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ESTIMATION OF THE LOCALISATION AND GEOMETRIC PARAMETERS OF THE SEMI-SOLID ZONE OF STEEL SAMPLES

OSZACOWANIE LOKALIZACJI I PARAMETRÓW GEOMETRYCZNYCH STREFY PÓŁCIEKŁEJ PRÓBEK STALOWYCH

Abstract

This paper presents the use of computer graphics methods for the initial estimation of the shape, position and volume of the semi-solid zone in samples from the Gleeble 3800 physical simulator. Simulations were performed for the verification of the heating and deformation process of steel with a semi-solid zone. The numerical model consists of three separate subsystems for describing the deformation of the solid and semi-solid zones: mechanical, thermal and predictive densities. Taking into consideration the specific localisation of these zones, the initial estimation of the location of the melting zone is very helpful in understanding the process and may be the starting point for further research. This article describes the technique of selecting areas in samples that meet the thermal criteria. This allows us to approximate the location and shape of the semi-solid zone and this information can be used at a later stage to further refine its parameters.

Keywords: computer simulation, computational geometry, convex hull, visualisation of calculation results

Streszczenie

W artykule przedstawiono wykorzystanie metod grafiki komputerowej do wstępnego oszacowania kształtu, położenia i objętości strefy półciekłej w próbkach z symulatora fizycznego Gleeble 3800. W celu weryfikacji procesu nagrzewania i odkształcania stali w strefie półciekłej przeprowadzono wiele symulacji. Model numeryczny składa się z trzech odrębnych części: mechanicznej, termicznej i przewidującej zmiany gęstości opisujących odkształcenie dla strefy stałej i półciekłej. Biorąc pod uwagę specyficzną lokalizację tych stref, wstępna ocena położenia strefy przetopienia jest bardzo pomocna w zrozumieniu procesu i może być punktem wyjścia do dalszych badań. W artykule opisano technikę wybierania obszarów w próbkach, które spełniają wyznaczone kryteria, co pozwala na przybliżenie lokalizacji, kształtu i parametrów geometrycznych strefy półciekłej, co można wykorzystać w celu dalszego poprawiania jej parametrów oraz dokładności samego modelu.

Słowa kluczowe: symulacja komputerowa, geometria obliczeniowa, otoczka wypukła, wizualizacja wyników obliczeń

1. 1. Introduction

The possibility of steel deformation in its semi-solid state has recently been a topic of interest for many companies [1–3]. The integrated strip casting and rolling process is enhancement of a conventional rolling process. The new solution offers a significant reduction in cost, increased productivity and low investment costs. Temperature is a factor that largely determines the mechanical parameters of steel such as strain and stress; therefore, it is necessary to define these parameters when processing materials with a semi-solid zone. These parameters are difficult to determine especially at very high temperatures. This is why it is necessary to use advanced numerical methods. The mechanical properties of the mushy zone determine the deformation of the entire sample and therefore determine the parameters that are required. For this type of problem, the best solution is a spatial model because the calculated area has a very irregular and complex shape. A good description of the mixed zone can be used for better control of the integrated rolling process.

The position, shape and volume of the mushy zone is very important. As a result of the development of computer graphics and computation geometry, it is possible to use computer graphics methods for analysis and identification of the zones of a sample where the coexistence of both liquid and solid phases may occur. Computer graphics methods are widely used in industry and can be very helpful for the interpretation of calculation results.

One of the techniques involved in describing objects is stereology. Stereological measurements can be performed on two-dimensional images of three-dimensional structures [4, 5]. Measurements of the elements of the image allows determining the parameters that appoint the classification of objects to the appropriate class [6].

Since the computation was performed for axially symmetric samples; for their visualisation, it was necessary to build 3D solids of revolution both for the whole sample and for a chosen area of potential occurrence of a semi-solid zone.

The article describes the process of building solids and an initial estimation of the position and parameters of the semi-solid zone.

2. The simulation system

Numerical simulations were performed with the DEFFEM package, which is developed in accordance with the ONEDES (ONEDECisionSoftware) design philosophy [7]. This is based on the assumption that a set of independent modules comprising the DEFFEM package is implemented numerically in the one system. It enable to performed a virtual test of resistance heating combined with deforming in a wide range of temperatures in particular at extra-high temperatures near the solidus line, as well as in conditions of the solid and liquid phase coexistence, without the need for any commercial applications.

