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Effect of temperature, strain rate and chromium content on the flow behavior of high-manganese steels

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Abstract

Compression tests and metallographic observation were conducted to investigate the effect of temperature (400 °C–1100 °C), strain rate (0.001–10 s−1) and chromium content (0.21–5.44 wt.%) on the flow behavior of high manganese steels for cryogenic application. The results showed that the flow stress reduced with increased temperature and decreased strain rate. The effect of chromium content on the flow stress of steels was not linear. The lowest flow stress was got when the content of chromium was 1.53 wt.%. The influence of strain rate and temperature was obvious while that of chromium content was minor. The maximum flow stress decreased 538 MPa–571 MPa when the temperature rised from 400 °C to 1100 °C at the strain rate 10 s−1. It ascended 146 MPa–149 MPa when the strain rate increased from 0.001 s−1 to 10 s−1 at 400 °C. However, the effect of chromium content on the maximum flow stress of steels did not exceed 50 MPa at tested temperatures and strain rates. Dynamic recrystallization (DRX) was observed for all tested steels at 1100 °C. Higher temperatures and lower strain rates seemed to promote DRX. The true strain required for DRX was the largest when the chromium content in steels was 1.53 wt.%. It delayed the occurrence of DRX.

1. Introduction

Cryogenic steels are mainly used in storage tanks and containers for the production and transportation of liquefied natural gas, liquid nitrogen and liquid ammonia [1–3]. At present, most cryogenic steels used in energy industry are nickel steels, and the cryogenic toughness of steels is improved by solid solution of nickel in steels [4–8]. The cost of nickel cryogenic steels is relatively high due to the addition of a large amount of expensive nickel. To reduce the production cost of cryogenic steels and its dependence on high-priced nickel, high manganese austenitic steels have attracted much attention because of its low price, excellent plasticity and toughness [9–13]. Using manganese rather than nickel can improve the low-temperature stability of austenite in cryogenic steels. It can greatly reduce the cost of cryogenic steels and improve the solid solubility of nitrogen in austenite. Moreover, the cryogenic strength of steels will be increased. Grain refinement and alloying are two main ways to improve properties of alloys. There are many relevant studies on high manganese steels [14–17]. The effect of grain size on mechanical properties of high manganese steels was studied. The results showed that grain refinement could improve the strength of high manganese steels without affecting its low temperature ductility and toughness [18]. The hydrogen embrittlement of high manganese steels for both crack initiation and propagation could be inhibited by adding copper in steels. However, this only affected the hydrogen embrittlement rate rather than the mechanism of hydrogen embrittlement [19]. A stress-induced martensitic transformation was found in high manganese steels without aluminum, while there was no martensite and deformation twins formed in high manganese steels containing aluminum. Therefore, adding aluminum in high manganese steels improved its yield strength and achieved a higher Charpy impact energy [20]. However, compared to that of the low-carbon steel, the addition of
aluminum in high manganese steels lowered the strain hardening rate and tensile strength at subzero temperatures, and led to a significant increase in the hot deformation resistance [21]. It had little effect on the static crystallization rate of steels, but delayed the occurrence of dynamic recrystallization (DRX) [21]. The main role of niobium in high manganese steels was to inhibit recovery and recrystallization. The effect of solution strengthening, grain refinement and precipitation hardening of niobium was weak in high manganese steels. Niobium alloying in high manganese steels could effectively inhibit dynamic strain aging, and decrease cryogenic impact toughness and tensile toughness of steels [22]. Solution strengthening caused by dissolved nitrogen was the most effective strengthening mechanism to improve the yield strength of steels [23]. The solubility of nitrogen could be increased by adding chromium and manganese in steels [24, 25]. An increasing manganese content in austenitic Fe-Mn alloys delayed the occurrence of DRX and the static recrystallization rate [21, 26]. It would increase the maximum flow stress of steels at low temperatures and decrease the maximum flow stress above 700 °C [26]. However, the manganese contents increased from 23 wt.% to 28 wt.% in Fe-Mn-C steels promoted the occurrence of DRX [26]. DRX was first observed for 28 wt.% manganese steel at 1000 °C while the 23 wt.% manganese steel showed DRX above 1100 °C [27]. Similar results were obtained in three ternary compositions steels (Fe-Mn22-C0.6, Fe-Mn16-C0.6 and Fe-Mn9-C0.9). Higher manganese contents promoted DRX and slightly increased the maximum flow stresses up to 1100 °C. The stress of steels was affected by strain rates. The stress at the strain rate of 10 s−1 was three times higher than that at 0.01 s−1 [28]. The maximum flow stress of TWIP steels with 17wt.% to 20 wt.% manganese increased 50 MPa when the strain rate increased from 5 s−1 to 100 s−1 [29]. The strain rate sensitivity of the flow stress in Fe-C0.14-Mn25 steels was similar to low-carbon steels [21]. The carbon content affected the flow stress of high manganese steels below 700 °C. The maximum flow stress of steels could be increased by increasing the carbon content in high manganese steels. This effect was weaker with increased temperature [30]. The oxidation resistance and corrosion resistance of steels could be improved by a 30% increase in the hot deformation resistance [31]. The oxidation resistance and corrosion resistance of steels could be improved by a 30% increase in the hot deformation resistance [31]. The oxidation resistance and corrosion resistance of steels could be improved by a 30% increase in the hot deformation resistance [31].

