Modelling of microstructure evolution during thermoplastic deformation of Steel by a finite element method

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Abstract

A microstructure evolution model was coupled with finite element method to evaluate the dynamic recrystallization (DRX) and deformation behavior of low carbon steel under hot working. The flow stress curves and recrystallized grain size is measured from hot compression tests performed on Gleeble-1500. The recrystallization kinetics is expressed as Avrami equation calculated from measured flow stress curves including the effect of work hardening (WH), dynamic recovery (DRV) and DRX. Taking a hot compressed cylinder sample of Q235 as an example, an obvious non-uniform deformation is observed although the assumption of uniform deformation is commonly applied in this case. Microstructure evolution and macroscopic mechanical behavior of this sample were simulated and compared with measurements to examine the availability of the developed model.

Keywords: low carbon steel; thermoplastic deformation; finite element method; dynamic recrystallization; microstructure evolution

1. Introduction

Thermoplastic deformation of metallic material not only changes the macroscopic shape and size of products but also adjusts their microstructure and mechanical properties. Dynamic recrystallization (DRX) is an important microstructure evolution mechanism of low-medium stacking fault energy metallic material undergoing...
deformation. As a widely used mechanical engineering material, DRX of low carbon steel not only alters the grain size of austenite at elevated temperature but also changes the deforming resistance during forming process. Furthermore, fine and uniform distributed austenite grain influences the grain size of ferrite and also its distribution uniformity during the following phase transformation, which contributes to improving mechanical properties of products. Therefore, it is of great importance to investigate the microstructure evolution of low carbon steel during DRX, which helps control the austenite grain size at high temperature and improve the mechanical property of final products.

In the field of microstructural evolution, the time dependence of physical quantities such as stress field, strain field and microstructure field can be calculated by coupling finite element method (FEM) with semi-empirical model of microstructure evolution. This method has the advantages of easy calculation and convenient applicability since the developed microstructure evolution model and flow stress model can be explicitly expressed as a function of deformation parameters. Hence, it has the potential of using widely in engineering application [1-4]. In this work, the flow stress curves and the DRX grain sizes were measured through hot compression tests performed on Gleeble 1500. The DRX kinetics model was developed from measured flow stress curves. These microstructural evolution models were coupled into the finite element model. The hot deformation behaviour and the microstructural evolution of Q235 cylinder sample under hot deformation were simulated and compared with the experiments.

2. Simulation procedure

2.1. Experimental materials and methods

A commercial as-extruded Q235 was applied in the present study. Hot compression experiments were carried out on Gleeble 1500. The cylinder sample of 8mm in diameter and 12mm in length was heated to 1473K at a rate of 10K/s, held for 3min to diminish the thermal gradient of sample, and then deformed at temperatures of 1173-1373K and strain rates of 0.01-10s\(^{-1}\). The maximum true strain, \(\varepsilon\), is 0.8, followed by water quenching.

2.2. Microstructural evolution model

In view of the dominant softening mechanism, the deformation process of Q235 can be divided into two stages. 1) Dynamic recovery (DRV) stage. From the onset of deformation to the occurrence of DRX, the flow stress increases rapidly with strain due to the effect of work hardening (WH) and DRV. 2) DRX stage. When the strain exceeds its critical value, DRX occurs. The flow stress firstly increases to a peak value and then drops gradually to a steady state value due to the effect of DRX, DRV and WH. Thus, the flow stress reflects the combined effects of WH, DRV and DRX. According to the above analysis, the experimental flow stress data were used to estimate the DRX fraction which cannot be accurately measured by experiments. Combining Sellars model [5, 6], Kopp model [7], Yada model [8], and Laasraoui-Jonas kinetics model [9], a DRX kinetics model was developed as [10]

\[
X_{\text{drx}} = 1 - \exp \left( -k_d \left( (\varepsilon - \varepsilon_c) / (\varepsilon_{0.5} - \varepsilon_c) \right)^{n_d} \right)
\]  

(1)

where \(X_{\text{drx}}\) is DRX fraction; \(\varepsilon_c = \varepsilon_{0.055} = 0.0055\) \((\varepsilon_{0.5} = 0.0127)\); \(39879.82 / (RT)\) is the critical strain for DRX; \(\varepsilon_{0.5}\) is the strain where the DRX fraction reaches 50% and \(\varepsilon_{0.5} = 0.127\); \(k_d\) and \(n_d\) are the material constants where \(k_d = 0.1783\) \((14592 / (RT))\) and \(n_d = 0.1385\) \((25880 / (RT))\), respectively; \(\dot{\varepsilon}\) is the strain rate; \(R\) is universal gas constant and \(T\) is deformation temperature.

