

NUMERICAL STUDY OF DEFORMATION CHARACTERISTICS IN PLANE STRAIN COMPRESSION TEST (PSCT) VOLUME CERTIFIED FOLLOWING MICROSTRUCTURE

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Thermal and mechanical parameters of forming and the process of microstructure development should be brought as close to real-world conditions as possible. The plane strain compression test and subsequent computer simulation provided an analysis of the recrystallization kinetics. A study of distribution of deformation characteristics in the sample upon upsetting was performed together with an analysis of microstructure of AISI 304 steel during hot forming. The result of the investigation is information on grain size in the sample in relation to applied strain.

Key words: Plane Strain Compression Test (PSCT), finite element method, AISI 304, microstructure development, fraction softening

Numerička studija deformacijskih karakteristika testa ravninske tlačne deformacije slijedom mikrostrukture (TRTD). Termički i mehanički parametri oblikovanja i stvaranje mikrostrukture trebaju biti što bliži realnim uvjetima. Test ravninskom tlačnom deformacijom i daljnja računalna simulacija omogućili su analizu kinetike rekristalizacije. Istraživanje raspodjele deformacijskih karakteristika u uzorku po rasterećenju provedeno je zajedno s analizom mikrostrukture čelika AISI 304 tijekom vrućeg oblikovanja. Dobiveni su podaci o veličini zrna uzorka ovisno o narinutoj deformaciji.

Gljučne riječi: test ravninskom tlačnom deformacijom (TRTD), metoda konačnih elementa, AISI 304, nastanak mikrostrukture, djelomično omekšanje

INTRODUCTION

The deformation mode during hot rolling of plates and strips is very similar to ideal plane strain conditions. For this reason it is highly desirable to obtain this deformation mode during laboratory experiments. That's why the PSC testing is now generally accepted as one of the most reliable methods for the generation of flow stress data and microstructural investigation of flat rolling. Interpretation of the results of the PSC tests is usually bind with strain inhomogeneity of deformation, lateral spread, influence of friction and rigid ends. In order to account such inhomogenities a numerous methods of correction have been developed [1]. The inverse technique is adopted as a most efficient method of identification of the flow stress model. Finite element simulation is usually performed as a solution of direct problem during inverse analysis for identification of flow stress data [2-9].

In the given work the aim of finite element simulation was the identification of distribution of deformation characteristics within specimen volume for further comparison with microstructure data.

The dependences of average grain size on deformation conditions obtained by this way were used for determination of SRX kinetics parameters.

Most research on static recrystallization kinetics are based on fractional softening method [10], but this method is not suitable when PSC test in use because of plastic flow inhomogeneity. Therefore, the method proposed by Kuziak et al. [11] and based upon analysis of average grain size changes during recrystallization has been used. It employs an equation relating current grain size during recrystallization to the recrystallized grain size D_{rex} , initial grain size D_0 end volume fraction of recrystallized material $X(t)$:

$$D = X(t)^{\frac{4}{3}} D_{\text{rex}} + X(t)^2 D_0 \quad (1)$$

$$X(t) = 1 - \exp\left(-0,693 \left(\frac{t}{t_{50}}\right)^n\right) \quad (2)$$

where the time for 50 % recrystallization t_{50} specifies as follows [7]:

$$t_{50} = A \varepsilon^p \cdot D_0^{p-1} \cdot \exp\left(\frac{Q_{\text{SRX}}}{R \cdot T}\right) \quad (3)$$

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$$D_{\text{rex}} = B\varepsilon^q \cdot D_0^{q_1} \cdot \exp\left(-\frac{Q_D}{8,31T}\right) \quad (4)$$

where T is a temperature, A , B , p , p_1 , q , q_1 , Q_{Srx} , Q_D are constants.

EXPERIMENTAL PROCEDURE

The AISI 304 stainless steel of normal chemical composition was chosen for investigation. The PSC tests were performed on fully integrated digital closed loop control thermal and mechanical testing system GLEEBLE 3800 in IMZ Gliwice.

The chemical composition of steel is as follows in wt %: 0,054 C; 17,52 Cr; 8,92 Ni; 1,5 Mn; 0,411 Si; 0,143 Mo; 0,114 V; 0,015 P; 0,016 S; 0,082 Cu; 0,046 Co; 0,021 Mg.

The PSC specimens measured $15 \times 10 \times 20$ mm and the width of the die was 5 mm. In order to decrease friction a graphite foil combined with nickel lubricant has been used. Prior to deformation the specimens were heated to initial temperature of 1100°C then deformed to a nominal strain 0,5 with a strain rate 1s^{-1} at 1000°C , annealed for 0,6; 2; 5; 10 and 100 seconds and quenched in water. Heating rates and holding time at temperature was carefully controlled and recorded. The time-temperature diagrams of the tests are presented in Figure 1.

