

High-temperature creep properties of fine grained heat-affected zone in P92 weldment

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Abstract: The simulated fine grained heat-affected zone (FGHAZ) specimens for P92 welded joints were prepared by heat treatment, then the creep tests were carried out at 650 °C under the applied stress of 90–120 MPa to investigate high-temperature creep behavior of FGHAZ. The results show that the creep property of FGHAZ is much inferior to that of the base metal, which exhibits the much higher steady creep rate and shorter time to creep fracture. The power law equation can describe the steady creep rate dependence on applied stress, indicating that the stress exponent n of FGHAZ is distinguished between two regions with $n=15.1$ at high stresses (more than 100 MPa) and $n=8.64$ at lower stresses. Based on Monkman-Grant equation, the relationship between the secondary creep rate and time to rupture is obtained to evaluate the creep life of FGHAZ with the applied stress above 100 MPa.

Key words: resistant heat steel; welding; fine grained heat-affected zone(FGHAZ); creep

1 Introduction

In order to improve the thermal efficiency of power plants and reduce CO₂ emissions, several types of advanced 9%–12% Cr martensitic heat steels strengthened by W have developed, because they have the advantages of low thermal expansion, high thermal conductivity, good steam corrosion resistance, and excellent creep resistance. 9Cr-0.5Mo-1.8W-VNb (ASME P92) and 11Cr-0.4Mo-2W-CuVNb (ASME P122) steels have been used as structural materials for boiler components of ultra-supercritical (USC) power plants operating at 600 °C and 25 MPa[1].

For these advanced high Cr steels with high creep strength achieved by alloy modification, creep cracking often occurs in the fine grained heat-affected zone(FGHAZ) of weld joints, which is named type IV cracking, leading to decrease of the creep life of weldment at higher temperatures[2–3]. It has been shown that the constraint effects introduced into the weld joints owing to the creep properties deterioration of FGHAZ, have a significant effect on the type IV cracking and the rupture life[4–5]. Finite element method(FEM)analysis of the stress-strain distribution in

weld joint specimens during creep was carried out to clarify the mechanisms of type IV cracking and predict the rupture life of joints[6–7]. The creep properties of the FGHAZ used in the FEM analyses for weldjoint should be investigated and obtained from creep tests. The creep properties and material constants for the HAZs of P122 steel have been reported in previous published work[7–8], however, that for P92 has not been known to date.

In this work, FGHAZ specimens for P92 were simulated by heat treatment, then they were exposed to creep tests at 650 °C to investigate the creep properties, including the creep curves of FGHAZ and the base metal, and the relationships between the secondary creep rate and the applied stress as well as time to rupture for FGHAZ were obtained.

2 Experimental

The material used in this work was P92 steel in pipe form with wall thickness of 71 mm and outer diameter of 325 mm. The chemical composition of this steel was 0.12%C, 0.43%Mn, 0.21%Si, 8.84%Cr, 0.50%Mo, 1.67%W, 0.21%V, 0.067%Nb, 0.042%N, 0.003 3%B, 0.014%P and 0.004%S (mass fraction).

Microstructure of the FGHAZ can be simulated either by heat treatments in a furnace or by employing a weld simulator. Heat treatments were employed in this work, and the schematic of the thermal cycles employed was shown in Fig.1. Furnace heating had the advantage that the whole of the specimen could be heated to the same temperature and hence the microstructure was uniform throughout the specimen. Although the heating rate that could be achieved was lower than that in an actual weld thermal cycle, it was found that there was little difference in microstructure and creep properties of the simulated FGHAZ obtained by this two simulation methods for P122 steel[9]. Peak temperature for simulation in the work was 930 °C. The material was heated rapidly in a furnace to a temperature corresponding to the peak temperature to which it was heated during welding, and then were cooled quickly. Finally, the simulated FGHAZ specimens were subjected to the post weld heat treatment (PWHT) at 755 °C for 5 h.

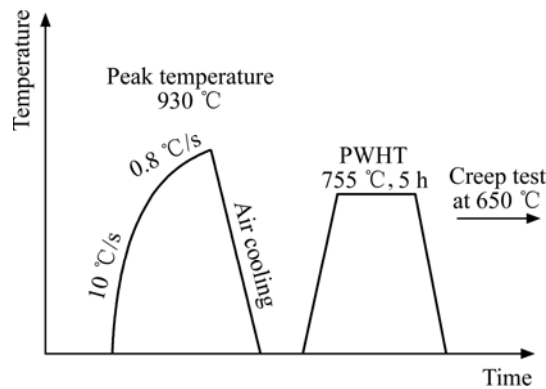


Fig.1 Conditions of heat treatment for simulated FGHAZ specimens

Specimens for creep tests were worked to the geometry as shown in Fig.2, with a gauge length of 100 mm and diameter of 10 mm. Constant load creep tests were performed at 650 °C under stress ranging from 90 to 120 MPa. Sample elongation was measured using high precision extensometer and continuously recorded. The creep tests of base metal specimens were also performed under the same conditions for comparison.