Therefore, this study aims to explain the role of chromium in high manganese steels. It may provide a theoretical reference for microalloying design of chromium in high manganese steels. In addition, the effect of chromium content, temperature and strain rate on the flow behavior will be revealed, which is conducive to developing the deformation technology of high-performance and low-cost high manganese cryogenic steels. In this work, experimental high manganese steels were compressed by a thermo-mechanical simulator to investigate the deformation characteristics of steels. The effect of temperature, strain rate and chromium content on the flow behavior are discussed.

2. Materials and methods

The chemical composition of the high manganese steels investigated are given in table 1, which were measured by Inductively Coupled Plasma-Atomic Emission Spectrometer (Thermo Fisher Scientific, Waltham, America). Cylindrical experimental samples with 8 mm diameter and 12 mm height were prepared to study deformation characteristics of the steels. Surfaces of the samples were polished and cleaned before experiments. Compression tests were conducted on a Gleeble 3500 thermo-mechanical simulator (DATA SCIENCES INTERNATIONAL, INC., St. Paul, America). Test temperatures were 400 °C to 1100 °C. Specimens were heated to their respective testing temperatures at 5 °C/s. Since there was a difference for the temperature between the core and the surface of samples [31, 32], soaking at the set temperature for 20 s was done to make the temperature evenly distribute in the cylindrical samples. Strain rates in compression tests were 0.001 s−1, 0.01 s−1, 0.1 s−1, 1 s−1 and 10 s−1, and the maximum true strain was 0.7. To prevent adhesion between specimens and the pressure head, tantalum sheets were added at both ends of samples during compression, and graphite lubricant was applied to minimize the influence of friction. Metallographic studies of samples were performed by VHX-5000 microscope (KEYENCE, Osaka, Japan). The chemical etching was conducted using 4% Nital solution.

| Table 1. Compositions of different high manganese steels (wt.%) |
|----------------|----------------|----------------|----------------|---|---|---|---|---|---|
| **C**  | **Si**  | **Mn** | **P**  | **S**  | **Cu** | **Cr** | **Fe** |
| HM-A  | 0.46  | 0.15  | 24.18 | 0.011 | 0.0015 | 0.45 | 0.21 | Bal. |
| HM-B  | 0.42  | 0.17  | 24.05 | 0.012 | 0.0023 | 0.38 | 1.53 | Bal. |
| HM-C  | 0.44  | 0.15  | 23.92 | 0.008 | 0.0017 | 0.47 | 3.78 | Bal. |
| HM-D  | 0.45  | 0.14  | 24.11 | 0.014 | 0.0015 | 0.53 | 5.44 | Bal. |
3. Results and discussion