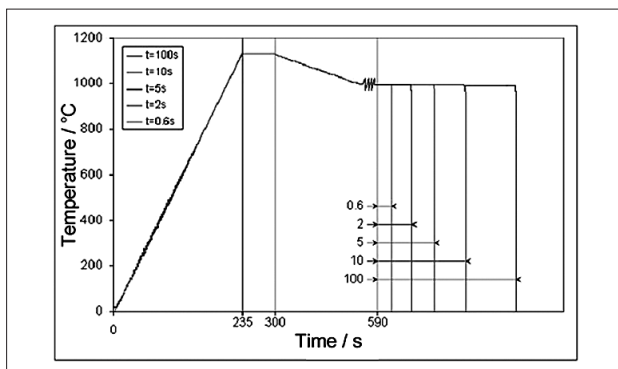


Figure 1. The time-temperature diagrams of the tests

CONDITIONS OF FEM SIMULATION

The SPLIN finite element code formulated on the basis of rigid visco-plastic theory for a material with slight compressibility has been used for simulation [12-14]. We solved 2D plane strain task in the central section of specimen. Two-dimensional approach leaves out of account deformations induced by lateral spread of the specimen. In our case, the maximal lateral spread of test-piece did not exceed 0,05 % of its breadth. Moreover it is obvious that the deformations induced by such spreading of deformation zone practically don't penetrate in to the centre of specimen because of rigid ends and friction. This conclusion is confirmed by comparison of 3D and 2D FEM simulations of PSC test provided by Kowalski et al. in [8]. The distribution of equivalent strain in the vertical cross section of specimen obtained by them from 3D FE

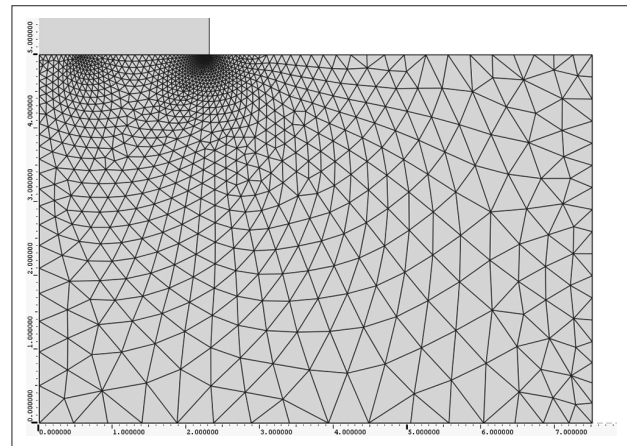


Figure 2. The initial finite element mesh of specimen.

simulation does not differ significantly from the results obtained by 2D FEM.

The finite element mesh of specimen and initial die position are represented in Figure 2. Because of double symmetry of the problem, it was solved in one fourth of the section. To improve the accuracy of the results the finite element mesh has been crowded in contact area of specimen.

The tool velocity has been calculated from the dependence of die displacement on time recorded in test protocol. We used the value of friction coefficient 0,14 which has been determined in [9] for graphite-nickel lubricant. A flexure of contact surface appearing after deformation of die and lubricant has been also taken into account. Figure 3 shows measured shape of the stamp and evolution of contact surface during deformation which have been set to the program. In the final stage of the test, the depth of die deflection equals to 0,177 mm.

The distributions of effective strain and effective strain rate are represented in Figure 4 and Figure 5. It can be clearly seen that the strain distribution obtained for this stage of deformation is significantly inhomogeneous in deformation zone.

METALLOGRAPHIC ANALYSIS

Metallographic analysis of specimens was performed subsequently in order to evaluate the impact of deformation conditions on microstructure development. Comparison of results of metallographic analysis and finite-element simulations requires very accurate identification of locations of individual micrographs on the given section. Micrographs were taken in locations 0,5 mm apart in order to obtain a combined photograph covering the whole section area. In total, 40 photographs were joined to cover each specimen. The image constructed in this way was correlated with the field of mechanical characteristics obtained from mathematical simulation. The resulting image is shown in Figure 6.

