Experimental study on the microstructure evolution of 55SiMnMo

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Abstract. Isothermal compressive experiments on 55SiMnMo steel were carried out with the Gleeble 3500 hot-simulation machine. High temperature flow stress-strain curves were measured over the deformation temperature range of 950 to 1050℃ and a strain rate from 0.01 to 10 s⁻¹. Experimental results revealed that the peak stress decreases with increasing deformation temperature and decreasing strain rate. In addition, when the deformation temperature T ≥ 1000℃ and the strain rate ̇ε ≤ 0.1 s⁻¹, the dynamic recrystallization of 55SiMnMo steel occurs. The stress and strain constitutive models and austenite recrystallization model were constructed to form the foundation for studying the forming process of drill rods.

1. Introduction

Drill steel is a kind of tool steel that is often used in the mining industry to produce drill rods, which are connected to rock drills and drill bits. Usually, drill rods have a hexagonal outer cross section that transfers torque from the rock drill in addition to a hollow center that allows high-pressure water to pass through and wash away rock powder. During operation, the rods are subjected to impact loads that cause considerable alternating stresses in the metal. In addition, the rods are subject to corrosion due to the water flowing through the hollow center. Therefore, it is necessary to construct rods with high-quality surface metals and accurate geometrical dimensions.

The drill rod is a performance component that transfers impact energy. In modern impact drilling, a drill rod ordinarily functions under fatigue load; therefore, the performance requirements for drilling steel should take into consideration the stress state of steel under fatigue loading, and in addition, a wet drill should also have good resistance to water corrosion. Furthermore, drill rods are most likely to fail due to fatigue fractures. If the requirements are not correctly implemented, then the drill experiences a fatigue-induced crack; then, it undergoes the fatigue arc zone development process, and finally, the final fracture occurs. The maximum stress that is borne by drill rods is the superposition of axial tensile stress and bending stress. Therefore, the requirements for drill steel include high purity, lower notch sensitivity, and fatigue resistance. In addition, the effectiveness of the drill steel production process and brazing process also should be considered. In a heat treatment, the drill rod is a

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long rod with a great slenderness ratio. Moreover, if the whole drill rod needs to undergo a quenching heat treatment, the equipment is complex, and deflection is inevitable. Furthermore, there are more than fifty types of drilling steel grades. Most carbon tool steel has 0.702% to 1% carbon content, such as Z708 in Sweden and LWS2 in Germany, and bearing steel and alloy structural steel with Ni, Cr, and Mo—such as 95CrMo and 30CrNi3Mo—are also used in drilling steel.

Drilling steel has been extensively researched. For example, Belusov reported the manufacturing experience with hollow drilling steel at various metallurgical plants. The U7 carbon steel billet was employed with a square cross section, with a hole through the center with an EI94 austenite steel core [1]. Furthermore, Larkin developed a technique to manufacture drilling rods by using high-frequency current in the final heat treatment [2]. Postonogov designed a pass system to roll the hexagon drilling steel, which is an oval -- edging oval -- special leader pass -- open finishing process [3]. Moreover, Petrov analyzed force and torque and determined that drilling rod breakdown is not caused by stability loss but is instead caused by the bending deformation of its free end that occurs as a result of deviation of the drill bit from the set direction due to unevenness in the rock [4]. Song studied the stress wave theory and strength design principle as well as discussed the dynamic responses of the fatigue strength of different rod steels under a typical technological process [5]. Finally, Xing acquired the fatigue test parameters of the tapering connection drilling rod through analyzing the combination of stress and strain wave [6].

Understanding material flow behavior in hot deformation by modeling is important for the analysis and optimization of metal-forming processes [7, 8]. In this paper, the hot compression test and the plastic finite element method were used to investigate the microstructure evolution of 55SiMnMo steel in the hot deformation process.