The developed simulation package also provides tools targeting the full identification of the selected parameters of numerical models on the basis of data coming directly from physical simulations (DEFFEM inverse module). In parallel with the design of such an advanced simulation tool, the development of visualisation tools and the analysis of findings are being implemented. Advanced numerical algorithms have been developed for plotting the isolines of scalar fields, visualising vector fields and enabling stereoscopic data to be visualised (module DEFFEM |pre&post).

3. Prediction of the mechanical properties of steel in semi-solid state

The computer-aided procedure leading to the determination of stress-deformation dependency was developed at AGH University of Science and Technology. The physical experiment was performed at the Institute of Iron Metallurgy in Gliwice using the GLEEBLE 3800 thermomechanical simulator (Fig. 1). The material used in the study was steel of C45 and S355 types [8, 9].

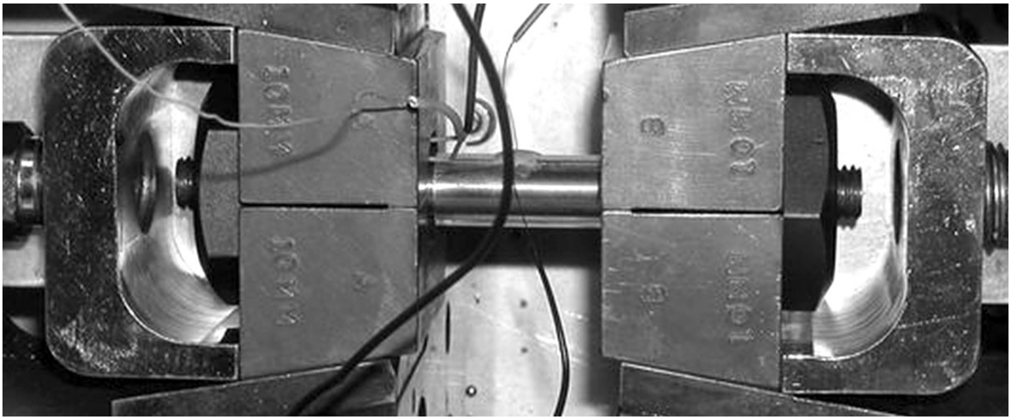

Fig. 1. Equipment before the experiment

The numerical part of the program was written in C++ and Fortran. The main objective of the program is numerical support for the measurement of the mechanical properties of steel at very high temperatures. Such an approach facilitates avoiding problems which appear while using traditional measurement methods and which are caused by strong inhomogeneity of deformations occurring in samples subjected to deformation at temperatures over 1400°C.

The solution in the form of a temperature field for the numerical model was found by solving the Fourier equation, which in the general form can be written as follows (1):

$$\nabla^T(\lambda \nabla T) + (Q - c_p \rho \frac{\partial T}{\partial \tau}) = 0 \tag{1}$$

where: T– absolute temperature, λ– thermal conductivity coefficient, Q – heat generation rate for volume unit, c_p– specific heat, ρ – density, τ– time

The thermo-mechanical solution was directly adapted to the boundary conditions pertaining to the Gleeble 3800 thermo-mechanical simulator system [10]. It allows the easy and fast verification of the obtained simulation results on the basis of experimental data. The resistance heating method is applied for heating samples in the simulator system [10] and used as the input data for the simulation with a semi-solid zone.

Due to limitations concerning the computer resources which are available to technologists of metal forming processes, a very accurate computation can sometimes be impossible or the computation time can be a barrier for the practical application of complex sequential models. This is why computer programs require very long processing times and parallel computing can be used to resolve this problem [11].

Due to the very significant influence of temperature on the mechanical properties in the range of very high temperatures, it is necessary to initially estimate the range of activity of the semi-solid zone during the deformation process. For the studied axially symmetrical case, it is possible to estimate the position of the semi-solid zone and determine the parameters which describe its shape and size.

