Investigation on creep law of QT600 ductile iron based on cellular automata

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Abstract. The steady state creep rates of QT600 ductile iron under various temperature are obtained by high temperature creep experiments. And the cellular automata model of creep microstructure evolution of QT600 ductile iron was established based on quantitative analysis of the microstructure. The results of the model are in good agreement with the results of the validation experiments. It’s shown that the cellular automata model is feasible and with high precision to predict the creep law of QT600 ductile iron. The results can provide some technical references for the safety analysis of QT600 ductile iron.

1. Introduction
Pearlitic ductile iron is widely used in engine crankshaft and machine spindle because of its good mechanical properties, wear resistance, shock absorption and other comprehensive properties. Such parts will creep inevitably during operation. It is of great practical significance to investigate the microstructure evolution law of ductile iron under creep.

Cellular automata (CA) method uses simple rules to express general regularities and is widely used in the fields of material microstructure evolution simulation. For example, cellular automata can be used to simulate the grain evolution during casting crystallization [1-3], dynamic recovery and recrystallization during rolling [4-6], grain growth law in welding fusion zone [7-9], and so on. Hydrogen diffusion in both grains and grain boundaries in X70 steel was modelled using Cellular Automaton technique combined with the finite difference method [10]. An innovative technique to calculate the elastic stress distribution in a 3D porous graphite microstructures under uniaxial or biaxial tension has been developed that uses Cellular Automata to understand the effects of porosity on component strength and its relation to small specimen data [11]. [12] proposed a multi-scale three-dimensional Cellular Automata fracture model of radiolytically oxidised nuclear graphite. The simulation results are in good agreements with the experimental results, and the simulation efficiency is high. However, the application of cellular automata method simulating microstructure evolution of metallic materials under high temperature creep conditions is rarely reported in literatures.

In this paper, the creep properties parameters and microstructure evolution laws of QT600 ductile iron are obtained by high temperature creep experiments. Based on these, the cellular automata model of creep microstructure evolution of QT600 ductile iron was established. The results can provide some technical references for the safety analysis of QT600 ductile iron.
2. Materials and experiments
The material used in this paper is ductile iron QT600. QT600 is a pearlitic ductile iron with good mechanical properties, wear resistance, shock absorption and other comprehensive properties. Its properties can be changed through various heat treatment processes such as quenching and tempering. The chemical composition and mechanical property parameters at room temperature of QT600 are shown in table 1 and table 2, respectively.

| Table 1. Composition of QT600 (m%) |
|---|---|---|---|---|---|
| Fe | C  | Si  | Mn | S  | P  |
| Bal | 3.9 | 2.4 | 0.7 | 0.035 | 0.094 |

| Table 2. Mechanical properties of QT600 under room temperature |
|---|---|---|---|---|
| Material | Tensile Strength | Yield Strength | Elongation | Brinell hardness |
| QT600 | 600 MPa | 370 MPa | 3 % | 170~270 HBW |
| Matrix microstructure | F + P |

In this paper, the high temperature creep test of QT600 are conducted by using the RPL50-type high temperature electronic creep-fatigue testing machine produced by Changchun Research Institute for Testing Machines. The accuracy grade of the test machine is 0.5, the maximum loading capacity is 50 kN, and the measurement error is ±0.5% of the indicated values. The temperature range of high-temperature atmosphere furnace is 300 °C ~ 1100 °C, and the measurement error is within ±2°C. This test machine can be subjected to creep tests, relaxation tests, as well as complex tests such as draw-compression fatigue, low cycle fatigue and creep-fatigue.

The specimen of high temperature creep should meet the requirements of standard GB/T 2039-2012 [13]. According to the design characteristics of the testing machine, each specimen should be subjected preload 0.5 kN at the right beginning of testing. The actual load of each specimen is subjected by slope mode, and the loading rate is 8.5 kN/min.

The loading conditions of these QT600 specimens are sorted into six group, 350°C, 400°C, 425°C, 450°C, 475°C, 500°C (stress of each specimen is 200 MPa). There are five standard specimens for each loading condition.

3. Experiments Results
The creep curves of QT600 specimens under various loading conditions are shown in figure 1. The original metallographic microstructure of QT600 at room temperature is shown in figure 2.

