Modeling of austenitic grain growth of 25CrMo4 steel for the high-speed railway axle during hot working

Yuanming Huo, Baoyu Wang*, Jianguo Lin, Yang Jiang & Jing Zhou

School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

Received 8 May 2013; accepted 17 March 2014

After hot deformation, the fine grains due to recrystallization are apt to grow up at high temperatures. The grain size affects directly the performance and quality of products, so it is of great significance to investigate the grain evolution. In this paper, 25CrMo4 steel samples are compressed until a strain of 0.6, under isothermal conditions using Gleeble-1500 at deformation temperatures in the range of 950-1100°C and at same strain rate 1.0 s⁻¹, and then the samples are held at deformation temperatures for 0, 10, 20 and 30 min. Microstructure is retained by using water quench. The grain growth model is expressed by a differential function of both temperature and holding time. The material constants in grain growth model are determined using genetic algorithm (GA) optimization technology from experimental data. A good agreement between predicted results and experimental data is obtained, which shows that the developed grain growth model enables the grain size evolution at various high temperatures to be well predicted.

Keywords: High-speed railway axle, 25CrMo4 steel, Austenite grain, Grain growth model, Hot working

High-speed railway shafts are made of 25CrMo4 steel due to its good mechanical properties (e.g. high cycle fatigue) in extreme conditions. In order to avoid large residual stress and microcracks, it is necessary to control the cooling rate of 25CrMo4 steel for high-speed railway axles after hot rolling or hot forging. For this reason, 25CrMo4 steel is normally held at high temperatures for a certain time after deformation. During this period, the fine grains, which are formed due to recrystallization in hot deformation, tend to grow up at high temperatures. Since the final microstructure greatly influences the mechanical properties of 25CrMo4 steel for high-speed railway axles, it is significant to study the grain growth rule of 25CrMo4 steel at various high temperatures. With the aid of grain growth model, the grain growth can be predicted to determine the temperature range and soaking time during hot working.

A lot of work on modeling of austenitic grain growth has been reported. Sellars and Whiteman constructed the grain growth model using empirical formula method in 1979. Yue et al. developed the isothermal austenitic grain growth model for GCr15 steel using the nonlinear regression method from experimental data. Xie et al. set up the equations to describe the grain growth law under isothermal conditions. Lee et al. gained the grain growth model of Arrhenius type based on experimental data and discussed the influence of alloying element on grain growth. Xu et al. developed the austenitic grain growth prediction model of dual phase steel during hot rolling. However, the model is established based on the empirical equation.

Compared with empirical equation, the advantages of differential equation are obvious: as internal variables are included in the microstructure evolution model, calculation is simplified. Lin et al. developed the grain size evolution rate model which describes the variation of grain growth with time. Grong and Shercliff expressed dimensionless normal grain growth rate equation to describe the change of average grain size with time. Humphreys analyzed discontinuous sub-grain growth and shown the rate of grain growth with time. However, hardly any research work was conducted on grain growth modeling of 25CrMo4 steel for high-speed railway axle.

The aim of this paper is to utilize the differential equation to express grain growth model of 25CrMo4 steel. Hot compression test of 25CrMo4 was conducted using Gleeble-1500 under isothermal conditions to obtain the experimental data. After compression, 25CrMo4 steel samples were held at different holding temperatures for different holding
times and then water quenched to retain the microstructure. The austenite grain growth model was established in term of differential equation of both temperatures and holding time. A novel objective function was selected to determine the model constants using genetic algorithm (GA) optimization technique from experimental data. The developed grain growth model was validated by the comparison between the predictive results and experimental data.

**Experimental Procedure**

**Materials**

Hot uniaxial compression tests using a thermomechanical simulator Gleeble-1500 have been conducted to characterize the microstructural evolution of high-speed railway axle steel 25CrMo4 at high temperatures. The chemical composition of the 25CrMo4 steel is shown in Table 1. Original ingot is a mixture of ferrite and pearlite formed during air cooling of as-forged. Cylindrical compression specimens of 8 mm diameter and 15 mm length were machined from the original ingot. The dimensions of the specimens are given in Fig. 1.

