Study on Static Recrystallization Behavior of 38MnVTi Non-Quenched and Tempered Steel

Luwei Dai , Yuanfang Chen*, Hui Zeng , Ding Xie and Tao Zhang
(College of Materials Science and Engineering, Chongqing University of Technology, Chongqing 400054, China)
Luwei Dai (1993-), female, Guang'an, Sichuan, master degree, mainly engaged in digital mold manufacturing and special processing research.
E-mail:574123364@qq.com.

Abstract. The static recrystallization behavior of 38MnVTi non-quenched and tempered steel within the interval of passes was investigated by double-pass compression experiments using Gleeble-1500 thermal simulation machine. The true strain-stress curves of the steel were obtained, and the effects of deformation temperature, strain rate and pre-strain on the static recrystallization behaviours were studied. Single-pass compression experiments for 38MnVTi non-quenched and tempered steel were finished with the same conditions to the double-pass compression experiments. The static recrystallization dynamics model and the static recrystallization grain size model can be established. The predicted results of the model accord well with experimental ones, which indicate the proposed model, can give an accurate prediction of the static softening behaviour for 38MnVTi non-quenched and tempered steel.

1. Introduction
38MnVTi non-quenched and tempered steel can achieve good comprehensive mechanical properties and uniform microstructure after forging or rolling, so it is widely used as automobile steering knuckle and semi-axle material [1-3]. During the hot forging and hot rolling, it needs to control the process parameters to control the final microstructure of the product, so as to control the final property of the product. Therefore, in order to predict and control the microstructure of non-quenched and tempered steel 38MnVTi more accurately and optimize the hot working process, it is necessary to study the static recrystallization law of 38MnVTi non-quenched and tempered steel in holding time after thermal deformation [4].

2. Experimental Materials and Methods
The experimental material is 38MnVTi non-quenched and tempered steel bar, and the chemical composition is shown in Table 1. In order to meet the experimental conditions, the bar is processed into a Φ10mm × 12mm cylindrical sample. The true stress-strain curves can be obtained by double-pass compression experiments on Gleeble-1500 thermal simulator.

| Element | C | Si | Mn | V | Ti | P | S |
|---------|---|----|----|---|----|---|---|
| Mass fraction(%) | 0.36 | 0.3 | 1.2 | 0.1 | 0.024 | 0.026 | 0.033 |

The thermal deformation process is as follows: the samples are rapidly heated to 1200 °C at a rate of 10 °C / s, and kept warm for 5 min, and then cooled to the respective deformation temperatures at
rate of 5 °C/s after complete austenitizing. Next, kept warm for 30s in order to eliminate the temperature gradient in the sample. Later carry out the first pass compression with the true strain of 0.15. After a different interval time, the second compression was made with the same true strain. The process flow chart is shown in Figure 1. Three different process parameters shown in Table 2. After hot compression, the samples were longitudinally cut, polished, polished, and etched (The etched was the mixed solution of picric acid and a small amount of SDBS). Then grain size was observed on an optical microscope.

![Figure 1. Experimental procedure for the double-pass hot compression experiments](image)

### Table 2. Process parameters for the double-pass hot compression experiments

| Process No. | Deformation temperature(°C) | The first true stain | Stain rate(s⁻¹) | Interval time(s) |
|-------------|-----------------------------|----------------------|----------------|-----------------|
| 1           | 950,1000,1100,1150          | 0.15                 | 0.1            | 1,5,10,50       |
| 2           | 1150                        | 0.15                 | 0.1,0.5,1      | 1,5,10,50       |
| 3           | 1150                        | 0.07,0.1,0.15        | 0.1            | 1,5,10,50       |

3. Experimental Results and Discussion

3.1. True Stress - Strain Curve of Static Recrystallization

Figure 2 shows the true stress-strain curve, which obtained by static recrystallization experiment of 38MnVTi non-quenched and tempered steel at different interval times, deformation temperatures, deformation degrees, and strain rates. The change of rheological curve reflects the softening behavior of the material. As Fig.2 (a) shows, when the heat distortion temperature, deformation degree and strain rate remain constant, the deformation resistance of 38MnVTi non-quenched and tempered steel decreases with the increase of the interval time. As shown in Fig. 2 (b), when the interval time, deformation degree and strain rate remain constant, the flow stress decreases significantly with the increase of the deformation temperature. It can be seen from Fig. 2 (c) that when other conditions are certain, the higher the deformation degree is, the lower yield stress of the second pass is, and the yield stress of the first pass is not changed. This is because the higher the degree of pre-strain, the greater the dislocation density, the greater the dislocation. In the second pass deformation, it will quickly reduce the degree of hardening work. From Fig. 2 (d), it can be inferred that when the deformation degree, deformation temperature and interval time remain constant, the flow stress increases with the
increase of strain rate. This is because in the thermal deformation process, to improve the deformation temperature or reduce the strain rate will make the material dislocation density decreased, and the degree of work hardening also reduced, finally the flow stress of metal materials reduces during thermal deformation process.

