Experiment research on the transformation plasticity by tensile/compressive stress and transformation kinetics during the martensitic transformation of 30Cr2Ni4MoV steel

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Abstract
The martensitic transformation plasticity and martensitic transformation kinetics in 30Cr2Ni4MoV steel were studied under different tensile/compressive stress conditions using the Gleeble-3500 thermal simulation machine. Elastic strain, thermal strain and transformation strain were separated out from the total strain, and the transformation strain under different loads was finally obtained. The transformation plasticity coefficient K in the Greenwood-Johnson’s mechanism, the coefficients α and Ms in the Koistinen-Marburg equation and the applied stress were particularly studied. The results provide the necessary coefficients for the numerical simulation during quenching process of the 30Cr2Ni4MoV steel.

1. Introduction
Low-pressure rotor is a key component in large nuclear power plant. It is subjected to a large load and high speed due to its special working environment. Therefore, it needs strict requirements for the hardness, strength, residual stress and internal microstructure of the material [1, 2].

In order to make low-pressure rotor of 30Cr2Ni4MoV steel exhibit excellent comprehensive performance, heat treatment is generally used as the last performance control process. Due to the large size of the large low-pressure rotor, the component is prone to serious distortion during the quenching process, making the component difficult or even impossible to assemble. Thus in order to master the deformation principle of 30Cr2Ni4MoV steel during quenching, it is necessary to study the effects of tensile and compressive stress on the transformation kinetics and transformation plasticity during martensitic transformation.

Martensite transformation is non-diffusion type which can be characterized by Koistinen-Marburger equation [3]:

$$f = 1 - e^{-(\alpha M_S - T)}$$

(1)

where f is the volume fraction of martensitic transformation, α, a constant that reflects the rate of transformation of martensitic, Ms, the martensitic start temperature, T is instantaneous temperature during cooling, α and Ms are two important characteristic coefficients of martensitic transformation kinetics, respectively. The martensitic transformation kinetics of steel is mostly considered to be only a function of temperature in the absence of stress. But the equation needs to be corrected when there is stress, that is, the relationship between Ms, coefficient α, and stress must be established. Transformation plasticity is an irreversible strain observed when metallurgical transformation occurs under small external stress that is much lower than the yield stress of the parent phase [4], and is widely studied using the Greenwood-Johnson’s method [5]. From an experimental point of view one can note the significant efforts made by scholars over the past 30 years in order to better know transformation plasticity [6–10]. In recent years, martensitic transformation plasticity and martensitic transformation kinetics has been investigated by many researchers, For example, Denis et al [11, 12] devoted to
show the temperature-stress-phase-change coupling relationship of eutectoid steel during cooling and established a model of the effect of stress on martensitic transformation kinetics. Liu et al [13], Mahnken et al [14] and Luo et al [15] investigated the influence of transformation plasticity and stress on martensitic transformation kinetics of 26Cr2Ni4MoV steel, 40CrMnMoS8-6 steel and 3Cr2Mo steel, respectively.

The test methods for determining the transformation plasticity coefficient mainly includes: single-axis loading, multi-axis loading, four-point bending, and specific resistance method. However, the single axis loading method is the most common application [16–19]. Thus following these researches, the effect of applied stress on the martensitic transformation plasticity and transformation kinetics of 30Cr2Ni4MoV steel is studied by means of uniaxial loading in this paper.

2. The method of transformation plasticity separation

In order to determine the transformation plasticity coefficient, the deformation $\varepsilon^{tp}$ caused by transformation plasticity must be determined at first, but it can not be measured directly. Since only the total deformation $\varepsilon$ of sample can be measured directly, how to separate the $\varepsilon^{tp}$ from the $\varepsilon$ is the key issue in the study of the transformation plasticity.

In the experiment of martensitic transformation (transformation of austenite to martensite during cooling) under uniaxial stress, the deformation of the specimen is the result of the combined effect of martensitic transformation strain, elastic strain, plastic strain, thermal strain and transformation plasticity effect. In order to separate the transformation plasticity from the total strain, it is necessary to analyze the deformation process and then to separate the transformation plasticity.

