ABSTRACT

To investigate dynamic recrystallization (DRX) of as-cast 25Mn steel, the hot compression experiments corresponding to a height reduction of 70% was conducted on Gleeble-3500 simulator in the temperature range from 900 to 1200 °C at an interval of 100 °C and the stain rate of 0.1, 0.5, 1 and 2 s\(^{-1}\). By analyzing and calculating the true stress-strain data, the deformation activation energy, characteristics strain model, DRX kinetic model and grain size model were obtained. The experimental results revealed that strain hardening and flow softening characterized the flow behavior. The higher temperature and the lower strain rate made DRX of as-cast 25Mn easier. The best final forging temperature is no less than 900 °C and strain rate is no more than 2 s\(^{-1}\). In addition, through the detailed comparison between predicted and experimental fraction of DRX, the predicted showed a very good agreement with the actual experimental.

INTRODUCTION

At present, the geometries of metal parts become more and more complex and its mechanical properties also need to be higher. As a result, some compound forming technologies such as casting-forging, casting-rolling, and casting-extruding are available and gradually replace the conventional forming technologies such as forging, rolling and extrusion. In the new technology, the complex geometries of metal parts can be obtained by employing the casting process, then, its sound mechanical properties will be ensured by the following another hot deformation
process. Compared with the traditional ones, the new method has advantages in saving material and improving productivity because of direct by using cast blank and eliminating blooming and blanking processes. But, during the research on the hot working and recrystallization of as-cast 316L and 317L, Martin C [1, 2] pointed out that there existed distinct difference in recrystallization between as-wrought and as-cast materials, and recrystallization of as-cast material is relatively slower than that of as-wrought. Mao [3, 4 and 5] compared the hot deformation behaviors of as-cast and as-wrought austenitic stainless steel and maintained that the hot deformation flow stress of as-cast steel is higher than that of as-wrought, while under the lower deformation temperature and higher strain rate conditions, their difference became much more significant. As indicated above, the question thus arises: when employing the new method, how to deform the as-cast material without blooming in the second process to ensure the sound mechanical properties? It is well known that the evolution of the new microstructures in hot deformation is extremely complex and influenced by various interconnected metallurgical mechanisms, such as work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX), and the DRX is an important factor for controlling microstructure and mechanical properties [6, 7]. Therefore, to probe the DRX of as-cast steel under hot deformation conditions is important for the application of compound forming technology.

Under the hot plastic deformation condition, when the normalized stress and strain respectively reach the critical values, DRX can be initiated [8]. The new grains produce softening, and thus decreasing the strain hardening rate until the occurrence of a peak stress. Then, the hot flow stress decreases with the strain increase until reaching the steady deformation state. Some studies indicated that the critical strain initiating DRX is a function of initial microstructure and deformation conditions, and is lower than the strain at peak stress [8, 9 and 10]. So far, many researches have been worked out to investigate the hot behavior of DRX [11-14] as well as its kinetic model [15-19].

25Mn steel as one representative of C-Mn steels is widely used in the field of chemical industry, petroleum, natural gas and wind power because of its good corrosion resistance and processing properties. In this study, the deformation behavior of as-cast 25Mn steel was investigated by conducting hot compression experiments on Gleeble-3500 thermo-simulator and its true stress-strain curves were analyzed in detail. Besides, the critical characteristics of DRX were determined by utilizing the working hardening rate versus true strain curves under different hot deformation conditions. Finally, DRX kinetic model and grain size model were established by regression of the experimental data. The study will provide theoretical instruction in compound forming of 25Mn steel.

EXPERIMENTAL PROCEDURE

The chemical compositions of as-cast 25Mn steel investigated in this study and its initial microstructure are presented in Table 1 and Fig. 1. The experimental specimen is a cylindrical billet with a diameter of 8 mm and a height of 12 mm and the hot compression tests were conducted on the Gleeble - 3500 thermo-simulator. The tests corresponding to a height reduction of 70 % were carried out at four different temperatures of 900, 1000, 1100 and 1200 °C and four different strain rates of 0.1 s⁻¹, 0.5 s⁻¹, 1.0 s⁻¹, 2.0 s⁻¹. The detailed experimental method is
Table 1. Chemical compositions of experimental steel (wt. %).

| Elements | C    | Si   | Mn   | S    | P    | Fe          |
|----------|------|------|------|------|------|-------------|
| wt. %    | 0.235| 0.37 | 1.0  | 0.022| 0.026| Bal.        |

Figure 1. Microstructure of the as-cast 25Mn steel.

Figure 2. Experimental procedure.