The DRX grain size was measured by quantitative metallography method. Its dependence on deformation condition was obtained by linear fitting method as

\[
D_{\text{drx}} = 12602 \times Z^{-0.1959}
\]

(2)

where \(Z\) is Zener-Hollomon parameter calculated by
where $Q = 301\text{KJ/mol}$ is the activation energy of Q235.

The grain size calculated by finite element method is average grain size since the severely deformed grains and the newly formed strain-free DRX grains exist together during hot deformation, which is expressed as

$$\bar{D} = D_0 \cdot (1 - X_{\text{drx}}) + D_{\text{drx}} \cdot X_{\text{drx}}$$  \hspace{1cm} (4)

where $D_0$ is the initial grain size.

2.3. Finite element model

The hot compression process of Q235 at 1273 K and 0.1 s$^{-1}$ was simulated by the finite element method. The cylindrical specimen has the same size of that used in Gleeble testing. This is a typical axisymmetric problem. Thus, half of the specimen are analyzed and four nodes rectangular axisymmetric element is chosen. The flow stress data of Q235 at elevated temperatures were input from user-defined material library, and the microstructural evolution model was input from UGRAIN subroutine of MSC.Marc [11,12]. Heat transfer coefficient between specimens and air is 0.073 W/(m$^2$.K). Heat transfer coefficient between specimens and dies is 10.989 W/(m$^2$.K). The initial temperature of specimens and dies is 1273 K. Temperature in working chamber is 353 K. Thermal-power conversion coefficient is 0.9. Friction coefficient between specimens and dies is 0.3. Other material parameters such as thermal expansion coefficient, heat conduction coefficient and Young’s modulus are taken from the manual [12].

3. Results and discussion

3.1. Equivalent strain distribution

Figure 1 shows the equivalent strain distribution of cylindrical specimen deformed at 1273 K and 0.1 s$^{-1}$. The strain distribution is non-uniform at different height reductions. The largest equivalent strain is observed at the central region and the lowest strain at two ends of the specimen. The strain at drum-shaped region is lower than that at the center but larger than that at the ends.

![Fig. 1. Distribution of equivalent strain at different height reductions of a) 2.1mm; b) 4.2mm; c) 6.3mm.](image)

Figure 2 presents the dependence of the standard deviation of equivalent strain on the height reduction. It is shown that the standard deviation of equivalent strain increases with increasing height reduction, but the increasing
rate of standard deviation increases firstly from the reduction of 2mm to 6mm and decreases slowly for further reduction. Generally speaking, the deformation non-uniformity increases with progressing deformation.

Based on the above analysis, the deformation level of Q235 is non-uniform due to the presence of friction between sample ends and compression dies. The axisymmetric sample can be divided into three regions as shown in Fig. 3. 1) Region I locates at the central area, where high deformation extent is observed. The reason lies in the fact that this region suffers from three directional compressive stress and is far away from the end, so the occurrence of deformation is relatively easy. In addition, quite large deformation level is observed from the central zone to the corner inclining to the compressive direction at an angle of 45. 2) Region II is called as adhesive region, where the deformation level is low due to the friction although three directional compressive stress still exists. 3) Region III is free deformation zone, where two directional tensional stress and one directional compressive stress is applied. The deformation level is fairly uniform here, the value of which is lower than that in region I but higher than that in region II. Therefore, we must take care to select the appropriate site for measuring the microstructural characteristics although the assumption of uniform deformation is commonly applied in Gleeble tests.