Flow curves of high manganese steels with different chromium contents at 400 °C under strain rates of 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), 0.1 s\(^{-1}\), 1 s\(^{-1}\) and 10 s\(^{-1}\) are shown in figure 1. The flow stress ascended with increased true strain. This is due to dislocation sliding, proliferation and interaction during deformation. They will lead to the rapid increase of dislocation density and cause work hardening. The slope of curves gradually decreased, indicating that the rate of flow stress increase reduced. Comparing with flow curves under different strain rates, higher strain rates gave larger flow stresses. Kliber et al.\cite{29} studied the flow behavior of Fe-Mn(17–20) steels under strain rates of 5 s\(^{-1}\) to 100 s\(^{-1}\), and found a similar trend. The maximum flow stress at a strain rate of 100 s\(^{-1}\) was 50 MPa higher than that at a strain rate of 5 s\(^{-1}\). Maximum flow stresses of four high manganese steels under different strain rates are summarized in table 2. It was shown that the maximum flow stress decreased when the chromium content increased from 0.21 wt.% to 1.53 wt.%. However, the maximum flow stress raised with the chromium content gradually increasing to 5.44 wt.%. This is consistent with previous studies by Wang et al.\cite{23}.
They found out that the yield strength of Fe-Mn24 steel raised from 305 MPa to 423 MPa and the tensile strength ascended from 830 MPa to 906 MPa when the chromium content changed from 3.3 wt.% to 6.3 wt.% [23]. The effect of chromium content on the maximum flow stress of high manganese steels were similar under different strain rates.

Figure 2 shows flow curves of four high manganese steels obtained at 600 °C under different strain rates. The change trend of flow stress under 600 °C was similar to that at 400 °C. Maximum flow stresses of steels under different strain rates at 600 °C are summarized in table 3. The maximum flow stress went up with the strain rate rising. The influence of chromium content on it was not linear. The maximum flow stress was the lowest when the chromium content was 1.53 wt.%. Increasing the temperature from 400 °C to 600 °C led to 127 MPa-146 MPa decrease in the maximum flow stress. The descending value of maximum flow stress went up with the increase of strain rates, and that of HM-B was the lowest in four tested steels under different strain rates.

Flow curves of steels at 800 °C under different strain rates are shown in figure 3. Maximum flow stresses of steels are listed in table 4. The typical work-hardening characteristic was observed in the flow curves below 800 °C and at 800 °C with a strain rate larger than 0.001 s\(^{-1}\). However, the flow stress did not raise continuously with increasing true strain at the strain rate of 0.001 s\(^{-1}\). The maximum flow stress was obtained during the deformation process. Flow stresses of high manganese steels with different chromium content were similar when the true strain was over 0.4. Maximum flow stress of HM-A, HM-B, HM-C and HM-D were 320 MPa, 317 MPa, 324 MPa and 327 MPa, and true strains at the maximum flow stress were 0.34, 0.36, 0.32 and 0.28, respectively (Circles in figure 3(a)). The flow stress reduced with increased true strain after the highest point, which might be caused by the occurrence of DRX. Work hardening of steels is offset by the strong softening caused by DRX, and the flow stress begins to decrease slowly after reaching the peak value [33]. Figure 4 shows microstructures of high manganese steels before and after compression test under the strain rate of 0.001 s\(^{-1}\). New DRX grains were observed in the microstructures of four compressed samples, which was indicated by arrows in figure 4. DRX might be caused by strain induced grain boundary migration or subgrain growth [34].