![Figure 1. Creep curves of QT600 specimens under various temperatures.](image1)

![Figure 2. The original metallographic microstructure of QT600.](image2)
The curves in figure 1 conform to the typical creep law of metal materials. The slope of the second stage of the curve is the steady-state creep rate of the material under a specific operation condition. As it can be seen from the figure, with the increase of temperature, the steady-state creep rate in the second stage increases significantly, that is, the creep curve is steeper. The second stage creep rates of QT600 sample under various loading conditions are shown in table 3.

### Table 3. Steady-state creep rates of QT600 under various loading conditions

| Temperature (℃) | 350 | 400 | 425 | 450 | 475 | 500 |
|-----------------|-----|-----|-----|-----|-----|-----|
| Creep rate (%)/h| 0.001257 | 0.019295 | 0.07642 | 0.48211 | 2.08715 | 9.40116 |

4. Creep microstructure evolution and its cellular automata model

4.1. Microstructure of QT600 after high temperature creep

The metallographic microstructures of QT600 after various creep conditions have been obtained which are shown in figure 3. All the scales label in figure 3 are 50 nm.

![Metallographic microstructures of QT600 after various creep conditions.](image-url)

**Figure 3.** Metallographic microstructures of QT600 after various creep conditions.
It’s shown that, under certain stress, the average equivalent grain side length of QT600 and the average equivalent diameter of graphite in QT600 both increase with the increase of creep temperature.

4.2. Cellular automata model

Quantitative metallography was used to quantitatively measure the QT600 microstructures in figure 3, and the results are shown in table 4.

| Temperature[℃] | 350 | 400 | 425 | 450 | 475 | 500 |
|----------------|-----|-----|-----|-----|-----|-----|
| Average equivalent grain side length [μm] | 34.26 | 38.43 | 41 | 44.2 | 46.68 | 50.2 |
| Average equivalent diameter of graphite [μm] | 9.8 | 10.48 | 11.2 | 12.44 | 13.4 | 14.387 |

The high-temperature creep microstructure evolution model of QT600, shown in figure 4, can be established based on these characteristic parameters.

In figure 5, the high-temperature creep microstructure evolution model of QT600 is expressed by Cellular automata method. According to the Ostwald ripening mechanism, the trigeminal grain boundary of the material tends to be a stable state of 120° [14]. Therefore, the regular hexagon is adopted to express the QT600 grain.
Figure 5. Cellular automata model of QT600 high temperature creep microstructure evolution.
5. Analysis and discussion

5.1. Model validation
The verification of the cellular automata model of QT600 high temperature creep microstructure evolution established in this paper is as follows. The loading condition, 375 ℃ and 200 MPa, was selected, and the prediction results based on the cellular automata model in this paper is shown in figure 6. At the same time, under this loading condition, a group of creep specimens were actually conducted to observe and quantitatively determine the metallographic microstructure, as shown in figure 7 and table 5.

| Table 5. Comparison between the predicted values and the experimental results |
|------------------|------------------|------------------|
|                  | Predicted values [μm] | Experimental results [μm] | Error [%] |
| Average equivalent grain side length | 36.5              | 36.47             | 0.08      |
| Average equivalent diameter of graphite | 10                | 10.13             | 1.28      |

It can be seen that the prediction results by using the cellular automata model established in this paper are in good agreement with the experimental results. The results show that the cellular automata model of QT600 high temperature creep microstructure evolution is feasible and with high precision to predict the creep law of QT600 ductile iron.

5.2. Further Study
In this paper, the cellular automata model of QT600 high temperature creep microstructure evolution was established under 200 MPa stress and within a limited temperature range, it can only cover a limited interval of service conditions. However, the idea is feasible. In future, more actual experimental under wider range of service conditions will be carried out. Hence, the established cellular automata model of QT600 high temperature creep microstructure evolution will be modified and improved, and its accuracy will also be improved.

6. Conclusion
In this paper, the steady state creep rates of QT600 ductile iron under various temperature are obtained by high temperature creep experiments. And the cellular automata model of creep microstructure evolution of QT600 ductile iron was established based on quantitative analysis of the microstructure. The results of the cellular automata model are in good agreement with the results of the validation experiments. It’s shown that the cellular automata model is feasible and with high precision to predict...
the creep law of QT600 ductile iron. The results can provide some technical references for the safety analysis of QT600 ductile iron.

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