![Stress-strain curves of double-pass experiment under different hot deformation conditions](image)

**Figure 2.** Stress-strain curves of double-pass experiment under different hot deformation conditions

### 3.2. Determination of Static Recrystallization Volume Fraction

In this paper, 0.2% stress compensation method was used to measure the static recrystallization volume fraction $X_{SRX}$ [5]. The static recrystallization volume fraction is calculated by the following equation:

$$X_{SRX} = \frac{\sigma_m - \sigma_2}{\sigma_m - \sigma_1}$$  \hspace{1cm} (1)

Where: $\sigma_m$ is the yield stress before unloading for the first pass; $\sigma_1$ and $\sigma_2$ are the values of the yield stress deviation of 0.2% at the beginning of the first and second pass compression respectively.

### 3.3. Effect of Deformation Conditions on Static Recrystallization Volume Fraction

Fig.3 (a) shows the effect of deformation temperature on the static recrystallization volume fraction of 38MnVTi non-quenched and tempered steel. It’s in consistent with the Avrami formula [6]. When other process parameters are constant, the static recrystallization volume fraction increases with the increasing deformation temperature, and the completion time of static recrystallization is shortened. This is because the static softening process is a thermal excitation process, under other constant conditions, with the temperature rose, on the one hand, the degree of recovery increases. On the other hand, the easier the dislocation climb and the grain boundary migration achieved, the smaller the degree of recrystallization critical deformation got.
Fig. 3 (b) is the effect of the pre-strain on the static recrystallization volume fraction of 38MnVTi non-quenched and tempered steel at 1150 °C and strain rate of 0.1 s⁻¹. It can be seen that when the temperature and strain rate remain constant, the static recrystallization volume fraction increases with the increasing pre-strain. This is because the work hardening plays a leading role while the degree of thermal deformation below the critical strain. With the degree of deformation increasing, the material dislocation density increases rapidly and the driving force of static recrystallization increases. So, static recrystallization has basically replaced static recovery, and new recrystallization grains lead to a rapid static recrystallization by dislocation motion, which makes the static recrystallization volume fraction become larger [7].

Fig. 3 (c) shows the effect of strain rate on static recrystallization volume fraction of 38MnVTi non-quenched and tempered steel at 1150 °C and pre-strain of 0.15. This is because in the same conditions, as the strain rate increases, the dislocation density rate increases, deformation storage energy increases, static recrystallization driving force becomes large, and the static recrystallization is promoted. It can be found that the static recrystallization fraction of 38MnVTi non-quenched and tempered steel is not sensitive to the strain rate.
3.4. Establishment of Static Recrystallization Kinetics Model

A large number of studies have shown that the static recrystallization kinetics equation is generally expressed by the Avrami equation [8]:

$$X_S = 1 - \exp \left[ -0.693 \left( \frac{t}{t_{0.5}} \right)^n \right]$$

(2)

Where: $X_S$ is the static recrystallization volume fraction; $t$ is the interval time; $t_{0.5}$ is the time of the static recrystallization volume fraction to 50%; $n$ is the material constant. Taking its double logarithm on both sides of equation (2), and then simplified:

Figure 3. Effects of deformation condition on the static recrystallization volume fractions
\[
\ln \left( \ln \left( \frac{1}{(1 - X_s)} \right) \right) = \ln 0.693 + n \ln t - n \ln t_{0.5}
\]  

(3)

Combined with the above experimental data, it can be calculated that the average value of \( n \) is 0.299 by linear regression. Substituting \( n \) into equation (2), it can be inferred \( t_{0.5} \) under different deformation conditions. \( t_{0.5} \) can be expressed as follows:

\[
t_{0.5} = A d_0^{m_1} \varepsilon^{m_2} \exp \left( \frac{Q_{srx}}{RT} \right)
\]

(4)

Where: \( d_0 \) is initial grain size; \( \varepsilon \) is strain; \( \dot{\varepsilon} \) is strain rate; \( Q_{srx} \) is static recrystallization activation energy, kJ/mol; \( R \) is molar gas constant (\( R = 8.314 \text{J/mol} \)); \( T \) is thermodynamic temperature; \( A, s, m_1, m_2 \) are material constants. Considering that the initial austenite grain size is coarse, the initial grain size is taken as 110μm, \( s = 1 \). Taking its logarithm on both sides of equation (4). It can be calculated that \( m_1 = -2.58 \), \( m_2 = -0.23 \) and \( Q_{srx} \) is 250.27kJ/mol by linear regression. Substituting the above data into the equation, it can be calculated \( A \) is \( 6.62 \times 10^{-15} \).