With the increase of strain, a section of original grain boundary may bow out to one side due to the increase of accumulated strain energy. The bowing out part can act as a crystal nucleus of recrystallization, and gradually grow up to form recrystallization grains. Moreover, the subgrain may gradually grow into recrystallized grains by the fusion of subgrains or growth of individual subgrain with the increase of temperature. DRX first occurred at the lowest test strain rate at 800 °C. A similar finding was reported by Wietbrock et al [27]. They conducted compression tests for Fe-Mn28-C0.3 steel under strain rates of 0.1 s\(^{-1}\) to 10 s\(^{-1}\), and found out that DRX was first observed at a strain rate of 0.1 s\(^{-1}\) [27]. The main reason may be that the migration time of grain boundary will be prolonged at lower strain rates, which is conducive to the growth of dynamic recrystallization grains [35]. The average kinetic energy of atoms is low at low temperatures and the deformation duration is short at larger strain rates [36]. The dynamic softening will be inhibited with reduced temperature and increased strain rate. Therefore, the typical characteristic of DRX was not observed in the flow curves below 800 °C and at 800 °C with a strain rate higher than 0.001 s\(^{-1}\). The true strain required for DRX of HM-D was the lowest among the four tested steels, indicating that a higher chromium content in HM-D promotes DRX. There were more new DRX grains in HM-D. It made the softening caused by DRX stronger and result in a higher decrease of flow stress after the peak stress. The maximum flow stress at 800 °C decreased 145 MPa-217 MPa comparing with that at 600 °C (tables 3, 4). The descending value of maximum flow stress dropped and then rised with increased strain rates. The highest drop was got at the strain rate of 0.001 s\(^{-1}\).

Flow curves of steels at 900 °C under different strain rates are illustrated in figure 5. The flow stress raised with increased true strain at strain rates of 0.1 s\(^{-1}\), 1 s\(^{-1}\) and 10 s\(^{-1}\). The rate of flow stress increase was quite low under higher true strains (figures 5(c), (d), (e)). The DRX appeared in the flow curves of four high manganese steels at strain rates of 0.001 s\(^{-1}\) and 0.01 s\(^{-1}\). The maximum flow stress of steels were obtained under fairly low true strains at the strain rate of 0.001 s\(^{-1}\), and the flow curves of four steels was not easy to distinguish in the whole compression process (figure 5(a)). There were some difference for the flow stress when the true strain was lower than 0.2 at the strain rate of 0.01 s\(^{-1}\). The difference decreased rapidly with increased true strain. Maximum flow stresses of HM-A, HM-B, HM-C and HM-D were got at true strains of 0.16, 0.18, 0.14 and 0.12,

| Strain Rate (s\(^{-1}\)) | 0.001 s\(^{-1}\) | 0.01 s\(^{-1}\) | 0.1 s\(^{-1}\) | 1 s\(^{-1}\) | 10 s\(^{-1}\) |
|-------------------------|----------------|----------------|----------------|----------------|----------------|
| HM-A                    | 642 MPa        | 678 MPa        | 714 MPa        | 751 MPa        | 789 MPa        |
| HM-B                    | 632 MPa        | 667 MPa        | 703 MPa        | 740 MPa        | 778 MPa        |
| HM-C                    | 659 MPa        | 695 MPa        | 732 MPa        | 769 MPa        | 807 MPa        |
| HM-D                    | 674 MPa        | 710 MPa        | 747 MPa        | 785 MPa        | 823 MPa        |
respectively. Maximum flow stresses of steels under different strain rates at 900 °C are listed in table 5. Increasing the temperature from 800 °C to 900 °C led to 146 MPa-176 MPa decrease for the maximum flow stress under strain rates of 0.01 s⁻¹ and 0.001 s⁻¹. However, the descending value was only 74 MPa-86 MPa under strain rates of 0.1 s⁻¹, 1 s⁻¹ and 10 s⁻¹.

