Simulation of deformation and static recrystallization in the stress relaxation test

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Abstract. A finite element (FE) simulation model illustrating the stress relaxation test was established with the Abaqus™ software. The microstructural evolution of steel during relaxation includes the complex phenomena of recrystallization. While the compression introduces the planned deformation and stress into the test piece, subsequent softening relieves the stress and at the same time creates microstructural reconstitution and refinement. In this study, a model was developed to simulate the kinetics of static recrystallization taking place during holding, using a technique based on FE-simulation. The simulation results have been compared to the experimental stress relaxation data obtained on a Gleeble™ 3800 thermo-mechanical simulator. The model can be used to estimate the recrystallization kinetics throughout the test piece. In the future, these results can be used for estimating the required rolling forces for multi-pass roughing with reasonable accuracy, for instance. The modelling methodology can be extended to other steels too, with or without microalloying additions.

1. Introduction

Steel research traditionally requires a lot of time-consuming and expensive experiments. Experimental methods also require simplifications when trying to study the industrial-scale processes. For these reasons, simulation appears to be an appealing alternative for studying the constitutive flow and recrystallization behaviours of multiple steel grades and associated thermo-mechanical processes.

In the current study, a comprehensive comparison has been made between experimental and simulated stress relaxation data. The experimental data has been obtained with the Gleeble™ 3800 thermo-mechanical simulator and the simulated data with a model that has been established using the Abaqus™ FEM software. The model includes constitutive static recrystallization (SRX) kinetics that has been implemented using a well-established model, as described in the modelling and simulation session, as well as various models for estimating the grain size of steel after SRX. In the current version the implementation is uncoupled, which is not a problem with single compression experiments. In the future, the model will be developed into a coupled model, which will be used to simulate industrial multi-pass roughing rolling with high accuracy.

2. Thermomechanical treatments and material characterization

A Gleeble 3800 thermomechanical simulator, equipped with the Hydrawedge module, was used to carry out (1) stress relaxation and (2) interrupted stress relaxation tests on a low-alloy steel of the following composition (in wt.%): 0.16C-0.3Si-1.0Mn-0.6Cr-0.2Mo. Cylindrical test specimens of the dimensions φ 10 x 12 mm were first reheated at 10 °C/s to 1200 °C, held for 5 minutes, followed by
cooling at 2 °C/s to a temperature at which the samples were deformed and relaxed for 200 s prior to subsequent quenching to room temperature (RT). The deformation temperatures were 950, 1000 and 1050 °C and the strain rates were 1, 10 and 40 /s and strains were 0.2 and 0.4. Interrupted relaxation experiments were performed at a constant true strain rate of 10 /s following compression to 0.2 and 0.4 strains to determine the prior austenite grain morphology. Holding times recorded for approx. 95 % recrystallization were 12 s at 950 °C and 6 s each at 1000 °C and 1050°C. The samples were quenched to RT following the stress relaxation / interrupted stress relaxation tests.

Prior austenite grain morphology was investigated using a laser scanning confocal microscope (LSCM) after picric acid etching and mean grain sizes were measured using mean linear intercept - procedure [1] from the centerline in the middle and quarter thickness of the deformed sample, as can be seen in figure 1.

3. Modeling and simulation

In order to calculate the non-uniform recrystallization kinetics and resulting average grain size after deformation, it is useful to apply the empirical equations describing the effect of temperature, strain and strain rate on these quantities [2].

3.1. SRX regression model

To estimate the time required for 50 % completion of static recrystallization, \( t_{50} \), we used equation (1)

\[
t_{50} = A' \varepsilon^p d^q \exp \left( \frac{Q_{rex}}{RT} \right)
\]

where \( \varepsilon \) is the strain, \( d \) the grain size prior to deformation and \( Q_{rex} \) the recrystallization activation energy. \( A' \) is a composition dependent constant, \( p \) and \( q \) are powers of strain and strain rate, respectively. The value for \( Q_{rex} \) is calculated using equation (2)

\[
Q_{rex} (J/mol) = 3803CF + 109418
\]

The composition factor \( CF = 2Cr + 10Cu + 15Mn + 50Mo + 60Si + 70V + 230Ti + 700Nb \), where the concentrations of elements are, in wt.%; Si and Nb are considered to have maxima of 0.4% and 0.044%, respectively, for higher concentrations. Modelling of \( A' \) in equation (2) has been earlier fitted by regression, \( \log A' = aCF + b \), where \( a \) and \( b \) are constants [3, 4]. The basis of selection of exponents \( p, q \) and \( Q_{def} \) has been given in detail elsewhere [3, 4]. The grain size exponent (s) has been found to be strongly dependent on grain size itself, decreasing nearly asymptotically with the grain size, varying from \(~2.1 \) at the finest grain size (12 \( \mu \)m) to \(~1.15 \) at large grain sizes (\(~800 \) \( \mu \)m), in agreement with the values suggested by Fernandez et al. [5]. The dependence of \( s \) on grain size is described with a power function: \( s = 2.13d^{-0.405} \) [6]

3.2. Grain size model

In order to estimate the average grain size \( D_r \), after the recrystallization has been completed, we applied equation (3), from [7, 8]

\[
D_r = 25 \left( 14.925 \ln \frac{10^{-9}Z}{8.5} \right)^{-0.67} \sqrt[3]{\frac{\varepsilon}{\varepsilon}}
\]

where \( Z \) is the Zener-Hollomon parameter, which is calculated using equation (4)

\[
Z = \dot{\varepsilon} \exp \left( \frac{Q_{def}}{RT} \right)
\]

Another equation was also applied, from [9]

\[
D_r = 0.5D^{0.67} e^{-0.67}
\]

3.3. Abaqus model

The Gleeble upsettings (hot compression tests) were modelled by the FEM software Abaqus. The model utilizes non-linear facilities of a coupled temperature-displacement solver of the software package
Abaqus Explicit. Abaqus is a multifunctional FEM software capable of handling a multitude of different cases, including coupled temperature-dependent deformation of a solid piece, as in upsetting.