Nine zones with various values of strain along the horizontal axis of symmetry of the specimen were se-

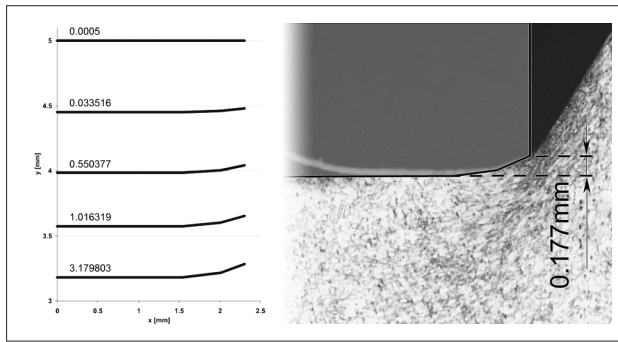


Figure 3. Distortion of contact surface

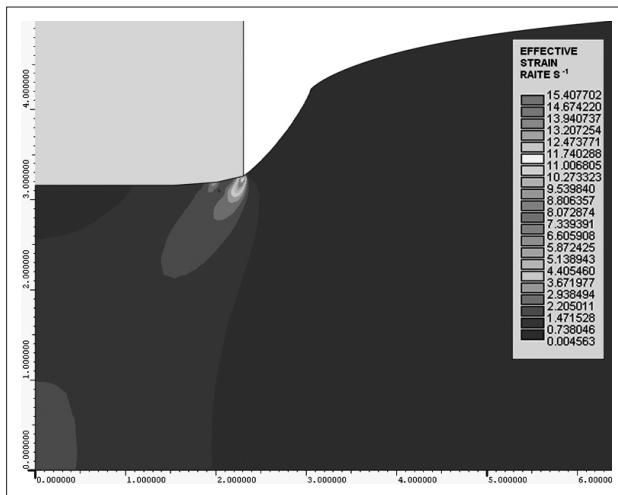


Figure 4. The effective strain rate distribution

lected for subsequent analysis. As mentioned above, the deformation conditions were identical in all five experiments. The only difference was in the post-deformation annealing time. This means that five micrographs showing microstructures upon different holding times were obtained for each of the nine selected zones. Selected micrographs corresponding to various amounts of strain and various holding times at the prescribed temperature are shown in Figure 7.

Such map of micrographs allows to trace the influence of deformation conditions on the development of microstructure during annealing.

RESULTS AND DISCUSSION

The following stage of investigation involved the measurements of grain size and identification of dependences of mean grain size on strain and annealing time. With this data, it was possible to determine the recrystallization parameters. The dependences of average grain diameter on effective strain and time of annealing are presented in figures 8 and 9. Figure 10 represents a pictorial rendition of dependence of average grain size on effective strain and annealing time in a 3D colour map surface form.

Obtained data have been used for determination of constants in constitutive equations which determines the dependence of average grain size and volume fraction of

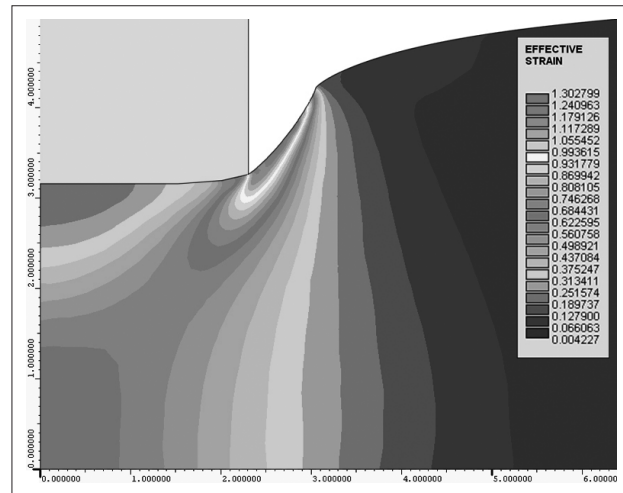


Figure 5. The effective strain distribution

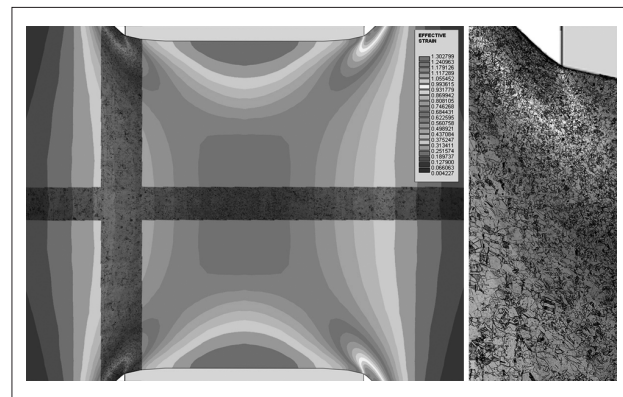


Figure 6. Comparison of calculated eq. strain with the results of metallographic analysis

