For the short-term creep behavior to be evaluated and the creep mechanism of P91 heat-resistant steels at low stresses and high temperatures to be clarified, stress-change testing was conducted with a “helicoidal-spring creep test” demonstrating a high strain resolution. The creep deformation consists of the primary creep stage, whereas no secondary creep stage was observed. Blackburn’s law was suggested to be the best choice for a short-term-creep-behavior description because it provides a good representation of an experimental creep curve. An anelastic backflow at a low stress was confirmed, following a high reduction in the stress. The absolute value of the instantaneous strain for a load increase was equal to the value for a load decrease and the creep of the P91 steels at low stresses might have been controlled by the viscous glide of dislocations. 

Keywords: P91 heat-resistant steel, creep, anelastic, stress change

At a high strain rate (a high stress) and a high temperature, a sudden-stress-change experiment has been widely utilized for pure metals and solution-strengthened alloys. In contrast, at a low strain rate, especially the ultra-low, lower than $10^{-10}$ s$^{-1}$, it is usually impossible for a conventional tension-creep technique to distinguish the instantaneous plastic strain from the total strain under a sudden stress change, due to the unsatisfactory strain resolution, existing between $10^{-6}$ and $10^{-5}$. As an additional creep technique, the helicoidal-spring creep test based on torsion deformation provides a significantly high strain resolution, even up to $10^{-9}$. Due to this high strain resolution, it is possible for very low instantaneous strains to be measured during a sudden stress change.

In the present study, the instantaneous creep of the P91 ferritic heat-resistant steels was studied during sudden-stress-change experiments using the helicoidal-spring-specimen technique for the creep mechanism under both a low stress and a high temperature.
2 EXPERIMENTAL PART

2.1 Materials

The P91 heat-resistant steel was utilized in this experiment. The chemical components are presented in Table 1.

2.2 Specimen processing

The steel was processed into helicoidal-spring specimens using the method of high-speed wire-electrode cutting machining; the outer and inner diameters of the specimens were 12 mm and 8 mm, respectively. The cross-section of the helicoidal-spring specimens was a rectangle. The side length of the rectangle was 2 mm, as presented in Figure 1.

The helicoidal-spring specimens were annealed at 1313 K for 60 min and consequently tempered at 1033 K for 60 min.

2.3 Test methods

Figure 2 presents the experimental apparatus, which includes an electric furnace with three adjacent heaters, a high-precision optical micrometer, a load, a weight and a system for receiving and processing information. By measuring the helicoidal-spring-specimen pitch change, the creep curves could be obtained. The test-apparatus details were previously reported.14

During the testing, the number of weights was increased or decreased for the instantaneous stress change to be observed. The weight was suspended under a load with a flammable thread. In order for a load to be increased, the load was hooked quickly. For a load to be decreased, the flammable thread was burned.

The test was performed at a temperature of 923 K and a slight oscillation. The specimen was loaded subsequently for five days when the strain rate was down to $10^{-6}$–$10^{-8}$ s$^{-1}$. Also, the stress consequently increased or decreased at various applied levels and the instantaneous strain was measured. The following equations$^{15,16}$ were utilized for calculating the mean surface shear stress, $\tau$, and the surface shear strain, $\gamma$, with the assumption of the pure torsion of the helicoidal-spring specimen:

\[ \tau = \frac{PD}{2L^2b} \]  
\[ \gamma = \frac{2L}{\pi D^2} \Delta \delta \]

where $P$ is the average load, $D$ is the coil diameter (12 mm) and $\Delta \delta$ is the displacement of the mean coil-pitch spacing. In this study, the torsion was the dominant component of deformation, because $D$ was quite higher than $d$ ($D/d > 12$)$^{13}$ and the value of $\delta$ was between 2 mm and 4 mm.$^{18}$ Since the stress and strain in the helicoidal spring had essentially shear components, the former could be transformed into the equivalent tensile quantities with the von Mises equations for the tensile stress $\sigma = \sqrt{3}\tau$ and the tensile strain $\epsilon = \gamma / \sqrt{3}$.

3 RESULTS AND DISCUSSION

Figure 3 demonstrates the creep curves obtained at 923 K and at various stresses: (34.85, 27.75 and 19.35) MPa.

---

Table 1: Chemical components of P91

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Mo</th>
<th>Si</th>
<th>V</th>
<th>C</th>
<th>Nb</th>
<th>Cu</th>
<th>N</th>
<th>P</th>
<th>Ni</th>
<th>Ti</th>
<th>Al</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content (%)</td>
<td>9.50</td>
<td>0.91</td>
<td>0.60</td>
<td>0.20</td>
<td>0.10</td>
<td>0.10</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

---

Figure 1: Helicoidal-spring specimen for the stress-change testing

Figure 2: Experimental apparatus including electric furnace, high-precision optical micrometer, load, weight and information-receiving and processing system
The creep rate which corresponded to the slope of the curves decreased as the duration increased.

