Analysis of the heating process and development of a microstructure suitable for thixoforming of steel

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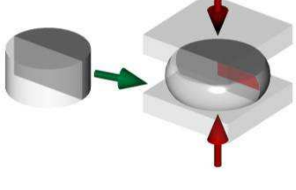
ABSTRACT: The thixoforming processes of metal alloys are carried out in the semi-solid state. The thixotropy phenomenon is conditional upon the globular microstructure that occurs in shaped material. In order to design and optimise such processes, some procedures of the Gleeble® system could be applied. The main objective of this work is an analysis of the resistance heating of samples in different material tests which are possible on the Gleeble® 3800 simulator. An example of development of steel alloy microstructure during heating on the Gleeble® simulator will also be presented. M2 tool steel was submitted for analysis. In this case, obtaining the globular microstructure was carried out on the basis of the SIMA method (Strain Induced Melt Activated).

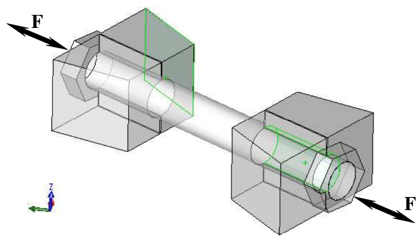
Key words: thixoforming, resistance heating, globular microstructure, numerical analysis

1 INTRODUCTION

Design and optimisation of thixoforming processes are effectively supported using physical simulations. One of the possible measuring apparatus that could be applied for analysis of such processes is the Gleeble® system having vacuum equipment [1]. 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 analysed. The basic reason for uneven temperature distribution inside samples on the Gleeble® simulator is their contact with tools during resistance heating. The compression material test was the first experiment to be considered. The second experiment was the tension test in the semi-solid state, which uses the "low force jaw system", special equipment for the measurement of low forces. Similar temperature distribution could be obtained in the L-Sico procedure, which is a kind of compression test (figure 1).



a)



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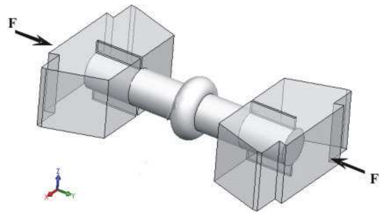

c)

Fig. 1. Material tests in the semi-solid state possible using the Gleeble® system; (a) the compression test, (b) the tension test, (c) the L-Sico test

In the second part of the paper, the SIMA method (Strain Induced Melt Activated) used to obtain the globular microstructure in steel alloy will be described [2]. This method allows the production of oval particles of the solid phase surrounded by the liquid phase.

2 RESISTANCE HEATING OF THE SAMPLES

2.1 Numerical model of the resistance heating

The samples in the Gleeble® system are heated by direct resistance Joule heating when an alternating current of 50 Hz 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. Temperature sampling is synchronized to intervals when the current is momentarily switched off. After heating, the specimens can be mechanically tested using a servo-hydraulic system. In our experiments, the steel alloy M2 was used (see table 1).

Simulations of heating were carried out using ADINA software [3]. One can describe the generation of the heat Q as follows

$$Q = \mathbf{J}^2 \sigma^{-1} \tag{1}$$

where $\mathbf{J}$ is the current density, which can be determined from the relation:

$$\mathbf{J} = -\sigma \nabla \varphi \tag{2}$$

Furthermore, σ is the electrical conductivity and φ is the electrical potential. One may evaluate φ using Laplace's equation [4]:

$$\nabla(\sigma \nabla \varphi) = 0 \tag{3}$$

Equation (3) is solved using the finite element method [3]. The variational form of Laplace's equation is:

$$\int_V \left(\sigma \nabla \varphi \cdot \nabla h^{\varphi}\right) \mathrm{d}V = -\oint h^{\varphi} \mathbf{J} \cdot \mathrm{d}\mathbf{S} \tag{4}$$

where h^{φ} is the virtual quantity. Laplace's equation is solved for the potential φ at each time step, and then the Joule heat Q is calculated and added to the right-hand side of the energy equation:

$$\rho c_P^{eff} \frac{\partial T}{\partial t} = \nabla (k \nabla T) + Q \tag{5}$$