RESULTS AND DISCUSSION

Hot Flow Curves

The true stress-strain curves under different deformation conditions are shown in Fig. 3a-d. Most of flow stress first increase rapidly, then reach the peak characterized by the peak strain and peak stress, after that begin to gradually decrease and finally come to steady levels. From the Fig. 3a-b, it can be seen that, at lower strain rate (0.1 s\(^{-1}\) and 0.5 s\(^{-1}\)), the peak stress appears at all the tested temperature due to the thermal softening caused by DRX, but the peak stress values at the temperature of 900 and 1000 °C are much higher than those at 1100 and
1200 °C. In addition, from the Fig. 3c-d, it also can be seen that, at higher strain rate (1 s\(^{-1}\) and 2 s\(^{-1}\)), DRX has not happened at temperature of 900 °C and the material has marked WH at this time. Meanwhile, the material shows dynamic balance between DRV and WH at the temperature of 1000 °C and obvious DRX occurs at 1100 and 1200 °C. Thus, it can be concluded that, within the experimental range of deformation, DRX of as-cast 25Mn steel doesn’t come easily at the lower strain rate and lower temperature and the peak stress can come up only at higher temperature and lower strain rate, otherwise, the stress just reaches a constant or increases continuously. That is to say, this material isn’t suitable for larger deformation at lower temperature and higher strain rate. The best final forging temperature is no less than 900 °C and strain rate is no more than 2 s\(^{-1}\).

![Figure 3](image)

**Figure 3.** True stress-strain curves for as-cast 25Mn steel under different temperature with strain rates of 0.1 s\(^{-1}\), 0.5 s\(^{-1}\), 1.0 s\(^{-1}\), 2.0 s\(^{-1}\).

**Activation Energy of Deformation**

During hot deformation, DRX is controlled by thermally activated process which can be described as the following equation:

\[ \dot{\varepsilon} = A[\sinh(\alpha\sigma)]^n \exp\left(-\frac{Q}{RT}\right) \]  

(1)

where, \(\dot{\varepsilon}\) is the strain rate (s\(^{-1}\)), \(R\) is the universal gas constant (8.31 J·mol\(^{-1}\)·K\(^{-1}\)), \(T\) is the absolute temperature (K), \(Q\) is the activation energy of hot deformation (kJmol\(^{-1}\)), \(\sigma\) is the flow stress (MPa) for a given stain, \(n\) are material stress index, \(A\) and \(\alpha\) are the material constants.

Taking the logarithm of both sides of Eq. (1) gives Eq. (2):

\[ \ln \dot{\varepsilon} = \ln A + n[\ln \sinh(\alpha\sigma)] - \frac{Q}{RT} \]  

(2)
For the given deformation temperature, taking partial derivative of Eq. (2) with respect to \( \ln \dot{\varepsilon} \) gives:

\[
n = \frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha \sigma)]}
\]  \hspace{1cm} (3)

From Eq. (3), we can find that the value of \( n \) is just the value of slope rate in the plot of \( \ln[\sinh(\alpha \sigma)] \) - \( \ln \dot{\varepsilon} \). The linear relationships between \( \ln[\sinh(\alpha \sigma)] \) and \( \ln \dot{\varepsilon} \) is shown in Fig. 4. The mean value of \( n \) can be calculated as 4.4602.

For the given strain rate \( \dot{\varepsilon} \), there exists a linear relationship between \( 1/T \) and \( \ln[\sinh(\alpha \sigma)] \), and by differentiating the Eq. (2), the calculation formula of activation energy can be obtained as follows:

\[
Q = Rn \frac{d[\ln[\sinh(\alpha \sigma)]]}{d(1/T)}
\]  \hspace{1cm} (4)

From Eq. (4), we can find the value of slope rate in the plot of \( 1/T \) - \( \ln[\sinh(\alpha \sigma)] \) is accepted as the value of \( Q/Rn \). To calculate the value of slope rates, the values of tested temperature and flow stress for all strain rates are substituted into Eq. (4) and the linear relationships of \( 1/T \) and \( \ln[\sinh(\alpha \sigma)] \) are shown in Fig. 5. The value of \( Q \) can be calculated at different strain rates. Thus, the mean value of \( Q \) is calculated as 336.049 kJ·mol\(^{-1}\).