To mark the border nodes which determine the semi-solid zone, algorithms of computational geometry were used in which the temperature characteristic for the studied material was the criterion.

4. Convex hull alghoritm

There are various models allowing the determination of the coexistence of a liquid and solid zone. One of these was presented by the authors of the publication [9]. However, in this article, a different approach was used which uses one of the algorithms of computational geometry, a gift wrapping algorithm or Jarvis [12] march to be precise, which solves the problem of convex hull, which has complexity $0(kn)$, where k is the number of points on the convex hull in a given set n of points. The gift wrapping algorithm is based on observation: a line segment $\overline{pq}$ bounded by two end points from the set S is the band of the convex hull if and only if all the points from S belong to the same closed half-plane defined by the straight line, and each point on the line belongs to the segment. If the segment $\overline{pq}$ is a side of the convex hull, which is not degenerated to the segment or a point, it must have a side different from $\overline{pq}$, starting in q (an analogical condition is met for point p). Figure 2 presents a schema of determining the convex hull for Jarvis march.

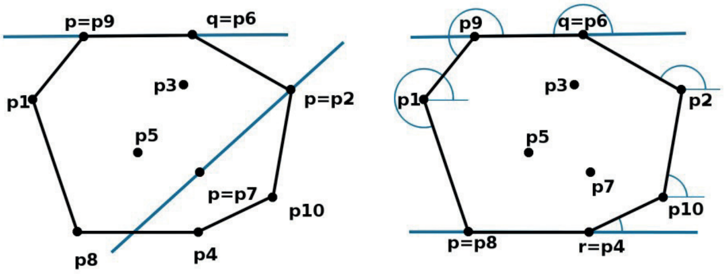

Fig. 2. Schema for determining the convex hull

This method allows separating the nodes of the mesh which met the assumed criterion of exceeding the solidus temperature for the studied material. Based on this, further analysis was performed using the chosen shape descriptors.

5. Shape descriptors

In order to describe representative sizes of the zone shape, a few shape descriptors were used [13]. The aim of the scalar measurement of the elements of the image is to reduce the element shape to a single size or a group of representative sizes for a particular element. Because the result of the simulation is a quantified and approximated representation of the real result, the determined representative sizes are a certain approximation of the real value. If the method of measurement itself is correctly chosen, the representative sizes present compact information on the shape itself.

Extensibility is the measurement of the aspect ratio, determined on the basis of equation (2).

$$k_{ar} = \frac{d_{\min}}{d_{\max}} \tag{2}$$

where:

$d_{\min}$ – the length of the smallest segment connecting two side points of the figure which crosses the centre of gravity of the element,

$d_{\max}$ –maximum length of the segment.

Circularity – is a form factor measuring the similarity of the element shape to a circle. This is determined as the ratio of the surface area of the element to the surface area of a circle the circumference of which is equal to the perimeter of the analysed element. This dependency was described with formula (3). The shape parameter takes a value close to 1 for circular-shaped elements.

$$k_{circularity} = \frac{A_i}{A_c} = \frac{A_i \cdot 4\pi}{p_i^2} \tag{3}$$

where:

A_i – surface are of the analysed element

p_i – perimeter of the element

Rectangularity is the measurement of the similarity of the object to a rectangle. This is determined as the ratio of the element's surface area to the surface area of the minimum bounding rectangle of the given element (4).

$$k_{rectangularity} = \frac{A_i}{A_p} \tag{4}$$

where:

A_p – surface area

Compactness of the object is a numerical measure of the degree of the elements' compactness described by the dependency (5T). The highest compactness takes the form of a circle for which this parameter takes the value of 1.

$$k_F = \frac{\sqrt[2]{\frac{A_i}{\pi}}}{d_{\max}} \tag{5}$$

where:

$d_{\max}$ – the length of the maximum chord of the analysed element

6. Building a solid of revolution

Since the calculations were performed for the axially symmetrical model in order to build a 3D model of samples, it was necessary to build a solid of revolution based on a 2D model with a fixed level of precision. A useful solution is determining points of the solid using the polar coordinate system. To determine the points in space which constitute the solid of the sample, it was necessary to move from the polar coordinate system to the Cartesian system. For a given radius vector where r and amplitude $\phi \in [0,2\pi)$ of point P, its Cartesian coordinates may be determined from the dependency (6), which is presented in Figure 3. The visualisation was performed using the OpenGL graphic library [14]. Creating visualisation is possible and is often performed using web technology [15] or stereoscopic techniques [16].