Effective specific heat c_p^{eff} is defined as follows

$$\begin{aligned} c_P^{eff} &= c_P & T &\le T_{sol} \\ c_P^{eff} &= c_P - \frac{\mathrm{d}f_s}{\mathrm{d}T} L & T_{sol} &\le T \le T_{liq} \end{aligned} \tag{6}$$

where: c_P – specific heat, f_S – solid fraction, T_{sol}, T_{liq} – solidus and liquidus temperatures, L – latent heat, ρ - density and k – thermal conductivity.

2.2 Numerical simulations of resistance heating

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 alloys, such distribution gives significant differences in the microstructure and the rheology. The numerical simulations allow to determine the temperature distribution. The resistance heating of samples made from M2 tool steel was simulated. The thermo-physical properties of this alloy, necessary in calculations, were determined using JMatPro software (figure 2) [5]. This software determines this properties on the basis of the chemical composition. The chemical analysis was carried out using the FOUNDRY-MASTER compact emission spectrometer for process-control and the chemical analysis of metals supplied by Worldwide Analytical Systems AG. The chemical composition of analysed M2 alloys is shown in table 1.

Table1. Chemical composition of M2 tool steel

Fe	C	Si	Mn	S	Cr	Mo	Ni	Co
80.8	0.85	0.25	0.25	0.02	4.15	4.55	0.17	0.55

Cu	Nb	V	W
0.15	0.01	1.72	6.43

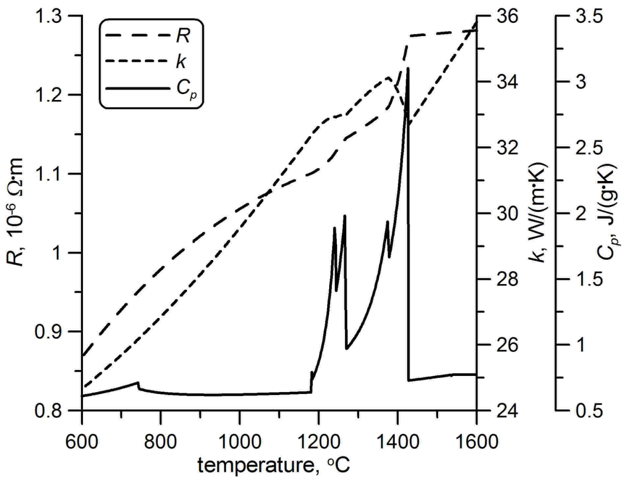

Fig. 2. The thermo-physical properties of M2 tool steel calculated using JMatPro software; electrical resistivity R, thermal conductivity k, specific heat C_p

The numerical simulations of the resistance heating for three kinds of samples were executed. In case of each simulation samples were heated to 1300°C. Different boundary conditions were applied in simulations. On the lateral surface of the samples the convection and radiation boundary conditions were applied. The most heat waste occur on the contact surfaces with system anvils. In this case the heat flux was applied. Assumed heating speed was 5°C/s. The distribution of temperature on the surface and inside sample for the compression test was shown on figure 3. Temperature non-uniformity average 30°C. The distributions of temperature for the L-Sico and the tension tests were shown on figures 4 and 5 respectively. In these cases the semi-solid state is achieved only in the middle of samples (approx. $T_{liquidus}$ = 1230°C and $T_{solidus}$ = 1450°C for M2 steel).