**Method**

Static grain growth test were conducted under isothermal conditions using Gleeble-1500 to determine austenitic grain growth after hot compression. An experimental procedure for static grain growth tests is shown in Fig. 2. Each specimen was heated to 980°C at a heating rate of 20°C/s and then heated to 1000°C at a heating rate of 2 °C/s to prevent overshooting. Specimens were soaked at 1000°C for 180 s to obtain complete austenitization. Subsequently, a specimen was either heated or cooled to one of the following deformation temperatures $T_1$: 950, or 1000, or 1050 or 1100°C. Then the specimen was compressed to an engineering strain of 0.6 (corresponding to 60% reduction in height) at a strain rate of 1.0/s at the deformation temperature $T_1$, which ensured the occurrence of recrystallization and thus refinement of the initial austenitic grain size. After deformation, the specimen was held at the deformation temperature $T_1$ for 0 min, 10 min, 20 min and 30 min, respectively, to allow the austenitic grain growth, and then was immediately water quenched to freeze the austenitic grain structure at the deformation temperature $T_1$.

Deformed specimens were sectioned along the axial direction. The section of specimen was polished and etched in a solution of 60 mL water, 0.1 mL H$_2$O$_2$, 0.2 g sodium dodecyl benzene sulfonate (SDBS) and 2.5 g saturated picric acid. The etched specimen was heated to 50°C for 2 min to reveal the microstructure on an optical microscope.

**Table 1 – Chemical composition of 25CrMo4 (wt%)**

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.28</td>
<td>0.77</td>
<td>0.34</td>
<td>0.01</td>
<td>0.004</td>
<td>1.16</td>
<td>0.07</td>
</tr>
<tr>
<td>Mo</td>
<td>0.23</td>
<td>V</td>
<td>Cu</td>
<td>O</td>
<td>H</td>
<td>Fe</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>0.12</td>
<td>0.0014</td>
<td>0.00016</td>
<td>balance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2 – Average austenite grain size (µm) at different temperatures and holding times**

<table>
<thead>
<tr>
<th>Holding time</th>
<th>0 min</th>
<th>10 min</th>
<th>20 min</th>
<th>30 min</th>
<th>Holding time</th>
</tr>
</thead>
<tbody>
<tr>
<td>950°C</td>
<td>10.48</td>
<td>36.35</td>
<td>44.79</td>
<td>49.50</td>
<td>950°C</td>
</tr>
<tr>
<td>1000°C</td>
<td>11.14</td>
<td>38.03</td>
<td>63.20</td>
<td>63.12</td>
<td>1000°C</td>
</tr>
<tr>
<td>1050°C</td>
<td>12.95</td>
<td>64.83</td>
<td>87.75</td>
<td>97.89</td>
<td>1050°C</td>
</tr>
<tr>
<td>1100°C</td>
<td>15.23</td>
<td>120.33</td>
<td>134.94</td>
<td>154.64</td>
<td>1100°C</td>
</tr>
</tbody>
</table>
Experimental Results and Discussion

The austenite grain micrographs are shown in Fig. 3. The grain boundary in grain micrographs is the original austenite grain boundary. By comparing all micrographs in Fig. 3, the austenite grain size varies at different temperatures with the same holding time. It is notable that the largest amplitude of grain growth takes place at 1100°C. Additionally, Fig. 3 (i)-(iv), (v)-(viii), (ix)-(xii), (xiii)-(xiv) vividly displays the process of austenite grain growth at deformation temperatures \((T_i)\) 950, 1000, 1050 and 1100°C, respectively. Since the grain growth is a time-dependent process, the grains gradually grow up with the increase of holding time at the same temperatures. The trend of grain growth gradually levels off with the time increasing at the same temperatures: the largest increase of the grain growth extent occurs in the first 10 min holding time, as shown in Fig. 3 (i) and (ii); after 20 min, grain grows up slowly, as shown in Fig. 3 (iii) and (iv).

The grain size was counted according to ISO643-2012. Statistical results from static grain growth tests are shown in Table 2. It can be seen that at a chosen temperature, grain size increases with the increase of holding time; at a chosen holding time, grain size increases with the increase of holding temperature. This indicates that grain growth is a function of both temperature and holding time.

Austenite Grain Growth Model and Prediction

The establishment of austenite grain growth model

Due to grain growth is a function of both temperature and holding time, the establishment of grain growth model should take two variable parameters, holding temperature \(T\) and holding time \(t\), into account simultaneously. At the present, most researchers apply Sellars’ model to predict the austenite grain growth. Sellars’ model takes the form as:

\[
d^n = d_0^n + A \cdot t \cdot \exp\left(\frac{-Q}{RT}\right) \quad \ldots (1)
\]

where \(d\) is the average austenite grain size (\(\mu m\)), \(d_0\) is initial austenite grain size (\(\mu m\)), \(t\) is holding time (min), \(T\) is absolute temperatures (K), \(R\) is universal gas constant (8.31 J/(mol.K)), and \(Q\) is the activation energy for grain growth (J/mol). The material constants \(A\), \(n\) and the activation energy \(Q\) in Sellars’ model can be calculated via non-linear regression with experimental data.