$$\begin{aligned} x &= r\cos(\varphi) \\ y &= r\sin(\varphi) \end{aligned} \tag{6}$$

where the Jacobian (factor) of the transformation is (7):

$$\frac{D(x,y)}{D(r,\varphi)} = \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \varphi} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi & -r\sin(\varphi) \\ \sin\varphi & r\cos(\varphi) \end{bmatrix} = r\left(\cos^2\varphi + \sin^2\varphi\right) = r \tag{7}$$

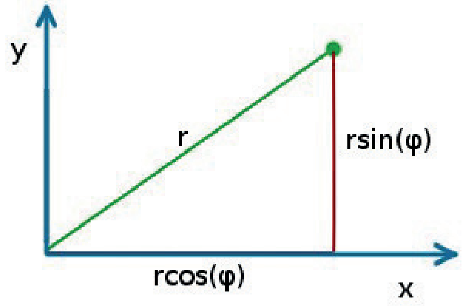

Fig. 3. Relation of Cartesian and polar coordinates

In order to build a 3D model, revolution of the 2D mesh of finite elements about the x coordinate is required. As a result, peripheral points were generated in order to create a solid of revolution with a set precision. The proposed solution allowed performing a visualisation of the samples and presenting the semi-solid zone in the form of a 3D solid for further analyses. One of these additional analyses is the determination of the volume measure of the zone in relation to the volume of the studied samples.

7. Results of analyses for exemplary samples

Four cases of samples were subjected to analysis, one before and one after deformation, and one in hot holders and one in cold holders in the Gleeble 3800 simulator. For all the samples, visualisation was performed and the chosen shape descriptors were calculated to determine the parameters of the semi-solid zone. Figure 4 shows a sample of C45 steel with the estimated position and shape of the semi-solid zone.

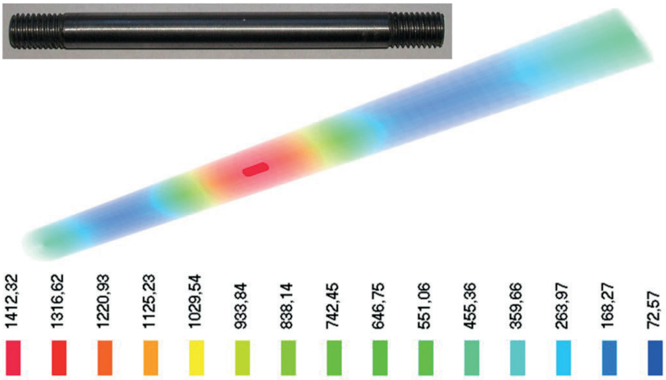

Fig. 4. Visualisation of the sample before deformation with a semi-solid zone for C45 steel with a real photo of the sample

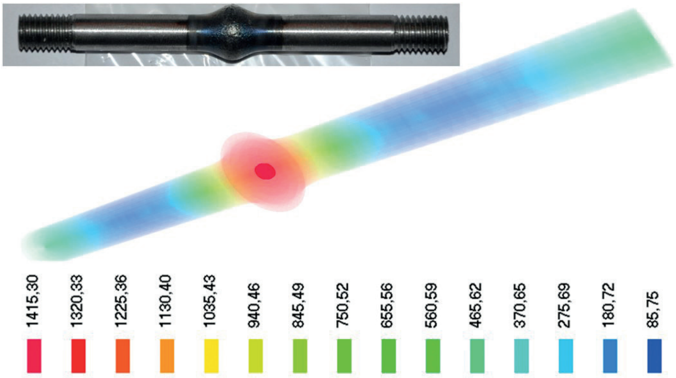

Fig. 5. Visualisation of the sample after deformation with a semi-solid zone for C45 steel with a real photo of the sample

Figure 5 presents the sample after deformation for C45 steel along with the estimated position and shape of the semi-solid zone.