Under the effect of external stress, the total strain can be expressed as follows

$$\varepsilon = \varepsilon^{el} + \varepsilon^{tr} + \varepsilon^{th} + \varepsilon^{pl} + \varepsilon^{tp}$$

where $\varepsilon$ is the total strain, $\varepsilon^{el}$, the elastic strain, $\varepsilon^{tr}$, the transformation strain, $\varepsilon^{th}$, the thermal strain, $\varepsilon^{pl}$, the classical plastic strain, and $\varepsilon^{tp}$, the transformation plasticity strain. Since the load added in the general test is less than the yield limit of the material at the experimental temperature, the classic plasticity due to equivalent stress variations is not activated. So it is considered that $\varepsilon^{pl} = 0$, and the separation of $\varepsilon^{tp}$ can be achieved.

The total strain during quenching can be divided into the following three parts due to the different loading stresses and cooling time.

(1) No stress is applied and no transformation occur. The period from the beginning of cooling to the period before the phase transition. If no stress is applied, the total strain has only thermal deformation.

$$\varepsilon = \varepsilon^{th}$$

(2) No stress is applied but a phase transition occurs. Martensitic transformation occurs during cooling, but no load is applied. The total strain consists of thermal strain and transformation strain.

$$\varepsilon^{th} = \varepsilon^{tr} + \varepsilon^{th}$$

(3) Stress is applied and transformation occurs. In the process of martensitic transformation, when a small load is applied at the same time (Since the load is less than the elastic limit of the overcooling austenite at this temperature, there is no classical plastic deformation), the total strain is composed of elastic strain, thermal strain, transformation plasticity, and transformation strain.

$$\varepsilon^{tr} = \varepsilon^{el} + \varepsilon^{tr} + \varepsilon^{th} + \varepsilon^{tp}$$

From (5) minus (4) as follows: (别的文献中，怎么写的你再看看)

$$\varepsilon^{tp} = \varepsilon^{tr} - \varepsilon^{th} - \varepsilon^{el}$$

The total radial strain at the applied uniaxial stress (applied stress less than the elastic limit of overcooling austenite at this temperature) can be expressed as:

$$\left( \frac{\Delta d}{d_0} \right)^{tr} = \left( \frac{\Delta d}{d_0} \right)^{el} + \left( \frac{\Delta d}{d_0} \right)^{tr} + \left( \frac{\Delta d}{d_0} \right)^{th} + \left( \frac{\Delta d}{d_0} \right)^{tp}$$

$\Delta d$ is the difference of radius of specimen with load and without load.
The radial strain variable under stress-free action can be expressed as:

\[
\left( \frac{\Delta d}{d_0} \right)^0 = \left( \frac{\Delta d}{d_0} \right)^{tr} + \left( \frac{\Delta d}{d_0} \right)^{th}
\]  

(8)

The radial plastic strain from (7) minus (8) is expressed as follows:

\[
\left( \frac{\Delta d}{d_0} \right)^{pl} = \left( \frac{\Delta d}{d_0} \right)^{tr} - \left( \frac{\Delta d}{d_0} \right)^{0} - \left( \frac{\Delta d}{d_0} \right)^{el}
\]  

(9)

The elastic strain is related to the type and size of the applied stress, which is expressed by Hooke’s law as follows:

\[
\left( \frac{\Delta d}{d_0} \right)^{el} = -\mu \varepsilon = -\frac{0.3\sigma}{E}
\]  

(10)

where \( \sigma \) is applied stress (MPa), \( \mu \), Poisson’s ratio, general metal elastic deformation range \( \mu \approx 0.3 \), plastic deformation range \( \mu \approx 0.5 \), \( E \), the Young’s modulus depending on temperature. It was calculated using JMatPro software in this article.

