TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
MECHANICS | MECHANIKA

1-M/2013

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COMPUTER AIDED OF EXPERIMENTS DETERMINING THE CHARACTERISTICS OF CUTTING STEEL DEFORMED AT HIGH TEMPERATURES

KOMPUTEROWE WSPOMAGANIE EKPERYMENTÓW OKREŚLAJĄCYCH WŁAŚCIWOŚCI STALI AUTOMATOWEJ ODKSZTAŁCANEJ W WYSOKICH TEMPERATURACH

Abstract

The main goal of the paper is modelling of phenomena accompanying the steel subjected to deformation in very high temperature. Analysis of the phenomena in solid surface part and semi-solid core is necessary due to inhomogeneity of material properties in both the zones of the sample. Experimental basis of the work were TESTS done in IMZ Gliwice using Gleeble 3800 physical simulator. The interpretation of the tests was done using Def_Semi_Solid software. This program allows the numerical analysis of steel behaviour during deformation of axial-symmetrical samples at very high temperatures. The paper presents the comparison of experimental and numerical results.

Keywords: *Strain-stress curve*, *Semi-solid state of steel*, *Very-high temperature deformation*, *FEM solutions*

Streszczenie

Tematem artykułu jest modelowanie zjawisk zachodzących w stali w trakcie odkształcania w ekstra wysokich temperaturach. Ze względu na niejednorodność właściwości związanych z występowaniem w części centralnej odkształcanej próbki strefy półciekłej (*mushyzone*), zachodzi konieczność analizy zjawisk występujących zarówno w warstwie naskórka (cześć zestalona), jak również w półciekłym rdzeniu. Część eksperymentalna pracy została wykonana z wykorzystaniem symulatora Gleeble® 3800. Do przeprowadzenia części symulacyjnej wykorzystany został program Def_Semi_Solid, który umożliwia analizę zjawisk zachodzących w stali w trakcie odkształcania próbek osiowosymetrycznych w bardzo wysokich temperaturach. W artykule przedstawiono także porównanie wyników eksperymentalnych i numerycznych.

Słowa kluczowe: *krzywe umocnienia*, *ekstra wysokie temperatury*, *stan półciekły*, *MES*

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1. Introduction

In the recent years, more and more new products and technologies are designed with particular emphasis on energy preservation and environmental protection. The integrated casting and rolling technologies are modern and efficient ways of hot strip production. Currently, new technologies of steel strip manufacturing are being developed. They are called ISP (Inline Strip Production) and AST (Arvedi Steel Technologies) processes and are characterized by very high temperature at the mill entry. 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 compared with traditional processes but this also entails certain problems specific to such metal treatment.

There are a few characteristic steel temperature values between the solidus and liquidus state. 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 level 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) is 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.

But the main problem concerning the simulation of semi-solid steel deformation processes is lack of appropriate strain-stress relationships. The knowledge of them is extremely important and has crucial influence on the metal flow paths. Special methods have to be applied for testing behaviour of steel being in semi-solid state.

There are also experimental problems. Keeping temperature constant during the whole experiment procedure is difficult. There are also some additional difficulties with interpretation of measurement results due to huge barrelling of central part of the sample, which is caused by strong temperature dependence of plastic resistance of mushy zone, which consist of skeleton of solid phase surrounding remaining particles of liquid phase. The solid phase may be subjected to the plastic deformation while liquid phase can flow through the porous solid phase.

The current paper presents a certain modification of previously presented methodology [1], which allows the process simulation and calculation of the stress-strain relationship for a wide ranges of temperature and strain rate. The computed yield stress functions depends now on temperature, strain and strain rate. The fact that the calculated yield stress relationship takes into consideration all the mentioned parameters makes the analysis results much more consistent with experimental data as compared to the original method.

2. The methodology

The temperature range was divided into two sub-ranges: lower – below NDT – and higher – above this temperature. 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 in aim to eliminate clearances in the testing equipment.

