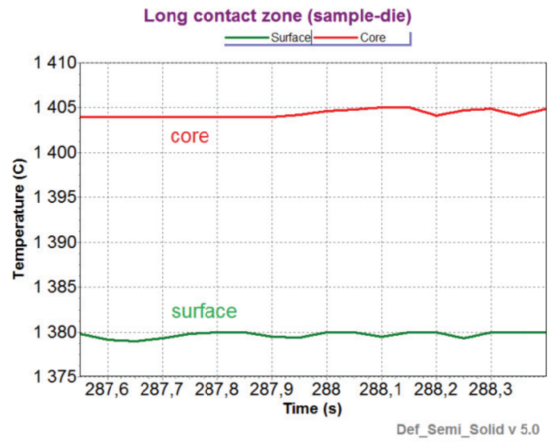

Fig. 9. *The temperature change versus time for cold handle (final stage of physical simulation right before deformation).*

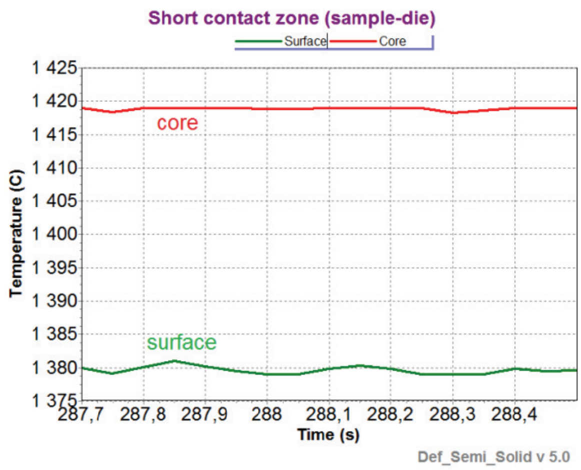

Fig. 10. *The temperature change versus time for hot handle (final stage of physical simulation right before deformation).*

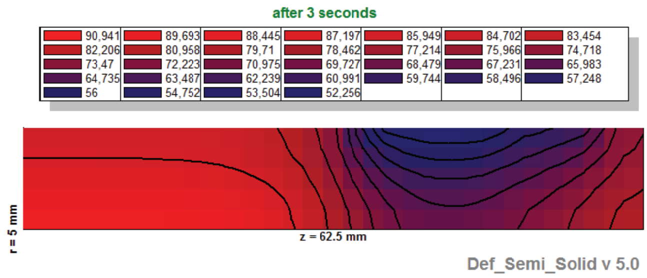

Fig. 11. *Distribution of temperature in the longitudinal section of the sample tested at temperature 1385°C after time heating: 3 seconds, Tools: "hot handle".*

Finally, the microstructure of the tested samples was investigated. The example microstructure in the longitudinal sections of two samples right before deformation deformed at 1385°C (together with magnification of the middle of the samples) are shown in figures 14-17. A lot of voids confirm that for analyzed temperature some liquid phase particle exist in the central part of the sample.

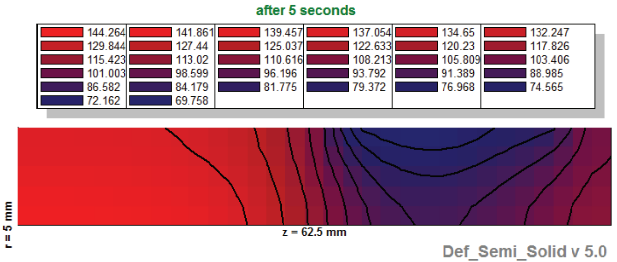

Fig. 12. *Distribution of temperature in the longitudinal section of the sample tested at temperature 1385°C after time heating: 5 seconds, Tools: "hot handle".*

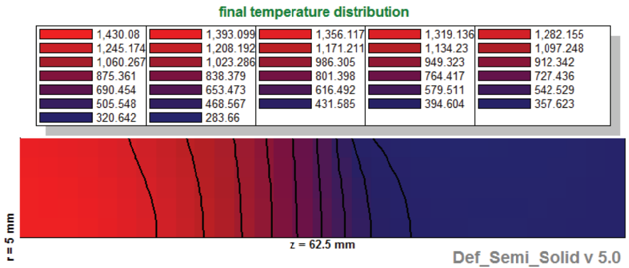

Fig. 13. *Distribution of temperature in the longitudinal section of the sample tested at temperature 1385°C after time heating: right before deformation. Tools: "hot handle".*