Table 3. Maximum flow stresses of high manganese steels under different strain rates at 600 °C (MPa).

|        | 0.001 s⁻¹ | 0.01 s⁻¹ | 0.1 s⁻¹ | 1 s⁻¹ | 10 s⁻¹ |
|--------|-----------|----------|---------|-------|--------|
| HM-A   | 514       | 545      | 577     | 610   | 644    |
| HM-B   | 505       | 535      | 567     | 600   | 633    |
| HM-C   | 530       | 562      | 594     | 627   | 661    |
| HM-D   | 544       | 576      | 609     | 642   | 677    |

Figure 2. Flow curves of high manganese steels under strain rates of (a) 0.001 s⁻¹, (b) 0.01 s⁻¹, (c) 0.1 s⁻¹, (d) 1 s⁻¹ and (e) 10 s⁻¹ at 600 °C.
Figure 6 shows flow curves of high manganese steels at 1000 °C. Maximum flow stresses of steels are summarized in Table 6. DRX occurred for four steels at relatively low true strains under strain rates of 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), and 0.1 s\(^{-1}\). Flow curves of four steels also showed the characteristic of DRX at a large true strain under the strain rate of 1 s\(^{-1}\). The maximum flow stress of HM-A, HM-B, HM-C and HM-D were 289 MPa, 286 MPa, 284 MPa, and 282 MPa, respectively.

Table 4. Maximum flow stresses of high manganese steels under different strain rates at 800 °C (MPa).

|        | 0.001 s\(^{-1}\) | 0.01 s\(^{-1}\) | 0.1 s\(^{-1}\) | 1 s\(^{-1}\) | 10 s\(^{-1}\) |
|--------|-----------------|----------------|--------------|------------|-------------|
| HM-A   | 320             | 398            | 424          | 450        | 478         |
| HM-B   | 317             | 390            | 416          | 442        | 469         |
| HM-C   | 324             | 412            | 438          | 465        | 493         |
| HM-D   | 327             | 424            | 451          | 478        | 509         |

Figure 6 shows flow curves of high manganese steels at 1000 °C. Maximum flow stresses of steels are summarized in Table 6. DRX occurred for four steels at relatively low true strains under strain rates of 0.001 s\(^{-1}\), 0.01 s\(^{-1}\), and 0.1 s\(^{-1}\). Flow curves of four steels also showed the characteristic of DRX at a large true strain under the strain rate of 1 s\(^{-1}\). The maximum flow stress of HM-A, HM-B, HM-C and HM-D were 289 MPa, 286 MPa, 284 MPa, and 282 MPa, respectively.
296 MPa and 301 MPa when true strains of them were 0.60, 0.60, 0.50 and 0.46, respectively. Work-hardening characteristic was observed under the strain rate of $10 \text{s}^{-1}$. The flow stress grew continuously with the increase of true strain. The maximum flow stress at 1000 °C decreased 76 MPa-174 MPa comparing with that at 900 °C. The highest decrease in the maximum flow stress was HM-D with a strain rate of 0.1 s$^{-1}$, while the lowest was HM-B with a strain rate of 10 s$^{-1}$.

The maximum temperature of compression tests conducted is 1100 °C, and flow curves of steels are displayed in figure 7. Steels underwent DRX at different strain rates. DRX occurred at relatively low true strains under strain rates of 0.001 s$^{-1}$ to 1 s$^{-1}$. At the strain rate of $10 \text{s}^{-1}$, DRX of HM-A, HM-B, HM-C and HM-D happened when true strains were 0.50, 0.60, 0.44 and 0.36, respectively. Maximum flow stresses of steels under different strain rates at 1100 °C are listed in table 7. Maximum flow stresses of four steels were similar at strain rates of 0.001 s$^{-1}$, 0.01 s$^{-1}$, 0.1 s$^{-1}$ and 1 s$^{-1}$. There was a relatively larger difference at the strain rate of $10 \text{s}^{-1}$.

**Figure 4.** Microstructures of high manganese steels before and after compression test under the strain rate of $0.001 \text{s}^{-1}$ at 800 °C (a) as-received HM-A, (b) compressed HM-A, (c) compressed HM-B, (d) compressed HM-C, (e) compressed HM-D (The new DRX grains are indicated by arrows).
The maximum flow stress raised 11 MPa when chromium contents increased from 0.21 wt.% to 5.44 wt.%. Increasing the temperature from 1000 °C to 1100 °C resulted in 134 MPa-145 MPa decrease of maximum flow stress under the strain rate of 1 s⁻¹. However, the descending value was only 35 MPa-36 MPa under the strain rate of 0.001 s⁻¹.