recrystallized material on deformation and time of annealing. Toward this end the measured dependences of average grain size on strain and annealing time have been fitted by equations (1)-(4) for the constant temperature and initial grain size. The algorithms which have been used for determination of constants are based on alternating-variable descent method. Resulting equations of static recrystallization are given below. Toward this end the measured dependences of average grain size on strain and annealing time have been fitted by equations (1)-(4) for the constant temperature and initial grain size. The algorithms which have been used for determination of constants are based on alternating-variable descent method. Resulting equations of static recrystallization are given below:

$$X = 1 - \exp \left[-0,693 \cdot \left(\frac{t}{t_{50}} \right)^{0,92} \right] \quad (5)$$

$$t_{50} = 0,48\varepsilon^{-4,11} \quad (6)$$

$$D_{\text{rex}} = 14,94\varepsilon^{-1,07} \quad (7)$$

The obtained equations describe the kinetics of SRX for AISI 304 stainless steel with initial grain size $56 \mu\text{m}$ at $1000 \text{ }^\circ\text{C}$. The comparison of theoretical results with experimental ones is presented in Figures 8 and 9.

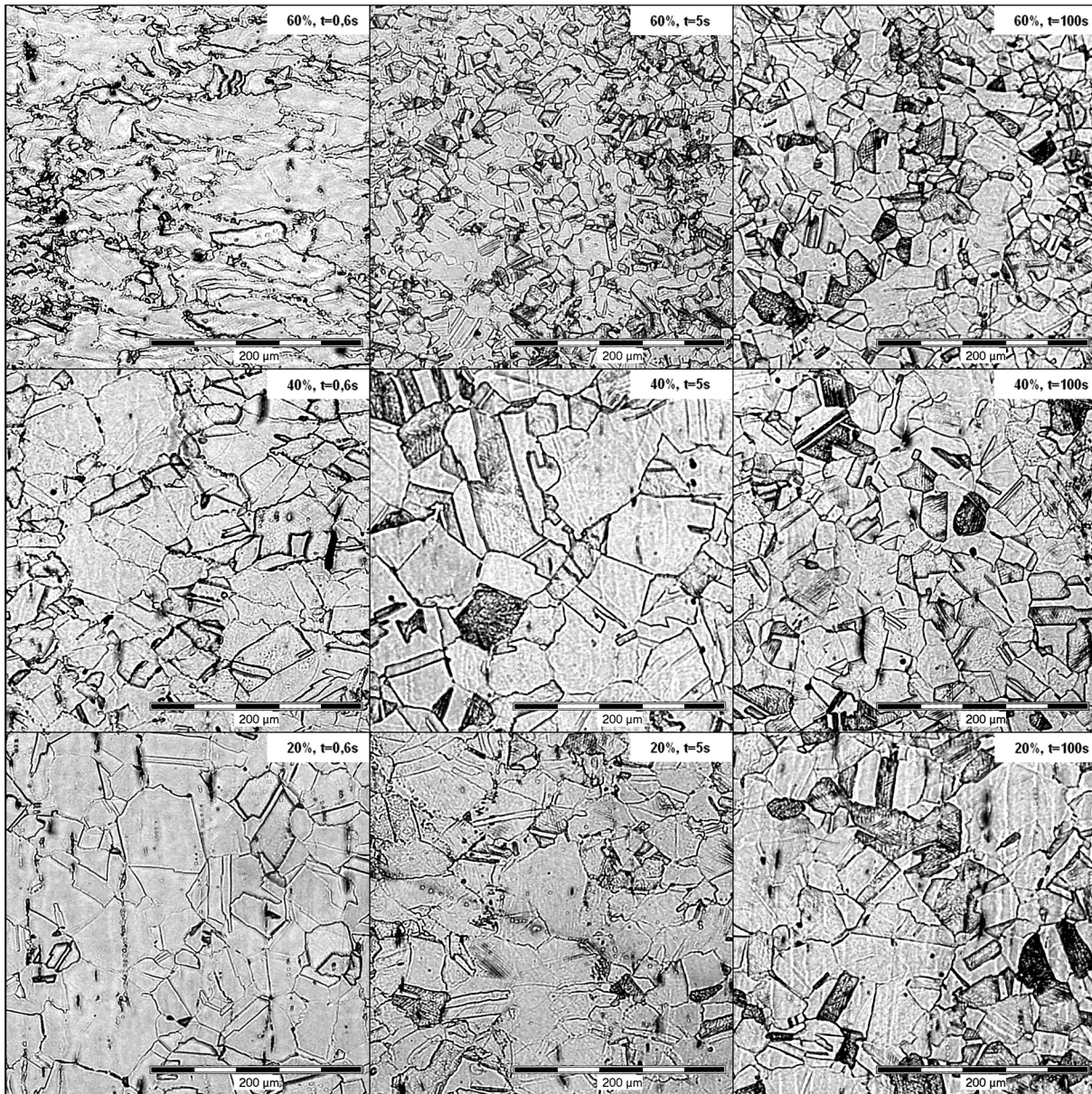


Figure 7. Microstructure obtained under strain of 60 %, 40 % and 20 % and annealing time of 0,6; 5 and 100 seconds