In Fig. 6, a sample for S355 steel is presented along with the estimated position and shape of the semi-solid zone for cold holders of the Gleeble 3800 simulator. The semi-solid zone may border the surface of the sample because a quartz cover was used.

In Fig. 7, a sample for S355 steel is presented along with the estimated position and shape of the semi-solid zone for hot holders of the Gleeble 3800 simulator.

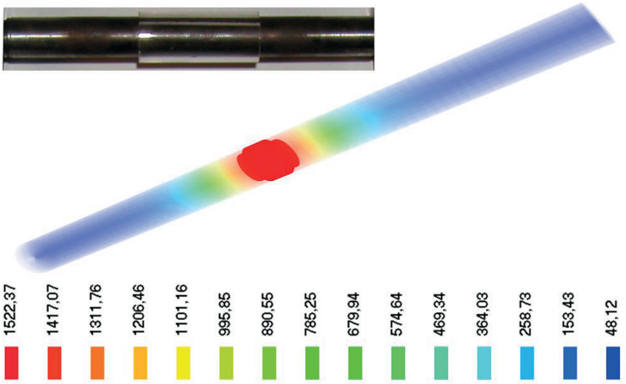

Fig. 6. Visualisation of the sample after heating with a semi-solid zone for S355 steel for cold holders with a real photo of the sample

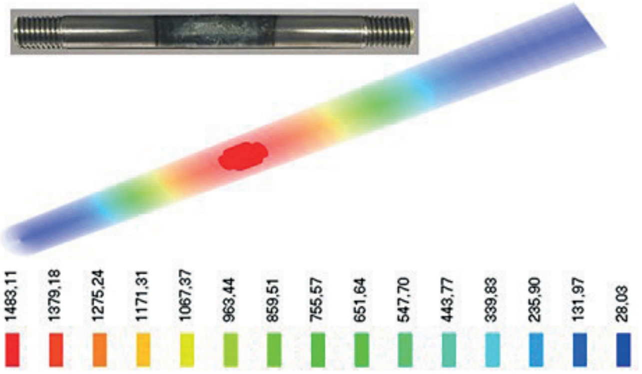

Fig. 7. Visualisation of the sample after heating with a semi-solid zone for S355 steel for hot holders

The results present the estimation of the geometrical position and shape descriptors of the remelting zone. In Figs. 4–7 the results for C45 and S355 steels are presented. Shape descriptors have been determined for each case, which are presented in Table 1. For C45 steel, it can be noted that geometrical parameters of the remelting zone worsened after deformation; the zone is more irregular, less compact, and its volume is smaller, which matters for planning further experiments and the optimisation of the process. The temperature of the holders influenced the size of the high temperature zone; it was observed that this was significantly limited in the case of cold holders. Higher temperatures caused the increase of volume of

Table 1. Overview of shape descriptors for the analysed samples

Descriptor	Material, case			
	C45 Before deformation	C45 After deformation	S355 Hot holder	S355 Cold holder
aspect ratio, extensibility	0.44	0.33	0.44	0.35
circularity, form factor	0.70	0.63	0.64	0.70
rectangularity	0.98	0.94	0.84	0.90
compactness	0.84	0.63	0.71	0.80
% of max volume	0.07	0.06	2.75	2.5

the remelting zone and its contact with the surface of the sample. In comparison to a sample heated to a lower temperature using hot holders, the remelting zone has worse geometrical parameters when heated to higher temperatures and its contact with the surface causes a lot of technical problems during the trial.

8. Summary and conclusions

Computer graphics provide many algorithms and solutions which may also be used in other areas. In the article, the use of computational geometry algorithms to determine representative points of the remelting zone for the simulation of the heating and deformation of steel samples in the Gleeble 3800 simulators has been presented. Estimation of the position and parameters of the remelting zone is very important for simulation of the process and increasing the precision of the model. Due to use of the axially symmetrical model, the polar coordinate system was used to visualise the sample. This allowed determining the points in space which constitute the zones of the sample. The remelting zone for a few samples has been described using shape descriptors, which allowed determining its shape and geometrical parameters. The obtained results may serve as a starting point for further research and to provide a more precise description of the zone, as well as to specify the input parameters of the model.

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