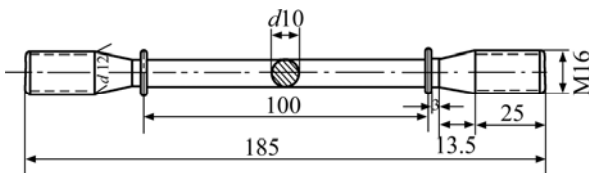


Fig.2 Dimensions of creep test specimen (Unit: mm)

3 Results and discussion

3.1 Creep curves

Some examples of creep curves measured in the

present experiments are shown in Fig.3. The creep curves of FGHAZ obtained consist of the primary (or transient) creep range where the creep rate decreases with increasing time, the steady rate stage (or rather a minimum creep rate range) where the creep rate is constant, and the tertiary (or acceleration) creep region where the creep rate increases with increasing time. For saving costs and time, the creep tests of base metal (BM) specimens were interrupted after reaching the secondary stage, and hence creep curves of BM observed in Fig.3 consists of only two stages without acceleration creep region. From creep curves of FGHAZ as shown in Fig.3, it can be seen that the duration of the secondary range becomes much longer as the applied stress decreases. By comparing the creep curves of FGHAZ and base metal, it can also be seen that the former exhibits much higher secondary creep rate, which promotes the onset of acceleration creep region, resulting in the shorter creep rupture time. The evidence presented above suggests that the creep properties of FGHAZ are inferior to that of the base metal for P92. The similar degradation behaviours of creep properties in FGHAZ were also observed in P122 and P91 steel[8, 10]. Some previous papers reported that the creep properties degradation of FGHAZ

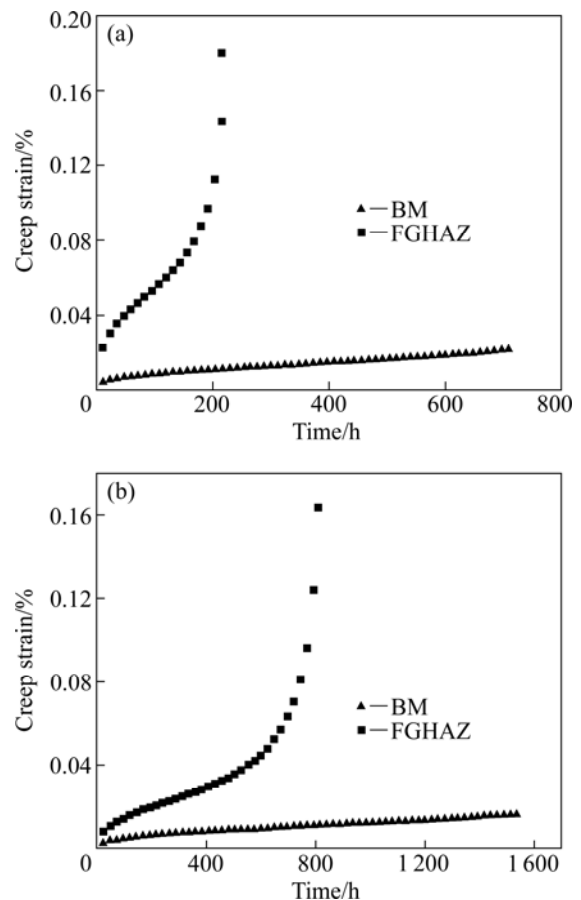


Fig.3 Creep curves of simulated FGHAZ and base metal specimens at 650 °C under different stresses: (a) 110 MPa; (b) 100 MPa

for advanced 9%–12%Cr steel is due to microstructure factors such as grain refinement[11], coarsening and agglomeration of $M_{23}C_6$ [8], and the shape changing of MX from thin platy to sphere[12].