Upsetting is assumed to be an axisymmetric forming process. The specimen is isolated from the compressive jaws to reduce the effect of friction and heat conductance. Tantalum and graphite together with a nickel paste are used in the insulating layers and thus the friction coefficient was set to a value of 0.05 using Coulomb’s friction theory. Heat conductance between the jaws and specimen was ignored. Due to vacuum used in upsetting tests, only heat radiation from the specimen surface is considered using emissivity of 0.8. Finely discretized geometry of the specimen is meshed with axisymmetric CAX4RT thermally coupled quadrilateral elements with enhanced hourglass control and reduced integration. Compressive jaws were modelled as rigid parts. Figure 1 shows the axisymmetric cross-section of a deformed test piece, with plastic equivalent elongation as field variable (blue is low, red is high) and includes the areas used for further simulations marked as black circles.

A previously fitted Hensel-Spittel (H-S) equation has been used to define the plastic stress-strain behavior of the Abaqus model. The H-S equation was implemented into the FE-model using the VUHARD-subroutine. Comparison of upsetting forces between experimental and FEM results are depicted in figure 2. Temperature dependent material properties (conductivity, specific heat, density and heat expansion) are specified with Inter Dendritic Solidification (IDS) analysis package using chemical composition of a selected steel grade.

The validity of the applied Abaqus model was checked using reaction force data from various Gleeble tests. The experimental data was then compared with the reaction forces obtained from the Abaqus simulations. The simulated reaction forces seem to correspond with experimental data very nicely. Based on this comparison, the model is deemed accurate enough to be used as a base for further simulations.

Data from the Abaqus model has been used in the SRX regression model and grain size model as input data, thus tying the models together. Strain and strain rate data from key points throughout the test piece cross-section has been obtained from output files using a python script. $t_{50}$ and grain size equations have then been applied to each point.
4. Results and discussion

4.1. SRX model

t_{50}-times estimated from the experimental data and the simulations were compared. Simulation data was chosen from test piece center and quarter thickness, since that area corresponds best to macroscopic relaxation data obtained experimentally. The results are shown in table 1 and figure 3.

Table 1. t_{50}-times [s] for simulated and experimental data

| Temperature | Simulated | Experimental |
|-------------|-----------|--------------|
| T1000 e02 SR1 | 6.85 | 4.10 |
| T1000 e02 SR10 | 4.04 | 2.90 |
| T1000 e04 SR1 | 1.16 | 1.50 |
| T1000 e04 SR10 | 0.67 | 1.74 |
| T1050 e02 SR1 | 2.27 | 1.80 |
| T1050 e02 SR10 | 1.35 | 1.80 |
| T1050 e04 SR1 | 0.38 | 1.50 |
| T1050 e04 SR10 | 0.23 | 1.80 |

Figure 3. t_{50}-times for simulated and experimental data

From figure 3 it can be seen that the simulation and experimental data show the effect of strain and strain rate for temperature 1000 °C in a similar fashion, where increasing the strain and strain rate seems to decrease the t_{50}-time. The same effects cannot be seen from the experimental data for 1050 °C though. When taking to consideration the small absolute differences between the values and the fact that the model variables are calculated based on composition, it can be said that the model works reasonably well. For temperature 950 °C the difference between experimental and simulation data was 15 s.

Due to the time-consuming experiments and extensive data analysis, a single stress relaxation test is carried out for each set of test parameters to determine the activation energy of recrystallization and various exponents. However, some tests may need to be repeated, if the corresponding data distinctly fall as outliers during the fitting with related trendlines, leading to poor fits.

The simulated t_{50}-times have also been compared with varying strains, strain rates, and temperatures for different areas around the test piece cross-section. Center of the sample was chosen for closer inspection in figure 4.

Figure 4. t_{50}-times for different strains, strain rates and temperatures in test piece center.
Large differences in $t_{50}$-times were observed for low strain, strain rate and temperature throughout the thickness of the test piece center. These differences seem to settle down when strain or temperature is increased. Strain rate has a small effect compared to the other variables.

4.2. Grain size model

Examples of etched austenite and mean grain size of experimental and simulated are shown in figures 5 and 6, respectively. Grain sizes with 0.2 strained are slightly bigger than 0.4 strain. Also increasing deformation temperature increased the experimentally defined mean grain size. Equation (3) is useful when comparing the grain sizes of 0.2 strain samples. However, equation (4) is more precise with the 0.4 straining samples.

5. Conclusions

An Abaqus FE model was successfully created for the Gleeble™ 3800 thermo-mechanical simulator and was shown to be accurate. The $t_{50}$-times and grain sizes were simulated in different points around the cross-section of the test piece and some significant differences were observed in $t_{50}$-times. The most significant factor affecting grain size was found to be strain, whereas temperature and strain rate had a negligible effect.

Grain size was simulated with two different equations, both of which seemed to correspond decently well to experimental data. The $t_{50}$-model was found to correspond well with experimental data in 1000 and 1050 °C, but this was not the case for 950 °C. There are several possible reasons for this, most likely
the variables used were not ideal and the difference between the calculated value and the experiment may be related to variations in the sample material. In any case, further studying is required to find the cause for these issues.

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