To differentiate formula (1) with time on both sides, the grain growth rate model can be obtained. The differential equation of grain growth is expressed as\(^8\):

\[
\frac{dS}{dt} = G \cdot \exp\left(\frac{-Q}{RT}\right) \cdot \left(\frac{H}{S}\right)^\psi
\]

where \(dS/dt\) is the austenite average grain growth rate function of both holding temperature and holding time, \(t\) is holding time (min), \(S\) is the average austenite grain size (\(\mu m\)), \(T\) is absolute temperatures (K), \(R\) is universal gas constant (8.31 J/(mol.K)), and \(Q\) is the activation energy for grain growth (J/mol). These coefficients \(G, H, \psi\) and the activation energy \(Q\) are the target variables, which can be calculated as the material constants using GA (genetic algorithm) optimization technology.

In this paper the ordinary differential equation (2) is used as the grain growth model framework of 25CrMo4 steel for high-speed railway shafts. The Eq. (2) is a function of temperature and holding time, which was integrated using the fourth order Ronge-Kutta method. The initial value in the ordinary differential equation is defined to be the average austenite grain size at the temperature of 950°C and holding time of 0 min, i.e., \(t = 0\) min, \(d_0 = 10.48\) \(\mu m\).

The formulation of objective function

Optimization techniques are used to determine the material constants in the grain growth model. The objective function was expressed to minimize the sum of the squares of the errors between the computed and experimental data. To improve the quality and efficiency of optimization, Cao and Lin\(^11\) proposed a novel objective function. For the grain growth model, objective function is defined in terms of the square of the logarithmic error instead of the differences between predicted and experimental data, for average grain size and holding time. The objective function is expressed as\(^11\):

\[
f(x) = \frac{1}{M} \sum_{i=1}^{M} \left( \frac{1}{N} \sum_{j=1}^{N} \left( \frac{\Delta S_i^c - \Delta S_i^e}{\Delta S_i^c} \right)^2 \right)
\]

where, \(x\) is the material constants vector that required to calculate, \(x=[x_1, x_2, \ldots, x_n]\), \(n\) is the number of material constants; \(f(x)\) is the residual for austenite average
Fig. 3 – The austenite grain micographs at different temperatures and holding times (i) 950°C, 0 min; (ii) 950°C, 10 min; (iii) 950°C, 20 min; (iv) 950°C, 30 min; (v) 1000°C, 0 min; (vi) 1000°C, 10 min; (vii) 1000°C, 20 min; (viii) 1000°C, 30 min
Fig. 3 – The austenite grain micrographs at different temperatures and holding times (ix) 1050°C, 0 min; (x) 1050°C, 10 min; (xi) 1050°C, 20 min; (xii) 1050°C, 30 min; (xiii) 1100°C, 0 min; (xiv) 1100°C, 10 min; (xv) 1100°C, 20 min; (xvi) 1100°C, 30 min.
Table 3 – Initial range of four material constants

<table>
<thead>
<tr>
<th>$G$ ($\mu$m)</th>
<th>$Q$ (J/mol)</th>
<th>$H$ ($\mu$m)</th>
<th>$\Psi$ (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~10000</td>
<td>0~10000</td>
<td>0~100</td>
<td>0~10</td>
</tr>
</tbody>
</table>

Table 4 – The determined material constants in grain growth model

<table>
<thead>
<tr>
<th>$G$ ($\mu$m)</th>
<th>$Q$ (J/mol)</th>
<th>$H$ ($\mu$m)</th>
<th>$\Psi$ (–)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{2.89}$</td>
<td>$10^{3.33}$</td>
<td>$10^{1.20}$</td>
<td>$10^{6.12}$</td>
</tr>
</tbody>
</table>

Determination of material constants

Genetic algorithm (GA) optimization technology has been developed to determine the material constants in many works\textsuperscript{11,12}. MATLAB provides genetic algorithm (GA) toolbox to optimize the objective function. The ordinary differential equation, objective function and experimental data were programmed into MATLAB to work out the material constants. The following GA parameters in MATLAB are selected: Population size 200, generation number 5000, crossover rate 0.8, initial ranges of four variables is shown in Table 3. Figure 4 shows the flow chart of GA optimization process\textsuperscript{12}. The determined material constants in grain growth model are shown in Table 4.