3.2 Steady state creep rates

The secondary creep rate dependence on the applied stress can be described by power laws, such as the well known Norton relationship,

$$\dot{\epsilon}_m = A\sigma^n \quad (1)$$

where $\dot{\epsilon}_m$ is the steady creep rate, σ is the applied stress, A is a constant, n is the stress exponent. The creep rate versus applied σ for FGHAZ and base metal is shown in Fig.4. It is observed that in FGHAZ the logarithmic plots of creep rate as a function of stress consist of two linear segments, separating the data into low stress and high stress regions with the breakpoints at a stress of 100 MPa. For $\sigma > 100$ MPa, the stress exponent n is found to be 15.1. On the other hand, for $\sigma < 100$ MPa, n is reduced to 8.64. The creep data published by FOLDYNA et al exhibit the similar phenomenon in the stress exponent n taking place at approximately 120 MPa for P92 base metal[13]. In this work, the applied stress in creep tests for base metal is not above 120 MPa, thus the two regions can not be observed in base metal. The transition in stress dependence indicates a change in creep mechanism from a higher value of n at higher stresses to a lower one at lower stresses. This may be explained that in the high stress region dislocations can overcome particles of secondary phases by Orowan mechanism, while in the low stress domain dislocations should climb over particles[14].

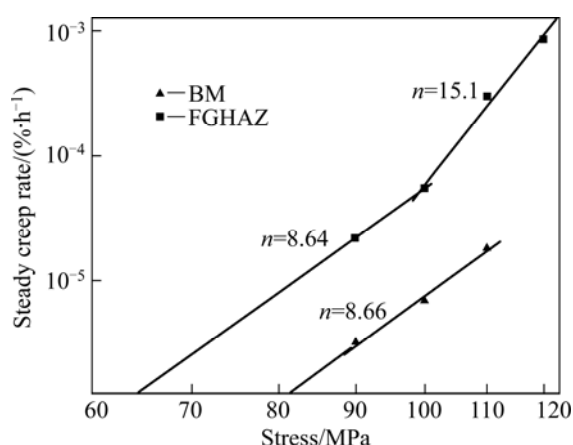


Fig.4 Steady creep rate as function of applied stress for FGHAZ and BM at 650

Fig.4 also shows that the stress exponent n of FGHAZ is approximately equal to that of base metal in lower stress region. It can be found that the stress applied for FGHAZ is much lower than that for base metal at the

same steady creep rate. The difference of creep resistance stress between the FGHAZ and base metal at 650 °C can be calculated from Fig.4, which is about 21 MPa. The strengthening effect due to interaction between dislocation and particles can be expressed by threshold stress concept σ_{th} [15], thus the deterioration in creep rupture strength of FGHAZ is considered as the reduction of σ_{th} , which is associated with the precipitate evolution in FGHAZ during welding and PWHT (e.g. the coarsening of $M_{23}C_6$ and the shape changing of MX) [8,12].

The creep properties constants obtained from the results of creep tests for both FGHAZ and BM of P92 steel are listed in Table 1.

Table 1 Creep properties constants for both FGHAZ and BM at 650

Material	High stress		Low stress	
	$A/(\text{MPa}^{-n}\cdot\text{h}^{-1})$	n	$A/(\text{MPa}^{-n}\cdot\text{h}^{-1})$	n
FGHAZ	3.98×10^{-35}	15.1	3.16×10^{-22}	8.64
BM	—	16[13]	3.98×10^{-23}	8.66

3.3 Creep fracture properties

To describe the creep fracture behaviour of FGHAZ, the well known Monkman-Grant (M-G) equation was used

$$(\dot{\epsilon}_m)^\beta t_f = C \quad (2)$$

where $\dot{\epsilon}_m$ is the steady creep rate, t_f is time to rupture, β ($0 < \beta < 1$) and C are material constants. Fig.5 gives the relationship between $\dot{\epsilon}_m$ and t_f for FGHAZ when the applied stress is in lower stress region. The M-G equation for FGHAZ can be approximately expressed as:

$$(\dot{\epsilon}_m)^{0.825} t_f = 0.254 \quad (3)$$

The creep life of FGHAZ can be evaluated by using Eqs.(1) and (3) when the applied stress is varied at 650

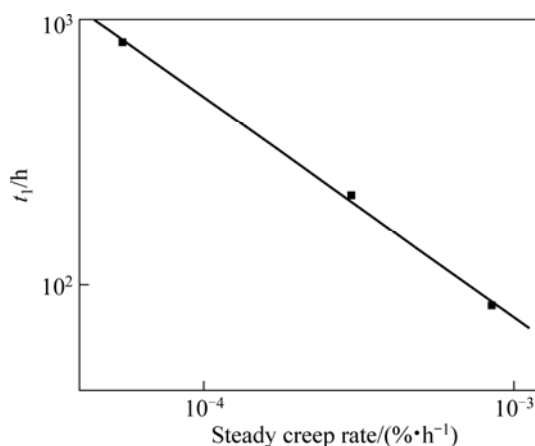


Fig.5 Dependence of time to fracture (t_f) on steady creep rate for FGHAZ

. To guarantee reliable results, extrapolation based on Eq.(3) is valid only at stress levels no more than 100 MPa, otherwise, it will lead to the considerable overestimation of the long term creep resistance. The reason is due to the creep mechanism change dependence on stress occurred in FGHAZ as mentioned above. Additional creep tests with longer rupture time will be performed to obtain the M-G equation at lower stress levels for FGHAZ in the following work.

