Creep behavior of Grade 91 steel under uniaxial and multiaxial state of stress

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Abstract. Creep rupture behavior of Grade 91 heat-resistant steel used for steam cooler under uniaxial and multiaxial state of stress was investigated. Creep tests were conducted at the temperature of 923K under the stress 125MPa. The notch root radii (r) of doubled circumferentially U-notched specimens were 0.6 and 6 mm. The creep rupture life of Grade 91 steel was found to increase with the increasing of notch acuity ratio. The creep rupture mechanism was investigated based on the SEM fractography analysis.

1. Introduction

In comparison with creep resistant austenitic steels, Grade 91 steels have been considered as superior material due to lower coefficient of thermal expansion and high thermal conductivity [1]. Grade 91 steel contains alloying elements like Nb and V, forming fine and stable carbides and/or carbonitrides, such as M23C6 and MX [2]. It is used for the steam and gas turbines or boiler at elevated temperatures due to the good creep strength.

In the past years, the creep rupture behavior under uniaxial state of stress of Grade 91 steel has been studied by many researchers [3-6]. In practical application, the components may be subjected to multiaxial state of stress due to mode of loading or from sharp changing in geometry which causes local stress concentration. So it’s necessary to investigate the creep deformation behavior of Grade 91 steel under multiaxial state of stress in order to accurately predict the life of such components. Goyal et al. [7] investigated the effect of multiaxial state of stress on creep rupture behavior of 2.25Cr-1Mo steel using two different circumferential U-notches in the uniaxial creep specimen. The results show that the creep rupture life of the material increases in presence of the notch with the consequent decrease in ductility. Goyal et al. [8] investigated the creep rupture life of 9Cr-1Mo steel under multiaxial state of stress at 873K over the net applied stresses in the range of 110-210MPa. The creep rupture life was found to be higher in the presence of notch than that of smooth specimen, which indicates notch strengthening behavior of this steel. Huang et al. [9] studied the effect of multiaxial stress state on creep behavior and stress rupture life of a Ni-based directionally solidified superalloy. Chang et al. [10] studied the notch strengthening effect of P92 steel using both plain and notched specimens at 650°C over a stress range of 120-185MPa. The influence of the multiaxial stress states on creep rupture behavior of P92 steel was investigated by the relationship between the fracture ductility and multiaxiality.

The effects of notch on creep behavior of Grade 91 steel used for steam cooler were investigated in this paper. The multiaxial state of stress at 923K and 125MPa has been studied by the introduction of different notch acuities.
2. Material and experimental
The studied hot rolled Grade 91 steel was obtained in normalized and tempered condition. The chemical composition (wt.%) of the Grade 91 steel is given in Table 1. As shown in figure 1, the creep tests specimens were machined from the Grade 91 plate with a diameter of 10mm and gauge length of 100mm. Uniaxial and multiaxial creep tests were conducted at 923K and 125MPa by GWT2504 high temperature creep and stress-rupture testing machines. The doubled circumferentially U-notched specimens having notch root radii (r) of 0.6 and 6 mm and notch throat diameter (d) of 6mm as that of smooth specimens. These notch geometries resulted in notch acuity ratio (d/r) of 1 and 10. The creep experiments refer to GB/T2039-2002 Metallic material-creep and stress-rupture test in tension.

| Element | C    | Mn  | Si  | Ni  | Cr  | Mo  | Cu  | Al  | S   | P    |
|---------|------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Amount (wt.%) | 0.10 | 0.40 | 0.23 | 0.13 | 8.34 | 0.98 | 0.06 | 0.00 | 0.002 | 0.0101 |
| Element | Sn   | V   | Nb  | N   | Ti  | Zr  | Al  | N/A |     |      |
| Amount (wt.%) | 0.005 | 0.229 | 0.079 | 0.044 | 0.002 | 0.001 | 4.9 |     |      |

Figure 1. Diagram of uniaxial and multiaxial creep test specimen.

3. Results and Discussions
Uniaxial and multiaxial creep strain-time curves of Grade 91 steel at 923K and 125MPa are shown in figure 2. It can be seen that the curves of plain specimen and the notched specimen (r=6mm) exhibit typical primary, steady-state and tertiary creep stages. The notched specimen (r=0.6mm) has no obvious tertiary creep stage, which means that the creep rupture mechanism is different from the others. It also can be seen that the creep rupture life was found to increase with the increasing of notch acuity ratio. It is generally known that high ductile materials show notch strengthening behavior when notches are present in the components.

Figure 2. Creep strain-time plots for Grade 91 steel.
The global fractography of plain and notched specimens (d/r=10) conducted at 923K and 125MPa is shown in figure 3. The typical cup and cone type appearance of transgranular ductile fracture of plain specimen is observed as shown in figure 3(a), which means that Grade 91 steel possesses fine plasticity under this test condition. It can be seen from figure 3(b) that the reduction of area decreases dramatically when the notch acuity ratio (d/r) is 10. It implies that the ductility of Grade 91 steel gets worse due to the multiaxial state of stress. Fracture appearance of the creep rupture specimens was found to be dependent on the notch geometry.

Figure 3. Global fracture appearance (a) plain specimen, (b) notch acuity ratio (d/r) =10.

The detailed SEM micrographs of center and root area of notched specimen (d/r=10) are shown in figure 4. It can be seen that more shallow dimples exist at the center (figure 4(a)), while rarely dimples are found at the root of the notched specimens (d/r=10) (figure 4(b)). It implies that the ductile fracture and intergranular brittle fracture co-exist under this test condition during creep. Comparing with the plain specimen, the ductility of Grade 91 steel declines due to the presence of notches.

Figure 4. SEM fractography of notched specimen (d/r=10): (a) center area, (b) root area.

4. Conclusions
Creep rupture behavior of Grade 91 steel under uniaxial and multiaxial stresses at 923K and 125MPa was investigated. Grade 91 steel showed notch strengthening at both notch acuities. Creep rupture life was found to increase with the increasing of notch acuity ratio.

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