Therefore, the transformation plasticity strain is within the plasticity strain range and the radial strain caused by it can be expressed as follows:

\[
\left( \frac{\Delta d}{d_0} \right)^{tp} = -\mu \varepsilon^{tp} = -\frac{0.5\varepsilon^{tp}}{2}
\]  

(11)

\[
\varepsilon^{tp} = -2 \left( \frac{\Delta d}{d_0} \right)^{tp}
\]  

(12)

Substituting (9) and (10) into (12) yields the following result:

\[
\varepsilon^{tp} = -2 \left( \frac{\Delta d}{d_0} \right)^{tp} = -2 \left\{ \left[ \left( \frac{\Delta d}{d_0} \right)^{tr} \right] - \left( \frac{\Delta d}{d_0} \right)^{0} \right\}
\]  

(13)

3. Experimental materials and method

3.1. Materials

The material is 30Cr2Ni4MoV steel, which is widely used for low-pressure rotor. Its chemical composition is shown in table 1. The original state of the material is after quenching and tempering treatment.

3.2. Experimental method

Experiments were carried out on a Gleeble-3500 thermal simulation machine. Geometry of the specimen is shown in figure 1. Process is shown in figure 2. Specific operational steps are as follows:

1. Install the specimen and high temperature extenders (when tensile stress is applied) or expanders (when compressive stress is applied), and then vacuum in the specimen chamber.

2. All the specimens were heated at a rate of 5 °C s^-1, and maintained at 870 °C for 10 min.

3. The samples were quenched to a given temperature (400 °C) at a rate of 100 °C s^-1, and then loaded to the required load (0 MPa, ±20 MPa, ±40 MPa, ±60 MPa, and ±80 MPa). The applied loads used in this study are lower than the yield strength of the steel investigated at the loading temperature, and the temperature remained unchanged.

4. Cool the specimen at a rate of 100 °C s^-1 while maintaining the load until it cools to room temperature, and then unload.
4. Results and discussion

Figure 3 shows the transformation expansion curves under different tensile/compressive stress loads. From this figure, one can get that before the austenitic temperature cools to martensitic transformation temperature, the microstructure of the sample is austenite, and its volume shrinks with the decrease in the temperature. The radial change of the specimen at this stage curve of the sample is approximately a linear change. When the temperature drops to the range of martensitic transformation temperature, the expansion curve shows a sharp turn because the volume expansion caused by the martensitic transformation is much larger than the volumetric shrinkage caused by the decrease in the temperature. The no-stress expansion curve has a significant turning point, which is caused by the volume expansion which is in turn caused by the phase transformation. When tensile stress is applied to the specimen, the radial expansion caused by the martensitic transformation and the radial contraction produced by the specimen due to the tensile and compressive stress cancel each other, which makes the radial expansion appear on the expansion curve. The amount of expansion is less than that no stress, and the greater the tensile stress, the smaller the expansion. When the compressive stress is applied to the specimen, on the one hand, the transformation from the austenite to martensitic causes the specimen to expand in the diameter direction. On the other hand, the specimen will be elastically deformed which would cause radial expansion. The two expansions are superimposed so that the expansion curve shows a greater amount of radial expansion than the no-stress expansion, and the greater the compression stress, the greater the expansion. After the martensitic transformation has finished, the volume of martensitic gradually shrinks as the temperature decreases, and the radial change curve of the specimen is also approximately to a straight line.
In addition, from figure 3 one also can get that the tensile stress reduces the temperature of the martensitic transformation, while the compressive stress decreases the temperature of the martensitic transformation, and the greater the stress, the more obvious effect on the temperature martensitic transformation.

4.1. The coefficient of transformation plasticity

According to the calculation results of the radial expansion curve of martensitic transformation (figure 3) and equation (13), the total strain minus elastic strain and transformation plasticity strain of martensitic under different loads were obtained and listed in table 2.