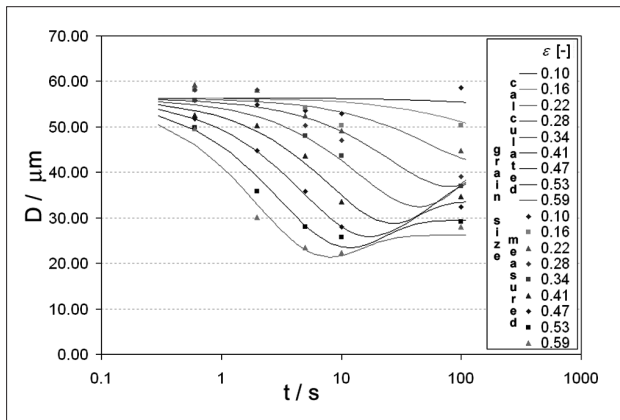


Figure 8. Calculated and measured dependences of grain size on equivalent strain

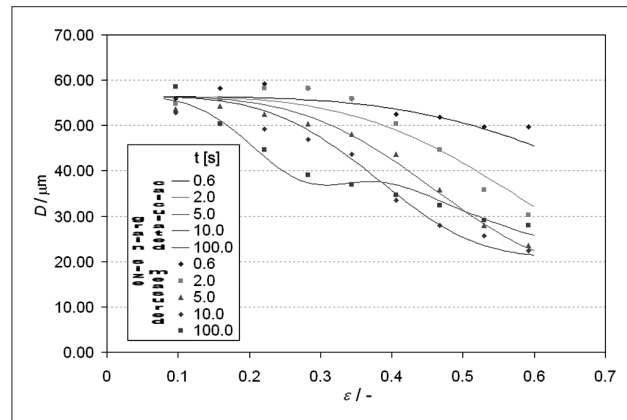


Figure 9. Calculated and measured dependences of grain size on annealing time

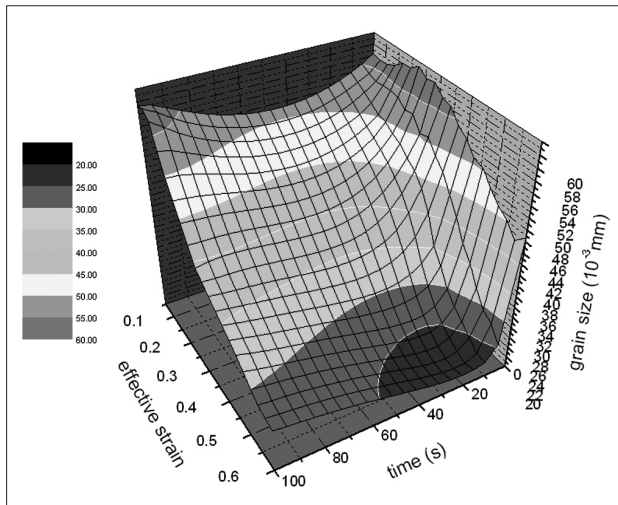


Figure 10. Dependence of grain size on equivalent strain and annealing time

CONCLUSIONS

Presented findings show a significant inhomogeneity of mechanical conditions in deformation zone of tested specimen with dimensions $20 \times 15 \times 10$ mm. In a test at nominal strain rate of $1,0 \text{ s}^{-1}$ the strain rate values varies from 0,0 to $15,4 \text{ s}^{-1}$. Nominal strain of 0,5 produces local deformations of 1,3 at the contact zone and 0,6 in the middle of test-piece.

The dependences of microstructure characteristics on deformation conditions and the time of annealing have been obtained by comparison of finite element model with results of microstructure analysis.

The parameters of static recrystallization kinetics for the AISI304 stainless steel at $1000 \text{ }^\circ\text{C}$ have been obtained by inverse method from the results of five laboratory experiments.

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Note: The responsible translator for English language is J. Drnek, Czech Republic