The newly developed methodology [2] allows the computation of curves depending on both temperature and strain rate. In this methodology, the temperature range was divided into exactly the same intervals as for the first variant. This approach allows to compute realistic yield stress curves depending on strain, strain rate and temperature from two different ranges. The first series of experiments was conducted between 1200°C and NDT and the second one above the NDT level. More details concerning the theoretical solution one can find in [3].

3. Computer aided experimental procedure

The computer aided experimental procedure was done at AGH-University of Science and Technology in Krakow Poland and (its experimental part) in the IMZ – Institute for Ferrous Metallurgy in Gliwice Poland. The testing material was the 11SMn30 grade steel and the testing machine the Gleeble3800 simulator. The mentioned steel grade has very poor weldability. Due to the high sulphur and phosphorus content free-cutting steel not destined to heat treatment are not generally recommended for welding. This steel grade is marked by a good machinability on machine tools and by an easy fragmentation of chips.

The following 3-stage schedule was applied for the experiments:

- stage 1: preparation of the sample (e.g. mounting thermocouples, die selection),
- stage 2: melting procedure,
- stage 3: deformation of the sample.

For the experiments were used samples shown in Fig. 1 and Fig. 2.

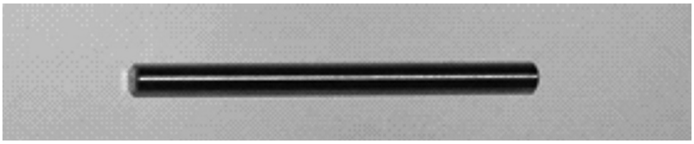

Fig. 1. Sample (6 × 82 mm) used to determine the NST temperature on the Gleeble 3800 simulator
Rys. 1. Widok próbki (6 × 82 mm) używanej do określania temperatury NDT
w symulatorze Gleeble 3800

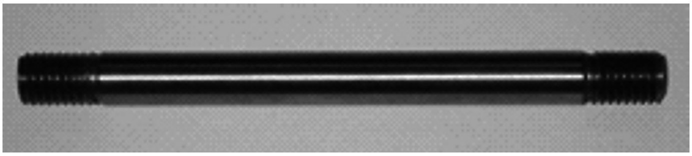

Fig. 2. Sample (10 × 125 mm) used to determine high-temperature characteristics of materials on the Gleeble 3800 simulator
Rys. 2. Widok próbki używanej do określania charakterystyk wysokotemperaturowych
w symulatorze Gleeblee 3800

Die displacement, force and temperature changes in the heating zone were the main parameters recorded during experiments. Simultaneously the Def_Semi_Solid program was calculated the optimal values of coefficients having influence on material properties. The software has two main tasks. It is able to calculate the shape and size of the deformation zone together with material mechanical properties. In aim to plan right experiments one can know the right values of liquidus and solidus temperatures. For the 11SMn30 grade steel they are 1518ºC and 1439ºC, respectively.

The temperature has strong effect on remaining parameters. The non-uniform temperature distribution is the source of significant variation of microstructure and material rheological properties. The changes of these parameters can be observed mostly along the sample. They source is the temperature gradient caused by resistance heating and contact of the sample with cold cooper handles [4].

In all series of experiments samples were first heated to 1430ºC and after maintaining at constant temperature they were cooled down to the required deformation temperature. Three thermocouples were installed in each sample (Fig. 3) in order to record the temperature gradients in its central parts. The TC4 thermocouple was the control sensor of the sample heating process. The second thermo-element, marked TC2 (S-type) was placed at a distance of 7.5 mm from the TC4. The third thermocouple, i.e. TC3 (1 mm thickness – R-type) was mounted near the sample axis in a hole drilled at an angle of about 45º.