Based on the above analysis, the static recrystallization kinetic model of 38MnVTi non-quenched and tempered steel is obtained as follows:

\[
X_s = 1 - \exp \left[ -0.693 \left( \frac{t}{t_{0.5}} \right)^n \right]
\]

(5)

\[
t_{0.5} = 6.62 \times 10^{-15} d_0^{m_1} \varepsilon^{m_2} \exp(250270 / RT)
\]

(6)

3.5. Validation of Static Recrystallization Kinetics Model

From the figure 4 above, it is obvious that the predicted results of this model accord well with the observed data, which indicates that the static recrystallization kinetics model can predict the static recrystallization behavior of 38MnVTi non-quenched and tempered steel accurately, and it can provide the basic theory for hot deformation process.
Figure 4. Comparison between the experimental static recrystallization volume fractions and the predicted result.

3.6. Establishment of Static Recrystallization Grain Size Model

After cutting the samples of the double-pass heat compression test along the axial direction, taking them into the mixed in the solution of picric acid and a small amount of SDBS more than 40 minutes until the austenite grain boundary appears in large area, and the average grain size is measured by the intercept method.

As shown in Fig.5, the average grain size of the static recrystallization is directly proportional to the deformation temperature. When the other process conditions are constant, the average grain sizes at deformation temperatures of 950 °C, 1000 °C, 1100 °C and 1150 °C are 40.2μm, 53.2μm, 61.3μm and 74.2μm, respectively. This is because the dislocation storage which provides energy for the static recrystallized nucleus is reduced by increasing the temperature and the nucleation rate of the static recrystallization decreases accordingly. The nucleated part grows rapidly with the increase of temperature, and annexed the small grains which are not enough to grow up, which makes coarse grain.
In the static recrystallization process, the grain size model is as follows:

\[ D_{SRX} = A_1 d_0 \varepsilon^{b_1} \dot{\varepsilon}^{b_2} \exp(-Q_{DSRX} / RT) \]  

(7)

Where: \( D_{SRX} \) is the grain size of the static recrystallization; \( d_0 \) is initial grain size; \( \varepsilon \) is strain; \( \dot{\varepsilon} \) is strain rate; \( R \) is a molar gas constant; \( T \) is thermodynamic temperature; \( A_1 \), \( Q_{DSRX} \), \( b_1 \), \( b_2 \) are material constants. Taking logarithm on both sides of equation(7). Through the same methods of linear regression, it can be inferred that \( Q = 39719.21 \text{ J/mol} \), \( b_1 = -0.408 \), \( b_2 = -0.2 \), \( A_1 = 5.17 \). Therefore, the static recrystallization grain size model of 38MnVTi non-quenched and tempered steel is as follows:

\[ D_{SRX} = 5.17 d_0 \varepsilon^{-0.41} \dot{\varepsilon}^{-0.2} \exp(-39719 / RT) \]  

(8)

The experimental values of average grain size of static recrystallization are in good agreement with predicted values. Therefore, the grain size model can be used well for the grain size of 38MnVTi non-quenched and tempered steel during the static recrystallization process, and it can provide theoretical guidance for making and optimizing production process of 38MnVTi non-quenched and tempered steel.

4. Conclusion

(1) 38MnVTi non-quenched and tempered steel was researched with double-pass compression experiments on Gleeble-1500. It can be concluded that deformation temperature, strain rate and pre-strain parameters have effects on the static recrystallization behavior of 38MnVTi non-quenched and tempered steel. The higher the deformation temperature, the greater the strain rate and the greater the degree of pre-strain, the greater the static recrystallization volume fraction. The effect of pre-strain and deformation temperature on static recrystallization is greater than strain rate.
(2) The linear recrystallization dynamics model and grain size model were established by linear regression as follows:

\[ X_s = 1 - \exp\left[-0.693(t / t_{0.5})^{0.9}\right] \]
\[ t_{0.5} = 6.62 \times 10^{-15} d_0 e^{-2.58} \varepsilon^{0.23} \exp(250270 / RT) \]
\[ D_{SRX} = 5.17 d_0 e^{-0.41} \varepsilon^{-0.2} \exp(-39719 / RT) \]

The predicted results of the model accord well with experimental data, which can provide guidance and theoretical basis for the thermal deformation process.

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