Following previous research [9], $\varepsilon^{\Phi}$ can be represented by

$$\varepsilon^{\Phi} = K f (2 - f) \sigma$$

(14)

Where $K$ is the coefficient of transformation plasticity, and $f$ is the volume fraction of the new phase. Combined (13) with (14), the following formula can be obtained:

$$K = -2 \left\{ \left( \frac{\Delta d}{d_o} \right)^\sigma + \frac{0.5 \sigma}{E(T,f)} \frac{\Delta d}{d_o} \right\} \frac{f (2 - f) \sigma}{f (2 - f) \sigma}$$

(15)

When martensitic transformation completely, that is to say $f = 1$, formula (15) can be transformed as follows.

$$K = -2 \left\{ \left( \frac{\Delta d}{d_o} \right)^\sigma + \frac{0.5 \sigma}{E(T,f)} \frac{\Delta d}{d_o} \right\}$$

(16)
According to the dilatometric curves under different stresses, the $K$ value can be obtained from the formula (16). Then the relationship between it and the equivalent stress can be obtained, and it is fitted in a straight line, as shown in figure 4.

According to the fitting results, one can easily obtain that the martensitic transformation plasticity coefficient $K$ of 30Cr2Ni4MoV steel has a linear relationship with the equivalent stress. That is, it increases with the increase in the applied equivalent stress. The results obtained after fitting the equivalent stress linearly are expressed by

$$K = 6.35 \times 10^{-5} + 4.69 \times 10^{-7} \sigma$$  \hspace{1cm} (17)

Then, take formula (17) into the (14), and the martensitic transformation plasticity model of 30Cr2Ni4MoV steel can then be expressed as follows.

$$\varepsilon^p = (6.35 \times 10^{-5} + 4.69 \times 10^{-7} \sigma)f(2 - f)\sigma$$  \hspace{1cm} (18)

4.2. The effect of stress on martensitic transformation kinetics

The volume fraction of martensitic transformation can be expressed by modifying the Koistinen-Marburger [3] relation as formula (1).

Following the method reported in [20], the amount of martensitic transformation $f$ can be calculated by using the lever rule (show in figure 5) through the expansion curve. The specific calculation method can be found in the literature [20].

![Figure 4. Relationship between transformation plasticity coefficient $K$ and equivalent stress $\sigma$.](image)

![Figure 5. Lever-rule method for calculation of fraction of phase transformation (in cooling).](image)
The relationship between $f$ and $T$ is calculated from the experimental data, and then (1) is simplified to the following formula according to the K-M equation.

$$1 - f = e^{(-\alpha(M_s - T))}$$  \hspace{1cm} (19)

Both sides of the equation (19) take logarithm at the same time.

$$\ln(1 - f) = -\alpha (M_s - T)$$  \hspace{1cm} (20)

Then the values of $\alpha$ and $M_s$ under different stresses can be determined by fitting the ln(1-f) - T line with the least square method as shown in table 3. Figure 6 shows the relationship between the coefficients $\alpha$ and $M_s$ and the stress $\sigma$.

According to the fitting result, the coefficient $\alpha$ is linear with the equivalent stress:

$$\alpha = 0.029 - 7.79 \times 10^{-6} \sigma$$
The relationship between $M_s$ and extra uniaxial stress is as follows.

$$M_s = 364.9 - 0.085\sigma$$

$\sigma$ is positive when tensile stress is used and is negative when compressive stress is used.

5. Conclusion

In this paper, martensitic transformation plasticity and kinetics for a 30Cr2Ni4MoV steel are investigated to understand the influences of transformation plasticity (TP) and transformation kinetics during under different tensile/compressive stress conditions on the austenite-to-martensite phase transformation. Test results enable us to make the following concluding remarks:

1. Martensitic transformation plasticity exists in the quenching process of large-scale components of 30Cr2Ni4MoV steel, and its transformation plasticity parameter $K$ and the applied uniaxial equivalent stress $\sigma$ can be linearly fitted as follows.

$$K = 6.35 \times 10^{-5} + 4.69 \times 10^{-7}\sigma$$

2. The relationship between the martensitic transformation kinetic parameter $\alpha$ and the applied uniaxial equivalent stress $\sigma$ in 30Cr2Ni4MoV steel is as follows.

$$\alpha = 0.029 - 7.79 \times 10^{-6}\sigma$$

3. The $M_s$ of 30Cr2Ni4MoV steel is proportional to the uniaxial stress $\sigma$, and its linear relationship is as follows.

$$M_s = 364.9 - 0.085\sigma$$

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