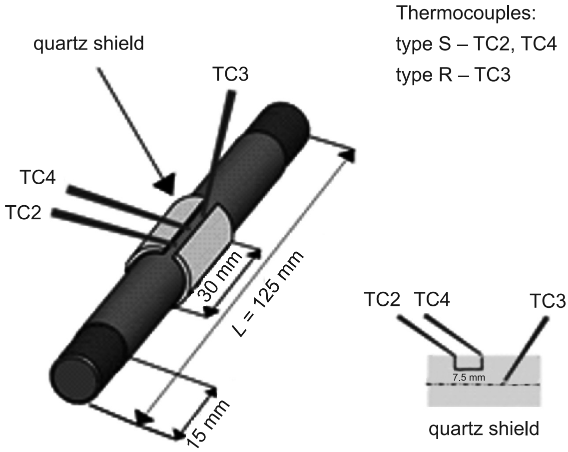

Fig. 3. Samples used for the experiments. TC2, TC3 and TC4 thermocouples

Rys. 3. Schemat próbki wraz z układem termopar

Besides the problems with maintenance of very high, constans temperature during the whole experiment there are also difficulties in the interpretation of recorded results. Due to significant inhomogeneity in deformation and stress distribution in the deformation zone the traditional methods of stress-strain curves calculation fail. Thus the application and Def_Semi_Solid software based on a sophisticated method described in details in [1] was necessary.

Figure 4 shows strain-stress curves at several strain rate levels for temperature 1400ºC and very strong strain rate dependence of the yield stress. The strain-stress curves were described by following equation:

$$\sigma_p = A\varepsilon^n \dot{\varepsilon}^m \exp(-BT) \tag{1}$$

where:

A, B, n, m – are material constant,
T – temperature,
ε – strain,
$\dot{\varepsilon}$ – strain rate.

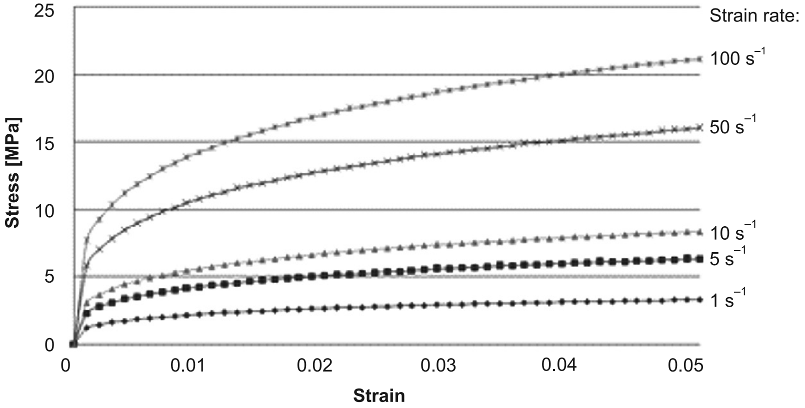

Fig. 4. Stress-strain curves at several strain rate levels for temperature 1400°C

Rys. 4. Krzywe naprężenie-odkształcenie dla różnych prędkości odkształcenia dla temp. 1400°C

Strong temperature and strain rate dependence of the yield stress require suitable experimental technique – first of all application of proper temperature program. The samples were heated to temperature of 1390°C with heat up rate of 20°C/s. Then the rate drops to 1C/s and the heating proceeds to temperature of 1460°C. Each sample is hold up in this temperature for 30 seconds and next cooled to temperature of 1430°C with rate of 10°C/s. Deformation usually starts after the sample lasts 10s in this temperature.

To eliminate disorders observed during the experiments a combination of FEM solution and inverse method was adopted. Figures 5 and 6 present a comparison of experimental and calculated forces accompanying the deformation process run at 1400°C for two different strain rate levels. The difference between both of them was the objective function of the inverse analysis.