![Figure 4. Relationships between \( \ln[\sinh(\alpha \sigma)] \) and \( \ln \dot{\varepsilon} \).](image)

![Figure 5. Relationships between \( 1/T \) and \( \ln[\sinh(\alpha \sigma)] \).](image)

**Critical Characteristics of DRX**

Fig. 6 displays the relationships between the working hardening rate \( (\theta = \frac{d\sigma}{d\varepsilon}) \) and the true stress \( (\varepsilon) \) at deformation temperature of 1200 °C and strain rates of 0.1, 0.5, 1 and 2 s\(^{-1}\). It can be seen that \( \theta \) changes with \( \varepsilon \) because of the combined effects of DRX and DRV. Referring to the approach of Zhang [20], the two points on the \( \theta - \varepsilon \) curves at which the working hardening rate equals zero represent the peak stress \( (\varepsilon_p) \) and steady stress \( (\varepsilon_{ss}) \), respectively. Besides, according to Laasarouli [21], there is the linear relation between \( \varepsilon_p \) and critical stress \( (\varepsilon_c) \): \( \varepsilon_c = 0.83\varepsilon_p \). So, we can work out \( \varepsilon_c \), \( \varepsilon_p \) and \( \varepsilon_{ss} \) at the temperatures of 1000, 1100 and 1200 °C with the strain rates of 0.1, 0.5, 1 and 2 s\(^{-1}\), and the values are summarized in the Table 2.
Figure 6. $\theta - \varepsilon$ curves of as-cast 25Mn steel at deformation temperature of 1200 ℃ and strain rates of 0.1 s$^{-1}$, 0.5 s$^{-1}$, 1.0 s$^{-1}$, 2.0 s$^{-1}$.

### TABLE 2. $\varepsilon_c$, $\varepsilon_p$ AND $\varepsilon_{ss}$ UNDER DIFFERENT DEFORMATION CONDITIONS.

| Temperature (℃) | 1200 | 1100 | 1000 |
|-----------------|------|------|------|
| Strain rate (s$^{-1}$) | 0.1 | 0.5 | 1.0 | 2.0 | 0.1 | 0.5 | 1.0 | 2.0 | 0.1 | 0.5 |
| $\varepsilon_c$ | 0.11 | 0.16 | 0.21 | 0.24 | 0.18 | 0.24 | 0.28 | 0.33 | 0.21 | 0.34 |
| $\varepsilon_p$ | 0.26 | 0.26 | 0.29 | 0.29 | 0.22 | 0.29 | 0.34 | 0.40 | 0.26 | 0.41 |
| $\varepsilon_{ss}$ | 0.60 | 0.63 | 0.65 | 0.73 | 0.61 | 0.74 | 0.80 | 0.84 | 0.59 | 0.80 |

Usually, for the given flow curve, there are the following function relations between the deformation parameter ($Z$) and the peak strain ($\varepsilon_p$) as well as steady strain ($\varepsilon_{ss}$):

$$\varepsilon_p = A_1 d_0^{m_1} Z^{n_1}$$  \hspace{1cm} (5)

$$\varepsilon_{ss} = A_2 d_0^{m_2} Z^{n_2}$$  \hspace{1cm} (6)

Where, $A_1$, $m_1$, $m_2$, $n_1$, and $n_2$ are the material constants; $d_0$ is the initial grain size before hot working; $Z$, the Zener-Hollomon parameter, is the temperature compensation strain rate factor described as the following equation:

$$Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right)$$  \hspace{1cm} (7)

According to $\varepsilon_p$ under different deformation conditions, the relationships of $\ln \varepsilon_p - \ln d_0$, $\ln \varepsilon_p - \ln Z$, $\ln \varepsilon_{ss} - \ln d_0$, and $\ln \varepsilon_{ss} - \ln Z$ can be obtained by linear regression as shown in Fig. 7, and the material constants are calculated as $A_1 = 0.000387$, $A_2 = 0.00539$, $m_1 = 0.3713$, $m_2 = 0.1212$, $n_1 = 0.2307$ and $n_2 = 0.1197$, respectively.
Figure 7. Relationships of $\ln \varepsilon_p - \ln d_0$, $\ln \varepsilon_p - \ln Z$, $\ln \varepsilon_{ss} - \ln d_0$, and $\ln \varepsilon_{ss} - \ln Z$.

Then, the characteristics strain model of DRX can be given:

$$\varepsilon_p = 0.000387 d_0^{0.3713} Z^{0.2307}$$  \hspace{1cm} (8)

$$\varepsilon_c = 0.00032 \ln d_0^{0.3713} Z^{0.2307}$$  \hspace{1cm} (9)

$$\varepsilon_{ss} = 0.00539 d_0^{0.1212} Z^{0.1197}$$  \hspace{1cm} (10)

**DRX Kinetic Model**

DRX kinetic model is a mathematical model to describe the variable relationship of the fraction of DRX with the stress under different deformation conditions, which is given as:

$$X_{drex} = 1 - \exp \left[ -k \left( \frac{\varepsilon - \varepsilon_c}{\varepsilon_{ss} - \varepsilon_c} \right)^m \right]$$  \hspace{1cm} (11)

where, $X_{drex}$ is the fraction of DRX, $k$ and $m$ are the material constants.