The Model Predicted Results and Discussion

The experimental data, grain size evolution at temperatures (950°C and 1050°C), were utilised for the optimization. The material constants determined in the grain growth model using GA optimisation techniques are listed in Table 4. The fitting results with experimental values, for grain size evolution at temperatures (950°C and 1050°C), are plotted in Fig. 5.

In addition, the determined grain growth model is validated using two other experimental data, grain size evolution at temperatures (1000°C and 1100°C), shown in Fig. 5. It is shown that the predicted results are in a good agreement with the corresponding experimental results and the error of predicted grain size is within 10%. This indicates that the grain size evolution of 25CrMo4 can be well predicted by using the developed grain growth model.

The predicted results for two temperatures (850°C and 1150°C) using grain growth model are plotted in Fig. 5. It can be seen that the extent of grain growth increases with the increasing of...
holding temperatures, and grain growth rate decreases with the increasing of holding time at a chosen holding temperature.

Figure 5 shows that at a holding temperature of 850°C, the austenite grain has little amount of grain growth. With an initial grain size of 10.48 µm, the austenite grain size is about 50 µm given a holding time of 30 min and a holding temperature of 950°C. Compared with other holding temperatures, the extent of austenite grain growth is largest at a holding temperature of 1150°C: the final austenite grain size almost reaches 250 µm at a holding time of 30 min at 1150°C.

The microstructure may not obtain complete austenitization because of the small difference between austenitizing temperature with 850°C\textsuperscript{13}. Grain structures become seriously coarse at 1150°C. Therefore, the holding temperatures should be higher than 850°C to ensure enough activity energy for hot forming and lower than 1150°C to avoid the coarse grain size. According to EN13261\textsuperscript{14}, the average grain size of 25CrMo4 steel for high-speed railway axles should be less than 63.5 µm. The holding temperature of 950°C is a critical temperature, at which the grain size can meet the requirement of EN13261.

During hot working, the average grain size would be refined due to recrystallization, which restricts the grain growth of 25CrMo4 steel. The hot working temperature can be a little higher than 950°C, in the vicinity of 1000°C, which is suitable to deform the 25CrMo4 steel for high-speed railway shafts.

Due to the fact that the average grain size increases with the increasing of holding time at a chosen holding temperature, the holding time is also a key parameter to obtain a required microstructure after hot working. The hot working time of 25CrMo4 steel, including hot forming and soaking time at high temperatures should be restricted within 30 min to ensure the final average grain size fine enough, which can be deduced from Fig. 5.

Conclusions

At a chosen temperature, grain size increases with the increase of holding time; at a chosen holding time, grain size increases with increase of holding temperature. This indicates that grain growth is a function of both temperature and holding time.

The grain growth rate model is established to describe the grain growth rate with temperature and holding time. The material constants in grain growth model are determined using genetic algorithm (GA) optimization technology from experimental data. A novel objective function in terms of the square of the logarithmic error is used to minimize the sum of the squares of the errors between the experimental and computational results.

The predicted results from the grain growth model were validated through the comparison with experimental data. The error of predicted grain size is within 10%. This indicates that the developed grain growth model enables the grain growth evolution under various temperatures and holding times to be well predicted for 25CrMo4 steel.

Prediction results show that the extent of grain growth increases with the increasing of holding temperatures at a chosen holding time, and grain growth rate decreases with the increasing of holding time at a chosen holding temperature.

The holding temperatures should be higher than 850°C to ensure complete austenitizing microstructure for hot forming and lower than 1150°C to avoid the coarse grain size. The holding temperature of 950°C is a critical temperature, at which the grain size can meet the requirement of EN13261. The hot working temperatures range of 25CrMo4 should be selected in the vicinity of 1000°C, and it is suitable to deform the 25CrMo4 steel for high-speed railway shafts. The hot working time of 25CrMo4 steel, including hot forming and soaking time at high temperatures, should be restricted within 30 min to ensure the final average grain size fine enough.

Acknowledgements

This research is supported by Natural Science Foundation of China (Grant No. 51375042), Science and Technology Major Projects (Grant No. 2009ZX04014-074), Specialized Research Fund by the Doctoral Program of Institutions of Higher Learning in the Ministry of Education (Grant No. 2012006110017) and Beijing Modern Transportation Materials and Processing Technology Laboratory.

References