2. Experimental procedure

2.1. Preparation of test specimen

55SiMnMo was designed based on an expected microstructure and based upon certain limited resources in China [9]. (There is a lack of Ni and Cr resources in China.) The chemical composition and the material properties of the 55SiMnMo steel are shown in tables 1 and 2, respectively. The drilling steel production process is a major factor in determining the overall quality and performance. Therefore, a study of the microstructure evolution process of 55SiMnMo steel has both important theoretical and practical significance [10].

Table 1. Chemical composition of 55SiMnMo.

| Grade | C    | Si    | Mn   | Mo   | S    | P    | Cu   |
|-------|------|-------|------|------|------|------|------|
| ZK55SiMnMo | 0.50-0.60 | 1.10-1.40 | 0.60-0.90 | 0.40-0.55 | <0.030 | <0.030 | <0.025 |

Table 2. Material properties of 55SiMnMo.

| Property                                | Value                             |
|-----------------------------------------|-----------------------------------|
| Modulus of elasticity E/Pa              | 2.0×10¹¹                          |
| Poisson's ratio                         | 0.3                               |
| Density kg/m³                          | 7.85×10³                          |
| Yield limits MPa                        | 634                               |
| Coefficient of thermal expansion K      | 1.1×10⁻³                          |
| Specific heat capacity J/(kg×K)         | 452                               |
| Heat conduction coefficient W/(m²×K)   | 48                                |

The 55SiMnMo steel was studied through hot compression tests that were conducted by the Gleeble 3500 thermal simulation-testing machine in order to simulate the austenite evolution process of specimen compression. The results were measured at different temperatures so as to determine deformation rates under various conditions and to obtain true stress data.

A wire-cutting machine obtained Φ6×9mm pieces of H22 drilling steel, and the specimen surfaces were polished with alcohol and a wipe.

In the isothermal compression experiment, the sample's friction surface is the main factor that affects the test precision. Theoretically speaking, the flow stress could only accurately reflect the real situation of plastic deformation when the following conditions were met: (1) when the compressed
samples did not have a central bulge and (2) when their axial strain and transverse strain were equal. Therefore, the sample surface friction had to be reduced in order to guarantee the accuracy of the compression test. For the test, a tantalum chip of a 0.1 thickness was placed between the plug and the specimen, and the tantalum chip was isolated and lubricated so as to reduce friction. In addition, deformation prevented oxidation.

2.2. Hot compression test

Figure 1 shows the simulation process. First, the specimens were heated to 1150°C at a rate of 10°C/s. After the maximum temperature was achieved, the temperature was maintained for 3 min in order to obtain a uniform austenite. Next, the specimens were cooled to 1050°C, 1000°C, and 950°C at a rate of 5°C/s so as to eliminate the temperature gradient inside the specimens. Thirdly, they were respectively compressed to 50% with strain rates of 0.1s⁻¹, 1s⁻¹, and 10s⁻¹, with online measuring and recording of the true stress data. Real-time acquisition of the specimen temperature, strain, and stress data was obtained according to the deformation time setting and the appropriate sampling period. Then, the quench heat treatment was performed on 35 specimens, and the sample photos are shown in figure 2. Finally, metallographic specimens were made so as to obtain an average grain size using quantitative metallography.

![Figure 1. Schematic diagram of simulation process.](image1)

![Figure 2. Deformation specimens.](image2)

3. Results and discussion

3.1. Stress-strain curve of hot deformation

High temperature flow stress is characteristic of a basic data of metal plastic processing performance. The research of materials in pressure processing on rheological stress has important academic significance and engineering value. Figure 3 details 55SiMnMo compression tests at different strain rates and deformation temperatures of the true stress-strain curve.