In the present working, $X_{drex}$ was determined in four ways: energy, metallographic, flow stress curves and JMA equation. Because the energy method has a problem of poor operation and calculating accuracy by using metallographic and flow stress curves is not high, the JAM equation is adopted to determine $X_{drex}$ in this paper. Thus, DRX kinetic model can also be described as:
\[ X_{drex} = 1 - \exp\left[ b t^p \right] \]  \hspace{1cm} (12)

In Eq. (12), due to \( b \) and \( p \) varying with the deformation parameters, they are taken as the functions of the Zener-Hollomon parameter \((Z)\), and Eq.(12) can be rewritten as:

\[ X_{drex} = 1 - \exp\left[ -b(Z) t^{p(Z)} \right] \]  \hspace{1cm} (13)

Supposing \( X_{drex} \) is 0.005 when DRX occurs and is 0.999 when DRX reach steady state, the Eq. (13) can be written as the following forms:

\[ X_{drex} = 1 - \exp\left[ -b(Z) t^{p(Z)} \right] = 0.005 \]  \hspace{1cm} (14)

\[ X_{drex} = 1 - \exp\left[ -b(Z) t^{p(Z)} \right] = 0.999 \]  \hspace{1cm} (15)

Then,

\[
p(Z) = \frac{\ln \left( \frac{1-0.005}{1-0.999} \right)}{\ln \left( \frac{t_c}{t_{ss}} \right)} \]  \hspace{1cm} (16)

\[
b(Z) = \frac{\ln(1-0.005)}{t_c^{p(Z)}} \]  \hspace{1cm} (17)

where, \( t_c = \varepsilon_c / \dot{\varepsilon} \), \( t_{ss} = \varepsilon_{ss} / \dot{\varepsilon} \). Taking the values of \( p(Z) \) and \( b(Z) \) from Eqs. (16) and (17) into the Eq. (12), the \( X_{drex} \) can be obtained under different deformation conditions. As a result, the DRX kinetic model is established by regression of \( X_{drex} \) and characteristics strain:

\[
X_{drex} = 1 - \exp \left\{ -3.1186 \left[ \left( \varepsilon - \varepsilon_c \right) / \left( \varepsilon_{ss} - \varepsilon_c \right) \right]^{2.651} \right\} \]  \hspace{1cm} (18)

Fig. 8 shows the detailed comparison between predicted and experimental \( X_{drex} \). It can be seen that the predicted \( X_{drex} \) shows a very good agreement with the experimental values.

![Figure 8. Comparison between predicted and experimental \( X_{drex} \).](image)

![Figure 9. Relationships between \( \ln Z \) and \( \ln d_{drex} \).](image)
Grain Size Model

The grain size of DRX ($d_{drex}$) mainly depends on the strain rate, which can be obtained as:

$$d_{drex} = HZ^{-u}$$

(19)

where, $H$ and $u$ are constants. Then, taking the logarithm of both sides of Eq. (19) gives Eq. (20):

$$\ln d_{drex} = \ln H - u \ln Z$$

(20)

Fig. 9 is the relationships between $\ln Z$ and $\ln d_{drex}$. The constants $H$ and $u$ can be calculated as 8806.39 and 0.16731 by using the least square regression. Thus, the grain size of DRX is given as:

$$d_{drex} = 88806.39Z^{-0.16731}$$

(21)

CONCLUSIONS

In this paper, the hot compression deformation behavior of as-cast 25Mn steel was investigated on the Gleeble-3500 thermo-simulator at the different temperature, different strain rate and height reduction of 70 %. The following conclusions can be obtained:

(1) Strain hardening and flow softening mainly characterize the flow behavior of as-cast 25Mn steel. Within the experimental range of deformation, the peak stress will turn up only at higher temperature and lower strain rate, otherwise, the stress just reaches a constant or increases continuously. The best final forging temperature isn’t less than 1 173 K and strain rate isn’t more than 2 s$^{-1}$.

(2) The deformation activation energy, characteristics strain model, DRX kinetic model and grain size model are obtained through analyzing and calculating the experimental data.

(3) The predicted $X_{drex}$ from established DRX kinetic model shows a good agreement with the experimental.

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