4 Conclusions

1) The fine grained heat-affected zone (FGHAZ) exhibits much higher secondary creep rate and shorter creep rupture time compared with base metal. The results indicate that the remarkable creep properties degradation occurs in the FGHAZ.

2) Norton relationship can be used to describe the secondary creep rate depending on the applied stress for FGHAZ. When $\sigma > 100$ MPa, the stress exponent n is found to be 15.1, and for $\sigma < 100$ MPa, n is reduced to 8.64.

3) Based on Monkman-Grant equation, relationship between the secondary creep rate and the time to rupture is obtained to evaluate the creep life of the FGHAZ when applied stress is higher than 100 MPa.

References

- [1] MASUYAMA E. History of power plants and progress in heat resistant steels [J]. ISIJ, 2001, 41: 612–625.
- [2] MASUYAMA F, MATSUI M, KOMAI N. Creep rupture behaviour of advanced 9–12Cr% steel weldment [J]. Key Eng Mater, 2000, 171–174: 99–108.
- [3] SHINOZAKI K, LI De-jun, KUROKI H, HARADA H, OHISHI K, SATO T. Observation of type IV cracking in weld joints of high chromium ferritic heat resistant steels [J]. Sci and Technol of Welding and Joining, 2003, 8: 289–295.
- [4] LI De-jun, SHINOZAKI K, KUROKI H, HARADA H, OHISHI K. Analysis of factors affecting type IV cracking in weld joints of high chromium ferritic heat resistant steels [J]. Sci and Technol of Welding and Joining, 2003, 8: 296–302.
- [5] ALBERT S K, MATSUI M, WATANABE T, HONGO H, KUBO K, TABUCHI M. Variation in the type IV cracking behaviour of a high Cr steel weld with post weld heat treatment [J]. Int J Pressure Vessels Piping, 2003, 80: 405–413.
- [6] LI D, SHINOZAKI K, KUROKI H. Stress—strain analysis of creep deterioration in heat affected weld zone in high Cr ferritic heat resistant steel [J]. Mater Sci and Technol, 2003, 19: 1253–1260.
- [7] WATANABE T, TABUCHI M, YAMAZAKI M, HONGO H, TANABE T. Creep damage evaluation of 9Cr-1Mo-V-Nb steel welded joints showing type IV fracture [J]. Int J Pressure Vessels Piping, 2006, 83: 63–71.
- [8] ALBERT S K, MATSUI M, HONGO H, WATANABE T, KUBO K, TABUCHI M. Creep rupture properties of HAZs of a high Cr ferritic steel simulated by a weld simulator [J]. Int J Pressure Vessels Piping, 2004, 81: 221–234.
- [9] ALBERT S K, MATSUI M, WATANABE T, HONGO H, KUBO K, TABUCHI M. Microstructural investigations on type IV cracking in a high Cr steel [J]. ISIJ, 2002, 42: 1497–1504.
- [10] OTOGURO Y, MATSUBARA M, ITOH I, NAKAZAWA T. Creep rupture strength of heat affected zone for 9Cr ferritic heat resisting steels [J]. Nuclear Eng Design, 2000, 196: 51–61.
- [11] ABDEL-AZIM M E, NASRELDIN A M, ZIES G, KLENK A. Microstructural instability of a welded joint in P91 steel during creep at 600 [J]. Mater Sci and Technol, 2005, 21: 779–790.
- [12] TSUCHIDA Y, OKAMOTO K, TOKUNAGA Y. Study of creep rupture strength in heat affected zone of 9Cr-1Mo-Nb-V-N steel by welding thermal cycle simulation [J]. Welding Int, 1996, 10: 27–33.
- [13] FOLDYNA V, PURMENSÝ J, KUBON Z. Development of advanced chromium steels with respect to microstructure and structural stability [J]. ISIJ, 2001, 41: S81–S85.
- [14] BROWN L M, HAM R K. Strengthening methods in crystals [M]. London: Applied Sci Publ, 1971.
- [15] SPIGARELLI S, CERRI E, BIANCHI P, EVANGELISTA E. Interpretation of creep behaviour of a 9Cr-Mo-Nb-V-N (T91) steel using threshold stress concept [J]. Mater Sci and Technol, 1999, 15: 1433–1440.

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