Creep rupture behavior of Grade 91 steel under multiaxial state of stress

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Abstract. Creep rupture behavior of Grade 91 heat-resistant martensitic steel under multiaxial state of stress was investigated. Creep tests were conducted at 923K with stress ranging from 125 to 200MPa. The notch root radii (r) of doubled circumferentially U-notched specimens is 0.6 mm. The test results show that the creep rupture life of Grade 91 steel decreases with the increasing of applied stress. The creep rupture behavior was investigated based on the scanning electron microscope and optical microscope analysis.

1. Introduction

Due to lower coefficient of thermal expansion and high thermal conductivity, Grade 91 steels are widely used in the power plants. In the past, some researchers investigated the creep rupture properties of different alloys under multiaxial state of stress.

Goyal et al. \cite{1} studied the effect of multiaxial state of stress on the creep rupture behavior of 2.25Cr-1Mo steel at 873K with stress ranging from 90 to 210Mpa. The results show that the creep rupture life increases with the consequent decrease of creep rupture ductility. Chang et al. \cite{2} conducted both plain and notched creep tests of P92 steel at 923K with stress ranging from 120 to 185Mpa. The results show that the notched specimens have notch strengthening behavior. Goyal et al. \cite{3} studied the creep rupture life of 9Cr-1Mo steel at 873K with stress ranging from 110 to 210Mpa. The results show that the steel indicates notch strengthening phenomenology. Kobayashi et al. \cite{4} investigated the biaxial, triaxial and uniaxial behavior of 304 stainless steel. The results found raised creep void formation in biaxial and triaxial stress states. Nikbin \cite{5} presented a new analytical/empirical approach to predict creep damage under uniaxial/multiaxial state of stress based constraint criterion. Yang et al. \cite{6} developed a finite element model to estimate the damage and multiaxial creep evolution process based on ductility exhaustion model. Alang et al. \cite{7} predicted uniaxial and multiaxial creep rupture and creep cracking rates of P92 steel using constraints/ductility based approach.

In this paper, the behavior of Grade 91 steel under multiaxial state of stress was investigated. The effects of different parameters on the creep rupture properties were analyzed.

2. Material and Experimental

The chemical composition of Grade 91 heat-resistant martensitic steel is shown in Table 1. The size of multiaxial creep test specimen is shown in Fig. 1. The test specimens are machined with a gauge length of 100mm and diameter of 10mm. The notch root radii (r) and notch throat diameter (d) of
doubled circumferentially U-notched specimens are 0.6mm and 6mm, respectively. The notch acuity ratio \((d/r)\) of the multiaxial creep test specimen is 10. The creep experiments refer to GB/T2039-2002 Metallic material-creep and stress-rupture test in tension. The multiaxial creep tests were conducted at 923K with the stress ranging from 125 to 200MPa on the high temperature creep and stress-rupture testing machines.

Table 1. Chemical composition of Grade 91 steel (wt.%).

| Element | C  | Mn | Si | Ni | Cr | Mo | Cu | Al | S  |
|---------|----|----|----|----|----|----|----|----|----|
| Amount  | 0.10 | 0.40 | 0.23 | 0.13 | 8.34 | 0.98 | 0.06 | 0.009 | 0.002 |
| Element | Sn | V  | Nb | N  | Ti | Zr | P  | N/Al |
| Amount  | 0.005 | 0.229 | 0.079 | 0.044 | 0.002 | 0.001 | 0.0101 | 4.9 |

Figure 1. Size of multiaxial creep test specimen.

3. Results and Discussions

3.1. Creep curves
The creep strain-time curves of Grade 91 heat-resistant steel at 923K under the stress ranging from 125 to 200MPa is shown in Fig. 2. It can be seen that the curves of 175MPa and 200MPa exhibit typical primary, steady-state and tertiary creep stages. The curve under 125MPa has no obvious tertiary creep stage. It also can be seen that the creep rupture life was found to increase with the decrease of stress level.

Figure 2. Creep strain-time curves of Grade 91 heat-resistant steel at 923K.

3.2. Fracture location
The specimens after creep rupture test under multiaxial stress are shown in Fig. 3. It can be seen that the fracture location is located in one of the notches. The fracture zones have no obvious plastic deformation phenomenon. It can be inferred that the presence of notch decreases the plastic deformation property of Grade 91 heat-resistant steel.
3.3. SEM analysis
The macroscopic fracture morphologies of Grade 91 heat-resistant steel crept at 923K under stress levels of 125MPa (Fig. 4(a)) and 175MPa (Fig. 4(b)) are shown in Fig. 4. It can be seen that the fracture area reduction is relatively small. Some cavities with different size and depth can be found on the fracture surface.

![Figure 4. Macroscopic fracture morphology.](image)

The central zone fracture morphologies of Grade 91 heat-resistant steel crept at 923K under stress levels of 125MPa (Fig. 5 (a)) and 175MPa (Fig. 5 (b)) are shown in Fig. 5. Compared with the low stress level specimen, the number of relative large cavities is more in the high stress level specimen.

![Figure 5. Fracture morphology of central zone.](image)

3.4. Microstructure evolution analysis
The microscopic morphologies of longitudinal section near the fracture of notched specimen crept at 723K and 200MPa are shown in Fig. 6. It can be seen from Fig. 6(a) that fracture zone has no obvious shrinkage deformation phenomenon. There are more cavities near the fracture surface. The cavity size is about 20μm as shown in Fig. 6(b). As shown in Fig. 6(c), the microstructure is martensite.
4. Conclusion
The creep rupture behavior of Grade 91 heat-resistant steel under multiaxial state of stress has been studied by optical microscope and scanning electron microscope analysis. The results show that the fracture zone has no obvious shrinkage deformation phenomenon. The microstructure of Grade 91 heat-resistant steel is martensite.

References
[1] S. Goyal, K. Laha, C.R. Das, S.P. Selvi. M.D. Mathew, Finite element analysis of uniaxial and multiaxial state of stress on creep rupture behaviour of 2.25Cr-1Mo steel, Mater. Sci. Eng., A. 563 (2013) 68-77.
[2] Y. Chang, H. Xu, Y.Z. Ni, X. Lan, H.Y. Li, Research on representative stress and fracture ductility of P92 steel under multiaxial creep, Eng. Fail. Anal. 59 (2016) 140-150.
[3] S. Goyal, K. Laha, Creep life prediction of 9Cr-1Mo steel under multiaxial state of stress, Mater. Sci. Eng., A. 615 (2014) 348-360.
[4] H. Kobayashi, R. Ohki, T. Itoh, M. Sakane, Multiaxial creep damage and lifetime evaluation under biaxial and triaxial stresses for type 304 stainless steel, Eng. Fract. Mech. 174 (2017) 30-43.
[5] K. Nikbin, A unified multiscale ductility exhaustion based approach to predict uniaxial, multiaxial creep rupture and crack growth, Eng. Fract. Mech. 179 (2017) 240-259.
[6] S.S. Yang, Y.Y. Zheng, X. Ling, Evaluation of multiaxial creep and damage evolution for small punch creep test considering critical-strain criterion, Eng. Fail. Anal. 91 (2018) 99-107.
[7] N.A. Alang, K. Nikbin, An analytical and numerical approach to multiscale ductility constraint based model to predict uniaxial/multiaxial creep rupture and cracking rates, Int. J. Mech. Sci. 135 (2018) 342-352.