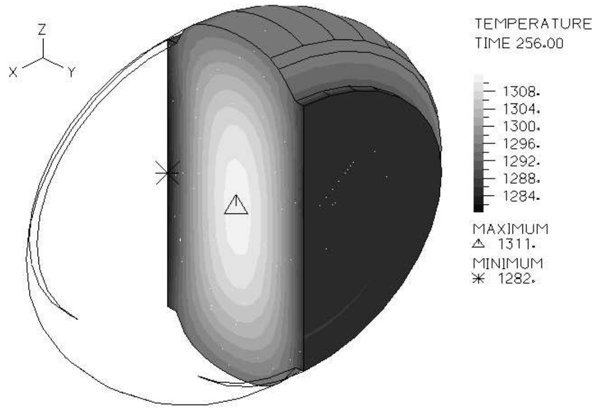

Fig. 3. Distribution of temperature on the surface and inside the sample for the compression test at 1300°C

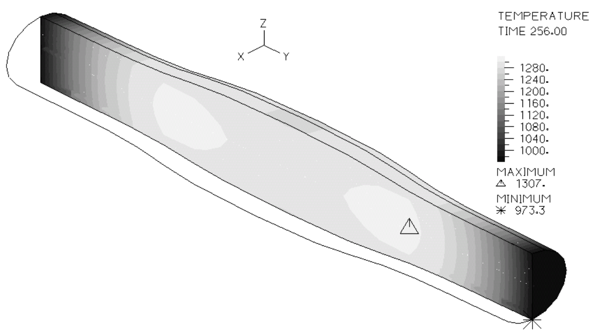

Fig. 4. Distribution of temperature on the surface and inside the sample for the L-Sico test at 1300°C

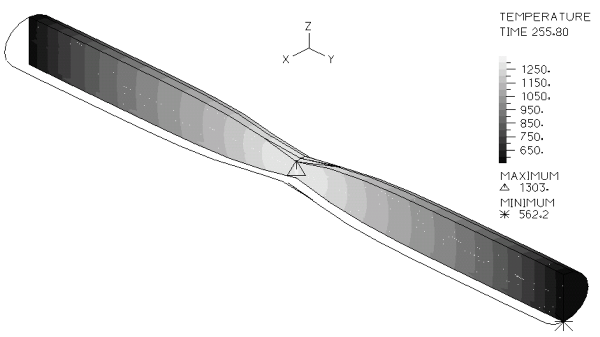

Fig. 5. Distribution of temperature on the surface and inside the sample for the tension test at 1300°C

3 MICROSTRUCTURE EVOLUTION IN HOT FORGED TOOL STEEL AFTER HEATING TO SEMI-SOLID STATE

SIMA (Strain-Induced Melt Activated) method is one of the most popular methods of obtaining globular microstructure [6]. This method can be relatively easy employed for plastic metal alloys. It was also tested for steels, giving good results [2]. SIMA method consists in partial melting of highly strained alloy. Globular microstructure is formed in the alloy during melting. Starting material for this method is cast alloy of dendritic structure. Such alloy subjects to hot working (in temperature higher than recrystallizing temperature). During deformation, energy is stored in the material. Finally, strained alloy is partially melted to semi-solid state. Recrystallization process takes place in the material during heating, and when solidus temperature is exceeded, liquid phase penetrates boundary of recrystallized grains, causing fragmentation of solid phase. One should pursue keeping size of equiaxial particles that create globular structure, below 30 mm. Experimental works have shown that this size largely depends on strain when in solid state, and on soaking time in semi-solid state. Changes in microstructure during soaking consist in spheroidization (irregular shapes of solid phase particles change to oval ones), and growth of solid phase particles. The advantage of this method is possibility of purchasing metal alloys that are plastic pre-strained, at very affordable prices. The material is most often strained by open die forging, rolling and extrusion forging. The problem encountered in such cases is non – homogenous strain, causing differences in obtained microstructure.