The temperature difference between core of the sample and its surface can be as low as possible. But in fact the difference of around 30ºC exists in the final stage of the testing procedure. For the presented series of experiments the core temperature was higher than surface temperature by around 32ºC for so called cold handle (handle with long contact zone between sample and tool) and temperature of 1350ºC. The difference has grown to 35°C

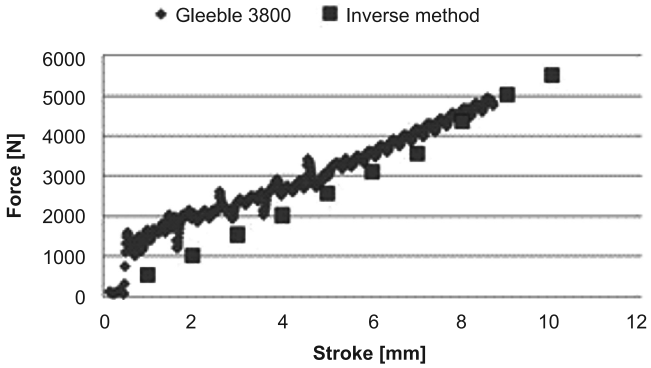

Fig. 5. Comparison between measured and calculated loads at temperature 1400°C for tool velocity 100 mm/s

Rys. 5. Porównanie zmierzonych i obliczonych dla temperatury 1400°C i prędkości narzędzia 100 mm/s

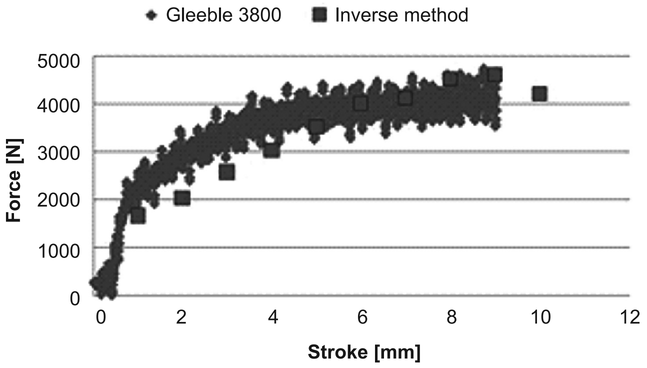

Fig. 6. Comparison between measured and computed loads at temperature 1400°C for tool velocity 20 mm/s

Rys. 6. Porównanie zmierzonych i obliczonych dla temperatury 1400°C i prędkości narzędzia 20 mm/s

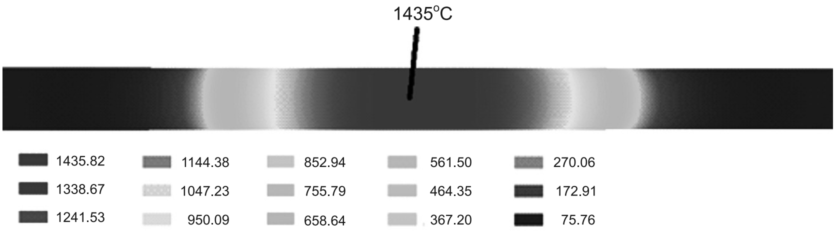

Fig. 7. Temperature distribution for simulation of heating to 1400°C – whole sample

Rys. 7. Rozkład temperatury dla symulacji nagrzewania do temperatury 1400°C – widok całej próbki for tests conducted at 1400°C while the temperature gradient along samples is much more significant. Figures 7 and 8 show the initial temperature distribution in samples heated to the mentioned temperature levels. One can see the huge temperature difference between the sample central regions and their cold ends.