![Figure 3. Hot deformation experimental curves for 55SiMnMo.](image3)
Analysis of the stress-strain curves shows that:

- Peak stress decreases with increasing deformation temperatures and decreasing strain rate.
- The curves can be classified as one of two types: dynamic recrystallization and dynamic recovery. In figure 3, those classified as dynamic recrystallization are stress-strain curves 0.1s\(^{-1}\), 0.01s\(^{-1}\) at 1000°C and 1s\(^{-1}\), 0.1s\(^{-1}\) at 1050°C. The dynamic recovery stress curve is shown as a strain curve. Initially, the flow stress increased rapidly; however, when hardening and dynamic recovery reached the equilibrium state, the increase began to level off, and the stress remained close to a constant value.
- When the deformation temperature was greater than or equal to 1000°C and the strain rate was less than or equal to 1/s, 55SiMnMo experienced dynamic recrystallization.
- The thermal simulation machine collected the experimental data. Each curve in the deformation area has a sampling point between 280 and 350. When the strain rate was larger than 0.1/s, the flow stress curves exhibited white noise. Matlab software was used to eliminate noise and obtain peak stress and peak strain in different deformations.

3.2. The flow stress constitutive equation

In addition to the metallurgical factors of the material itself, flow stress also depends on the temperature, deformation, and strain rate. The constitutive equation was built to describe the relationship between the flow stress and other influences by physical simulation and numerical modeling. In the flow stress constitutive equations, equation (1) is suitable for high temperatures and low strain rate conditions, and the process is controlled by diffusion. On the other hand, equation (2) is suitable for low temperatures and high strain rate conditions, and the process is controlled by slip.

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

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

where T is the thermodynamic temperature; Q is the activation energy; R is the gas constant, 8.314 J/(K·mol); and A, n, B, β, C, α, and m are all material constants.

\[
\beta = m n
\]

Peak strain (\(\varepsilon_p\)) constitutive equation:

\[
\varepsilon_p = 4.362 \times 10^{-4} d_0^{0.3} \varepsilon^{0.1131} \exp\left(\frac{54283}{RT}\right)
\]

We got the parameters using above medals by experimental data and show as table 3.

| A   | n  | Q   | R   | B      | β     | α   | m   | C       |
|-----|----|-----|-----|--------|-------|-----|-----|---------|
| 314.0 | 6.43 | 314219.8 | 8.314 | 9.417e12 | 0.0396 | 0.00616 | 5.22 | 2.55e15 |

3.3. Recrystallization model

In deformation conditions, the deformation temperature was 1000°C, and the strain rate was 0.1s\(^{-1}\). As can be seen in figures 4(a)-4(f), six different strains were tested, ranging from 0 to 0.693. Figure 4 shows the core photomicrographs. The true strain of every specimen was calculated by using formula (5):
\[ \varepsilon = \ln \frac{h}{h_0} \]

where \( h \) is the height (mm) of the specimen after deformation, and \( h_0 \) is the height (mm) of the specimen before deformation.

Figure 4. Grain size at different strains (1000°C, 0.1 s\(^{-1}\)).

To determine the austenite grain size, saturated picric acid and a small amount of Seagull brand shampoo were used as the etchant. The specimens were placed into an HHS-112 electric heated water bath whose temperature ranged from 50 to 60°C, and then, they were immersed in the etchant for 5 to 7 minutes. Afterwards, the surfaces were wiped and dried. Finally, the Austenite grain boundaries were observed using an optical microscope, as are shown in figure 4.

In figure 4(a), the specimen strain is 0. This specimen was heated to 1150°C at a rate of 10°C/s and then kept at this temperature for 3 min. It was subsequently cooled to 1000°C at 5°C/s, maintained at this temperature for 1 min, and then quenched. This specimen's initial grains were in a non-deformation condition. The subsequent specimens underwent the same heating process as this specimen.

In figure 4(b), the specimen strain is 0.324. Its final height was 6.51 mm. The figure shows that there are some small dynamic recrystallization grains in large crystal grain boundaries. Recrystallization primarily occurred in the original location of the austenite grain boundaries. The dynamic recrystallization grain size was small (<10 μm), whereas the grain size of those with no recrystallization was still large.

In figure 4(c), the strain of the specimen is 0.481. This specimen was also deformed by a strain rate of 0.1 s\(^{-1}\), and its final height was 5.54 mm. The figure shows a fine recrystallized grain size and large grains with incomplete grain boundaries. The increase in deformation caused the initial large grains to rupture.