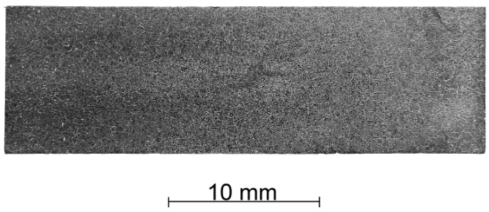

Fig. 14. *Sample pickled in Oberhoffer reagent – right before deformation at 1385°C. Tools: "hot handle".*

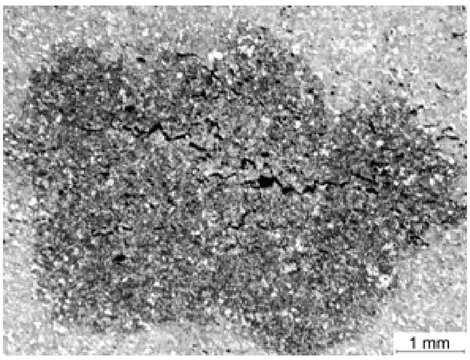

Fig. 15. *Middle of the sample right before deformation at 1385°C. Variant with hot handle. Magnification: 10x.*

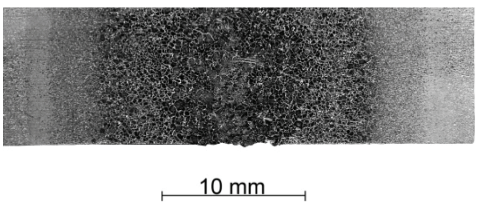

Fig. 16. *Sample pickled in Oberhoffer reagent – right before deformation at 1385°C. Tools: "hot handle".*

Fig. 17. *Middle of the sample right before deformation at 1385°C. Variant with cold handle. Magnification: 10x.*

4. CONCLUSIONS

The main objective of this work was experimental verification of resistance heating module. In all cases (experiments) the temperature difference between core of the sample and surface was about 25°C for variant with "cold handles" and 40°C for variant with "hot handles". The numerical results shows that mean deviation between core temperature measured and calculated is about 5°C for "hot handles" and about 7°C for "cold handles".

On the other hand, modelling and simulations of resistance heating of steel samples in the Gleeble® requires resolving a number of problems for the discussed temperature range e.g. the difficulties in measurement of material constants and necessity of determination of characteristic temperatures. Concluding, the presented module allows the virtual simulation of the resistance heating in the Gleeble® equipment for different temperature program and it can be used to support future physical simulations performed by Gleeble® simulator.

ACKNOWLEDGMENTS

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ZMIANY TEMPERATURY PODCZAS ETAPU NAGRZEWANIA REALIZOWANEGO W RAMACH PROCEDURY TESTOWEJ WYZNACZANIA NAPRĘŻENIA UPLASTYCZNIAJĄCEGO W UKŁADZIE SYMULATORA GLEEBLE®

Streszczenie

Głównym celem prezentowanej pracy jest eksperymentalna weryfikacja solvera symulującego nagrzewanie oporowe. Moduł symulujący nagrzewanie oporowe jest integralną częścią opracowanej przez autorów komputerowo wspomaganej procedury wyznaczania krzywych odkształcenie-naprężenie dla stali odkształcanych w bardzo wysokich temperaturach. Procedura wyznaczania krzywych odkształcenie-naprężenie łączy duże możliwości badawcze symulatora termo-mechanicznego Gleeble® z opracowanym przez autorów dedykowanym systemem MES (Def_Semi_Solid v.5.0). W związku z tym, rozkład temperatury w objętości próbki powinien być wyznaczony z bardzo dużą dokładnością. Z powodu dużej czułości wartości naprężenia uplastyczniającego na zmianę temperatury, procedura testowa wymaga w miarę jednorodnego pola temperatury. Głównym powodem powodującym niejednorodność pola temperatury w objętości próbki, jest jej kontakt z uchwytami miedzianymi symulatora podczas symulacji nagrzewania. W artykule przedstawiono wpływ użytych uchwytów miedzianych na rozkład temperatury w objętości próbki. Końcowym etapem było porównanie wyników otrzymanych na drodze eksperymentu i symulacji komputerowej co pozwoliło na oszacowanie jakości opracowanego modułu nagrzewania oporowego.

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