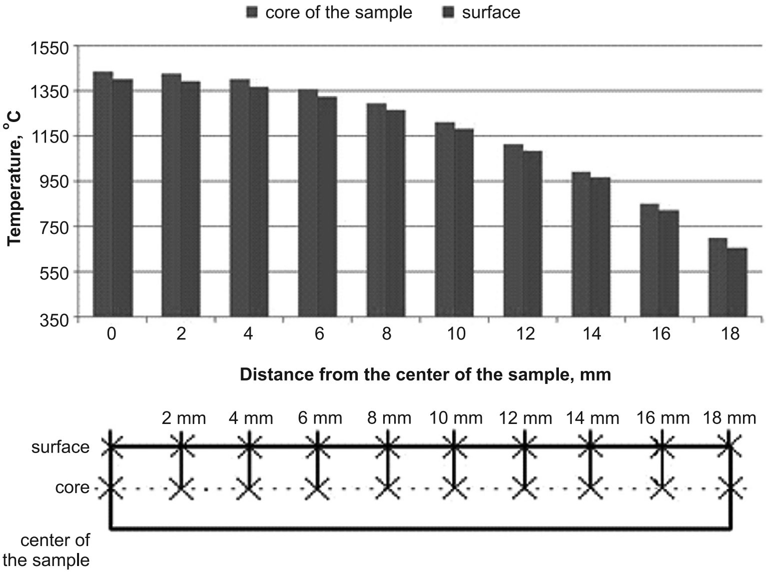

Fig. 8. The temperature difference between core of the sample and its surface for tests conducted at 1400°C – half of the sample

Rys. 8. Różnica temperatur pomiędzy rdzeniem próbki a jej powierzchnią dla prób przeprowadzonych w temperaturze 1400°C – widok połowy próbki

The numerical analysis of deformation level shows quite different results. High speed(tool speed of 100mm/s) and average speed (20mm/s) experiments are presented in Figures 9 and 10. The figures present the distribution of the effective strain for both the considered strain ranges showing similar distribution in terms of strain level and shapes of isoclines.

Metallographic investigation of samples were made as well. After deformation the samples were cooled with water. The cooling rate of the samples was variable and it changed with the temperature drop from initial level of about 20°C/s to final 5°C/s after the solid phase transformation. Macro photographical analysis leads to the conclusion that the temperature and strain rate have impact on macrostructure and the shape of deformation zone. At higher rate of deformation (tool speed 20 mm/s and 100 mm/s) one can draw a conclusion that that higher deformation temperature results in higher level of stratification of the compressed area. The deformation process itself is short, the material did not regain plasticity and the liquid phase is pushed to the outside, where it solidifies faster.

Studies of the microstructure showed that due to high deformation temperature, and relatively high cooling rate the deformation zone is dominated by acicular ferrite. The others components of the microstructure are bainite (grey phase mainly near the borders of grains)

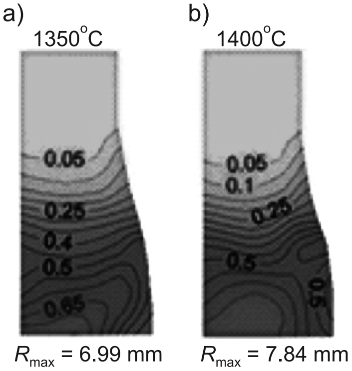

Fig. 9. The strain rate for average speed experiment (20 mm/s) – quarter of the sample (R_0 = 5 mm)
Rys. 9. Prędkość odkształcenia dla średniej prędkości (20 mms) – 1/4 próbki (R_0 = 5 mm)

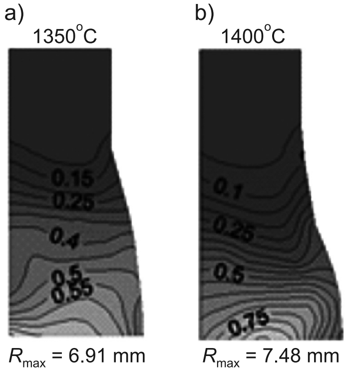

Fig. 10. The deformation intensity for high speed experiment (100 mm/s) – quarter of the sample (R_0 = 5 mm)
Rys. 10. Intensywność odkształcenia dla „dużej dynamiki" (100 mm/s) – 1/4 próbki (R_0 = 5 mm)