In order to analyze the time dependence of equivalent strain, characteristic points A, B, C and D are taken from region II, region I at the corner, region I at the center and region III respectively. As shown in Fig.4, the equivalent strains at four points increases with the time. At the initial stage of deformation, equivalent strains at B and C in region I grow much faster than that at A and D. When time increases from 60 s (height reduction of 6mm), the increasing rate of strain at B declines rapidly while that at A enhances slightly. Therefore, the increasing rate of strain deviation decreases, which corresponds well with that given in Fig.2.

3.2. Equivalent stress distribution

The equivalent stress distribution at height reduction of 2.1 mm is shown in Fig.5. Similar as the equivalent strain, the equivalent stress distribution exhibits characteristic of non-uniformity. The level of stress at the center (region I) is quite large while that at two ends (region II) is rather small, which agrees well with heterogeneity of strain.

The variance of the equivalent stress at point A, C and D with the time is given in Fig.6. At the initial stage of deformation, the equivalent stress at point C increases to a peak value at the height reduction of 2.88mm (corresponding to the true strain of 0.24), and then reduce gradually to a steady state value. This variance is consistent with the characteristic of stress-strain curves under the similar deformation condition [10]. The peak stress of point D emerges later than that of point C because the deformation extend at D is smaller than that at C.

3.3. Distribution of DRX volume fraction

Figure 7 presents the distribution of DRX volume fraction at the height reduction of 6.3 mm. The DRX has almost completed at the central zone and the DRX volume fraction here reaches 95%. The variance of DRX fraction
at points A, C and D are also tracked in Fig. 8. It is shown that the DRX fraction at all points is zero at the onset of deformation. When the height reduction reaches 2.16 mm, namely the true strain of 0.18, DRX occurs firstly at the point C where large deformation level is found in section 2.1. The onset and development of DRX at point D is delayed due to the non-uniform deformation. For the same reason, the onset of DRX at point A is fairly late and the DRX volume fraction only reaches about 25% as deformation finishes.

Fig. 5. Distribution of equivalent stress at height reduction of 2.1 mm.  

Fig. 6. Time dependence of equivalent stress at point A, C, D.  

Fig. 7. Distribution of DRX volume fraction at reduction of 6.3 mm.  

Fig. 8. Variance of the DRX fraction with time at A, C and D.  

Fig. 9. Comparisons of the average grain size between the experimental and simulated results when the reduction is 6.3 mm.
3.4. Distribution of DRX grain size

Figure 9 compares the simulated average grain sizes with the experiments at the height reduction of 6.3mm. It is found that DRX develops sufficiently at the central deformation region (point C), and the grain size is fine and uniform. The simulated average grain size is 55 μm, close to the measured value of 57.8 μm. The average grain size at the adhesive region (point A) is 109.6 μm while the initial grain size is 123.8 μm [13]. Meanwhile, only a small amount of DRX grain size forms on the initial grain boundary. At the free deformation zone (point D), the refinement of grain is obviously. The average grain size is 78.9 μm and the measured one is 87.4 μm. But the grain size is somewhat non-uniform because of the unsufficient development of DRX, which agrees well with the analysis in the above sections. In general, the simulated average grain sizes corresponds with the experiments, which demonstrates that the developed model can be used to predict and control the microstructural evolution of Q235 undergoing hot deformation.

4. Conclusions

1) Deformation heterogeneity is observed in cylinder specimen of Q235 undergoing thermo-plastic deformation due to the presence of friction. The equivalent strain in the central zone is large, those in the free deformation zone takes second place and the strain in the adhesive zone is small. Similar characteristic is found in the distribution of equivalent stress.

2) Deformation heterogeneity influences the uniformity of the microstructure. Dynamic recrystallization occurs when the local strain exceeds the critical value. In the central zone, the onset of DRX appears early and the grain size is fine and uniform due to the fully development of DRX. In the free deformation zone, the development of DRX and the refinement of grain size is delayed. In the adhesive zone, coarse grain and non-uniform microstructure is found. Carefulness must be taken to select appropriate sites in Gleeble samples as investigating the microstructure evolution behavior.

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