From figures 4(c)-4(f), the specimen strains increased, and dynamic recrystallization continued to occur and accumulate with increasing strain. At the largest tested strain (0.693), the grain size was significantly uniform and refined.

We measured the dynamic recrystallization percentage (Xd) and the average austenite grain size (d) of the specimens, which were deformed by the same temperature but at a different strain rate and
strain.

Figure 5. Curve of Xd.

Figure 6. Crain size complied with strain.

Figure 5 graphs the change in the dynamic recrystallization percentage (Xd) complied with the strain; the faint line represents the specimens that were deformed by the 0.01 s\(^{-1}\) strain rate, and the dark, solid line represents the specimens that were deformed by the 0.1 s\(^{-1}\) strain rate. This figure shows that: 1) after reaching critical, the dynamic recrystallization percentage accumulated as the strain increased; 2) when the strain reached 0.7, the dynamic recrystallization percentage increased to 100%; and 3) in the same strain condition, when the strain rate was small, the recrystallized percentage was large.

Figure 6 shows the change in grain size complied with strain. Again, the faint line represents specimens deformed by a 0.01 s\(^{-1}\) strain rate, and the dark, solid line represents specimens deformed by a 0.1 s\(^{-1}\) strain rate. The figure shows that the dynamic recrystallization size (d) is smaller when the strain rate is larger. Therefore, within the scope of dynamic recrystallization, improving the strain rate increases grain refinement.

Using linear regression calculation, both the dynamic recrystallization mathematical model and the dynamic recrystallization grain size model can be obtained:

\[
X_d = 1 - \exp\left[-0.693 \left(\frac{\varepsilon - 0.83 \varepsilon_p}{\varepsilon_{0.5}}\right)^{3.15}\right]
\]  

(6)

\[
\varepsilon_{0.5} = 0.037d_0^{0.2}\varepsilon_0^{0.058}\exp\left(\frac{1.2 \times 10^5}{RT}\right)
\]  

(7)

\[
d = 1.301\varepsilon^{0.61}\varepsilon_0^{-0.14}\exp\left(1.2 \times 10^5 / RT\right)
\]  

(8)

where Xd is the dynamic recrystallization percentage, \(\varepsilon_{0.5}\) is the strain when Xd is at 50%, and d is dynamic recrystallization size.

4. Conclusions

Studies on hot deformation behavior and critical strains for dynamic recrystallization are important in controlling the metal-forming processes and for improving production quality. This paper studied the hot deformation behavior and microstructure evolution of 55SiMnMo steel, which is a bainitic carbon alloy steel used for drilling rods.

The stress-strain curves of the 55SiMnMo steel in a wide range of temperatures and strain rates were measured by hot isothermal compression tests. The experimental results reveal that the peak stress decreases with increasing deformation temperature and decreasing strain rate. Moreover, the dynamic recrystallization of 55SiMnMo steel occurs when the strain \(\dot{\varepsilon} = 0.01 \text{s}^{-1}\), or when \(\dot{\varepsilon} = 0.1 \text{s}^{-1}\) and
The deformation temperature $T \geq 1000^\circ\text{C}$.

The constitutive equation was built to describe the relationship between the flow stress and temperature ($T$), activation energy ($Q$), gas constant ($R$), and material constants by physical simulation and numerical modeling.

Under the deformation condition of $T=1000^\circ\text{C}$, $\dot{\varepsilon} = 0.1 \text{s}^{-1}$, and strain from 0 to 0.7, the dynamic recrystallization percentage ($X_d$) and the average austenite grain size ($d$) of the specimens were measured by metallurgical tests. Figure 6 shows that some small dynamic recrystallization grains first appear in large crystal grain boundaries. When the strain of the specimen was 0.693, the grain size was significantly uniform and refined. Using linear regression calculation, the dynamic recrystallization mathematical model and the dynamic recrystallization grain size model were obtained.

The model’s correctness was tested and validated by combining the microstructure model with the finite element method.

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