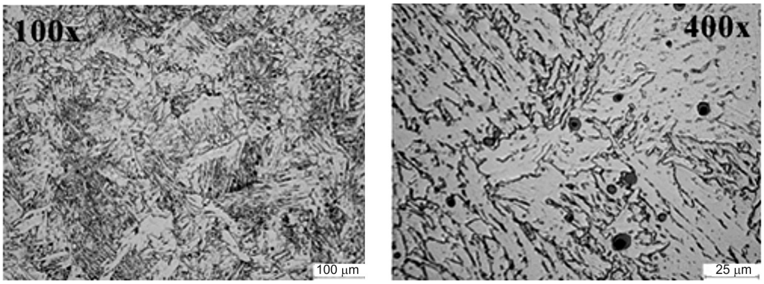

Fig. 11. Microstructure of sample deformed at 1350°C with tool velocity of 1 mm/s
Rys. 11. Mikrostruktura próbki odkształcanej w temperaturze 1350°C z prędkością narzędzia 1 mm/s

and likely martensite. Due to the large content of sulfur ($S = 0.27\%$), manganese sulphides in microstructure are demonstrated. Figures 11–13 show the microstructure of the investigated samples at different temperatures and strain rates.

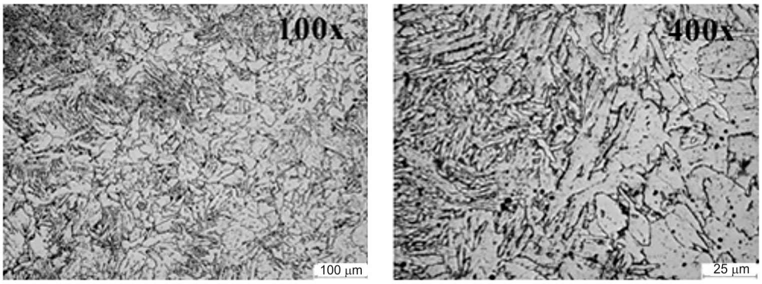

Fig. 12. Microstructure of sample deformed at 1400°C with tool velocity of 1 mm/s

Rys. 12. Mikrostruktura próbki odkształcanej w temperaturze 1400°C z prędkością narzędzia 1 mm/s

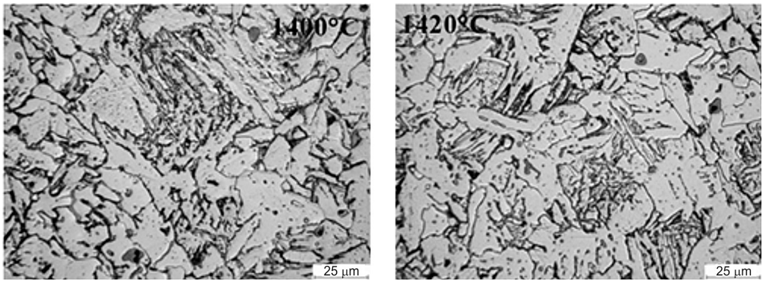

Fig. 13. Microstructure of samples deformed at 1400°C and 1420°C. Tool velocity 100 mm/s. Magnification: 400×

Rys. 13. Mikrostruktura próbek odkształcanych w temperaturze 1400°C i 1420°C. Prędkość narzędzia 1 mm/s. Powiększenie 400×

4. Conclusions

Computer aided testing of steel samples deformation at coexistence liquid and solid phase requires resolving a number of problems and the main is the interpretation of compression tests results leading to strain – stress curves. The difficulty in determination of other material thermal and mechanical properties, such as: heat transfer coefficient (and many other thermal properties) and diagrams of temperature dependent density changes are also important issues.

The presented research was focused on mechanical properties of investigated 11SMn30 steel grade. Compression tests carried out for semi-solid materials could only be interpreted using inverse analysis. The paper has thrown light on the investigation methodology and resulting temperature, shape and size of the deformation zone.

The paper has been supported by the Polish Ministry of Science and Higher Education Grant N N508 585539.

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