**Figure 4** presents the strain rate on a logarithmic plot versus the strain at 923 K and various stresses. The creep deformation of the P91 steels consisted of the primary creep stages where the creep rate decreased along with the strain and no apparent secondary (steady-state) creep stage was observed where the creep rate would not change along with the strain.

The constitutive creep equations expressing the primary stages should be utilized in the experimental creep-curve analysis. The following constitutive creep equations were utilized, being widely accepted as the basic creep equations.\(^{19,20}\)

- **Power law:**
  \[
  \varepsilon = \varepsilon_0 + a t^b
  \]
  (3)

- **Exponential law:**
  \[
  \varepsilon = \varepsilon_0 + a[1 - \exp(-bt)]
  \]
  (4)

- **Logarithmic law:**
  \[
  \varepsilon = \varepsilon_0 + a \ln(1+bt)
  \]
  (5)

Blackburn’s law:
\[
\varepsilon = \varepsilon_0 + ac[1 - \exp(-bt)] + c[1 - \exp(-dt)]
\]
(6)

where \(\varepsilon\) is the strain, \(\varepsilon_0\) is the instantaneous strain on dead weight, \(t\) is the elapsed time and \(a, b, c\) and \(d\) are the parameters characterizing the primary creep region. The \(a, b, c\) and \(d\) values were called the “scaling factors”.\(^{21}\)

**Figure 5** presents representative results of a regression analysis, for the creep at 923 K and 27.75 MPa. The exponential-law and power-law equations did not reproduce the experimental data. Compared to the logarithmic-law equation, the Blackburn equation provided a better representation of the experimental creep curve. Therefore, the short-term creep for the P91 heat-resistant steels at low stresses could be described with the Blackburn equation.

In order for the creep mechanism of the P91 steels at low stresses to be studied, the instantaneous creep behavior was investigated. The specimens were loaded for \(4.3 \times 10^5\) s until the strain reached \(6 \times 10^{-3}\). In this case, the dislocations could be expected to move. The stress increased or decreased at various levels that were consequently applied and the instantaneous strain was measured.
Figure 7 presents instantaneous-elongation and contraction examples upon low changes in the stress of the P91 steels. In the figure, the $\Delta e^-$ was the instantaneous strain under a stress decrease and the $\Delta e^+$ was the instantaneous strain under a stress increase.

The relationship between the stress increment $|\Delta \sigma|$ and the instantaneous strain $|\Delta e|$ is presented in Figure 7. The creep demonstrates a viscous behavior because the absolute values of the instantaneous strain for the load increase were equal to the values for the load decrease.

Two types of creep at low stress exist. One is creep controlled by the diffusion including the lattice diffusion creep (Nabarro-Herring type)\textsuperscript{22} at a high-$T$ and grain boundary diffusion creep (Coble type)\textsuperscript{22} at an intermediate-$T$. The other is creep associated with dislocation movement including free flight motion (climb controlled) and viscous motion (glide controlled)\textsuperscript{23}. When creep is controlled by the diffusion, the creep should be a non-viscous behavior. In this case, the absolute values of the instantaneous strain for a small-load increase should be apparently larger than the values for a small-load decrease. If creep is controlled by free flight motion of dislocation, plastic strain can occur instantaneously when the stress is increased by a small amount. Therefore, creep shows non-viscous behavior. When creep is controlled by the viscous glide of dislocations, instantaneous plastic strain does not occur even if the applied stress is increase suddenly. Thus, creep shows viscous behavior. In this study, the creep demonstrates a viscous behavior, because non instantaneous strain is observed during the stress increase. It means creep may be controlled by the viscous glide of dislocations.

Figure 8 gives an example of the anelastic backflow, observed for a high reduction in the stress during the transient-creep stage. Specifically, the helicoidal spring specimen was loaded at 27.75 MPa and 923 K for 120 h and consequently unloaded all the stress for 120 h. Two different parts of the creep strain existed: the anelastic strain was reversible, which is presented with solid double arrows, whereas the plastic strain was irreversible and it is presented with dashed double arrows. Therefore, the instantaneous strain that occurred under a sudden stress change included both elastic and anelastic components.

4 CONCLUSIONS

The short-term creep behavior in the P91 heat-resistant steels was investigated using instantaneous-stress-change tests. The results were as follows:

1) The creep deformation consisted of the primary creep stages, but no secondary creep stage was observed.
2) The Blackburn equation could be utilized for the creep-curve description because it provided an improved representation of the experimental creep curve.
3) The viscous glide of dislocations might have been the dominant creep mechanism because the creep displayed a viscous behavior.
4) The short-term creep at a low stress displayed an anelastic behavior.

Acknowledgment

This project was supported by the National Natural Science Foundation of China (Grant No. 51605330).

5 REFERENCES

2 K. Maruyama, J. S. Lee, Creep & Fracture in High Temperature Components: Design & Life Assessment Issues, DEStech
13 H. Gikawa, H. Sugawara, Instantaneous plastic strain associated with stress increments during the steady state creep of Al and AI - 5.5 At.