Table 5. Maximum flow stresses of high manganese steels under different strain rates at 900 °C (MPa).

|        | 0.001 s⁻¹ | 0.01 s⁻¹ | 0.1 s⁻¹ | 1 s⁻¹ | 10 s⁻¹ |
|--------|-----------|----------|---------|-------|--------|
| HM-A   | 153       | 246      | 349     | 372   | 396    |
| HM-B   | 153       | 245      | 342     | 364   | 388    |
| HM-C   | 154       | 248      | 362     | 385   | 410    |
| HM-D   | 154       | 248      | 365     | 397   | 422    |

Figure 5. Flow curves of high manganese steels under strain rates of (a) 0.001 s⁻¹, (b) 0.01 s⁻¹, (c) 0.1 s⁻¹, (d) 1 s⁻¹ and (e) 10 s⁻¹ at 900 °C.
Flow stresses of four high manganese steels decreased as the temperature rised from 400 °C to 1100 °C and they raised with increased strain rate (figures 1–3, 6, 7). The maximum flow stresses of steels at different temperatures under tested strain rates are summarized in figure 8. The results showed that the maximum flow stress decreased with increased temperature at different strain rates. The decline rate of maximum flow stress decreased as the temperature rised from 400 °C to 1100 °C and they raised with increased strain rate (figures 1–3, 6, 7). The maximum flow stresses of steels at different temperatures under tested strain rates are summarized in figure 8. The results showed that the maximum flow stress decreased with increased temperature at different strain rates. The decline rate of maximum flow stress decreased with increased strain rate.
increased below 900 °C and then decreased gradually at the strain rate of 0.001 s\(^{-1}\) (figure 8(a)). It was nearly constant at the strain rate of 0.01 s\(^{-1}\) when the temperature was lower than 800 °C. However, it decreased as the temperature increasing from 800 °C to 1100 °C (figure 8(b)). With the increase of strain rate, the transition temperature of the maximum flow stress reduction rate increased. It was close to linear reduction at the strain rate of 0.001 s\(^{-1}\) and then decreased at higher strain rates.

Table 7. Maximum flow stresses of high manganese steels under different strain rates at 1100 °C (MPa).

|       | 0.001 s\(^{-1}\) | 0.01 s\(^{-1}\) | 0.1 s\(^{-1}\) | 1 s\(^{-1}\) | 10 s\(^{-1}\) |
|-------|-----------------|----------------|--------------|-------------|--------------|
| HM-A  | 37              | 59             | 94           | 152         | 241          |
| HM-B  | 37              | 59             | 94           | 152         | 240          |
| HM-C  | 38              | 60             | 96           | 155         | 248          |
| HM-D  | 38              | 61             | 97           | 157         | 232          |
rate of $10 \text{s}^{-1}$ (figure 8(e)). Maximum flow stresses of steels at larger strain rates were higher than that at smaller strain rates under constant temperatures. Comparing with the maximum flow stresses of four steels, there was some difference at low temperatures. The maximum flow stress of HM-D was the highest while that of HM-B was the lowest. The difference gradually declined with the increase of temperature, especially at low strain rates. DRX occurred at relatively high temperatures, which would cause the softening of steels. Among the four steels, the steel with a higher flow stress was more prone to DRX and the softening effect might be more sufficient. That might be the reason for the smaller difference on the maximum flow stress of four high manganese steels at high temperatures.