Within the confines of this work an analysis of microstructure evolution in hot forged tool steel after heating to semi-solid state was carried out. Supplied material was in the form of hot forged rod of 80 mm diameter. The heating experiments were carried out in Institute for Ferrous Metallurgy in Gliwice using Hydrawedge unit of the Gleeble® system. The geometry of the samples was such as the geometry used for the compression test (10 mm diameter, 12 mm height). The samples were heated in an argon gas environment to reduce oxidation. The heating speed was 5°C/s. The control thermocouple was welded to the surface in the middle of sample. The compression tests on the Gleeble® system are possible in semi-solid state up to 10% liquid fraction. Higher liquid fraction causes movement of the samples because of horizontal position of the system anvils. Moreover during heating small load is applied to samples by anvils. This load could cause deformation of the samples in higher temperatures.

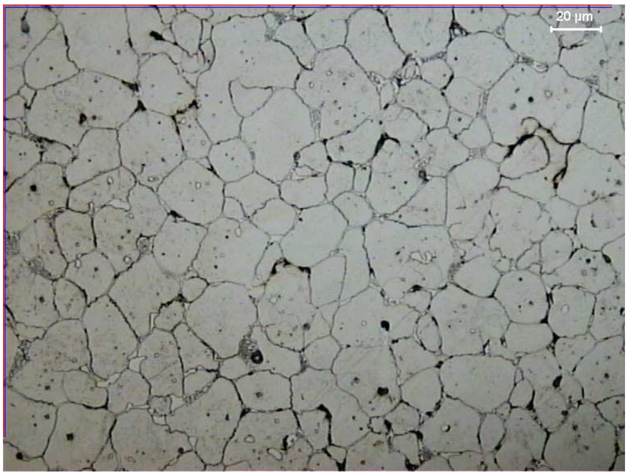

Fig. 6. Optical micrograph of M2 steel heated to 1250°C and next quenched (zero minute holding)

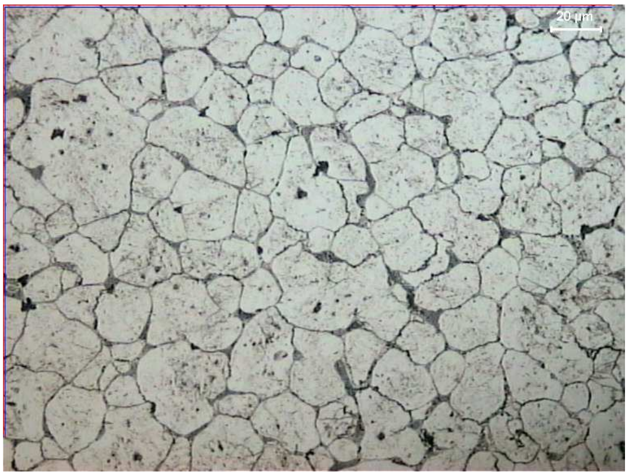

Fig. 7. Optical micrograph of M2 steel heated to 1300°C and next quenched (zero minute holding)

The samples were heated to 1250°C and 1300°C and after heating they were quenched in a water to freeze structures. Figures 6 and 7 shows the structures at mentioned above temperatures. The structures show solid grains surrounded by traces of the liquid matrix. The liquid fraction includes mostly carbides. One can observe that higher temperature gives more traces of the liquid fraction both inside solid grains and along their boundaries. The optical micrographs shown on figures 6 and 7 were made in Institute of Metallurgy and Materials Science PAS in Kraków. Samples were etched using alcoholic solution of nitric acid (5% HNO_3).

4 CONCLUSIONS

The numerical analysis of the resistance heating of the compression, the L-Sico and the tension tests shows that the Gleeble® system could be used for analysis of both the microstructure development and the rheology of the steel alloys in the semi-solid state. Due to non-uniform temperature distribution inside shaped material the quantitative analysis of the rheological properties will require application of the full thermo-mechanical model of the tests and the inverse method. An application of the wrought steel alloys is a simple way of obtaining of the globular microstructure for the thixoforming processes.

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