According to the Arrhenius equation, the flow stress is related to strain rate and temperature. The relationship of them is formulated as the following equation [37, 38]:

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

(1)
where \( \dot{\varepsilon} \) is the strain rate (s\(^{-1}\)), \( A \) and \( \alpha \) are the materials constants, \( \sigma \) is the true stress (MPa), \( n \) is the materials stress index, \( Q \) is the activation energy of hot deformation (kJ mol\(^{-1}\)), \( R \) is the universal gas constant, and \( T \) is the absolute temperature (K).

The effects of strain rate and temperature on the flow behavior of materials can also be formulated by Zener–Hollomon parameter \( Z \) in the following equation:

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

where \( Z \) is the temperature compensation strain rate factor during hot deformation.

The flow stress can be written as a function of \( Z \) parameter according to equations (1) and (2), and it is shown in equation (3):

\[
\sigma = \frac{1}{\alpha} \ln \left\{ \frac{Z^{n+1}}{A} + \left[ \frac{Z^{2n+1}}{A} + 1 \right]^{1/2} \right\}
\]

A higher strain rate caused an increase for Zener–Hollomon parameter (equation (2)) and resulted in a higher flow stress (equation (3)). For a metal deformed at a constant strain rate, a higher temperature decreased Zener–Hollomon parameter (equation (2)) and resulted in a lower flow stress (equation (3)).

An appropriate constitutive equation for transient stress has been proposed to describe the relationship between flow stress and true strain (equation (4)) [39].

\[
\frac{\partial \sigma_r}{\partial \varepsilon} = \frac{\mu(T)}{\theta} \left[ 1 - \left( \frac{\sigma_r - \sigma_y(T, \varepsilon)}{\sigma_p(T, \varepsilon) - \sigma_y(T, \varepsilon)} \right)^2 \right] \\
\times \left[ \frac{\sigma_p(T, \varepsilon) - \sigma_y(T, \varepsilon)}{\sigma_r - \sigma_y(T, \varepsilon)} \right]
\]

Where \( \sigma_r \) is the transient stress, \( \theta \) is a material constant, \( \sigma_p(T, \varepsilon) \) and \( \sigma_y(T, \varepsilon) \) are the peak stress and yield stress under a certain deformation temperature and strain rate, \( \mu(T) \) is the shear modulus as a function of temperature.

The critical strain decreases with increased peak stress under a constant temperature and strain rate (equation (4)). The peak stress of HM-D was the highest, resulting in the lowest critical strain for DRX. \( \mu(T) \), \( \sigma_p(T, \varepsilon) \) and \( \sigma_y(T, \varepsilon) \) are related to temperature and strain rate. They descend with increased temperature and decreased strain rate. Therefore, the critical strain of high manganese steels reduced with increased temperature and decreased strain rate.

### 4. Conclusions

In this paper, the flow behavior of four high manganese steels (Fe–Mn24–Cr0.21, Fe–Mn24–Cr1.53, Fe–Mn24–Cr3.78 and Fe–Mn24–Cr5.44) was investigated by isothermal compression tests. The effects of temperature, strain rate and chromium content in steels were discussed. The following conclusions were drawn.

The flow stress of tested steels raised with decreased temperature and increased strain rate. A polynomial trend of flow stress against the increase of chromium content was observed. The flow stress reduced when the chromium content increased from 0.21 wt.% to 1.53 wt.%, and it began to ascend with the continuous increase of chromium content. Fe–Mn24–Cr1.53 steel had the lowest flow stress. Chromium content had a stronger influence on the flow stress at low temperatures, and this effect gradually reduced with the increase of temperature. The change of temperature and strain rate led to a much larger variation of flow stress than that of chromium content.

DRX might occur during compression and it was first observed at 800 °C with a strain rate of 0.001 s\(^{-1}\). For all experimental steels, lower strain rates and higher temperatures were beneficial to the occurrence of DRX. At a constant temperature, a lower strain rate gave a smaller true strain required for DRX. Among the four steels, the true strain required for DRX of Fe–Mn24–Cr1.53 steel was the largest at constant temperature and strain rate. It indicated that 1.53 wt.% chromium in steels delayed the occurrence of DRX at tested chromium contents range.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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