1. Introduction

High Cr ferritic heat-resisting steel is often regarded as the most potential material for ultra-supercritical (USC) fossil-fired power. ASME P122 (11Cr–2W–0.4Mo–CuVNb in wt%) and ASME P92 (9Cr–1.8W–0.5Mo–NbV in wt%) are typical of these steels and have been used as structural materials for boiler components at 873 K and 25 MPa due to their good material properties, especially high creep rupture strength, the most important property for high pressure and temperature applications.1–7) Further, these two steels are being tried for applications at higher temperatures.

However, creep crack often occurs in the FGHAZ of welded joints of high Cr ferritic heat-resisting steels. Internal pressure creep tests were carried out to investigate the features of Type IV cracking in pipe components and single pass welded joint creep tests were to investigate the accurate relationship between Type IV cracking and welding thermal cycle. Auger Electron Spectroscopy (AES) point analysis showed that many precipitates existed in creep voids. Based on this observation, it was suggested that large precipitates were preferential sites for void nucleation. Finally, simulations using a welded joint model and a matrix/precipitate model were performed to investigate creep void occurrence.
P122 and ASME P92 were tempered martensite.

2.2. Internal Pressure Creep Tests

Internal pressure creep tests were used to investigate the effect of applied stress on creep crack in welded joints. Figure 1 shows dimensions of creep test specimen for ASME P92. The tube was machined for the U groove and was welded by pulse TIG in 15 passes, then post weld heat treatment (PWHT) was conducted at 1018 K for 4.5 h. Table 2 shows the welding condition for the internal pressure creep specimen. Internal pressure creep tests were performed at 923 K. Apparent stress in the wall of the tubes was controlled to be 108, 137, 167 MPa for ASME P122 specimens and 116, 137, 167 MPa for ASME P92 specimens by changing steam pressure according to the following equation.

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\sigma = P \left( \frac{D}{2t} - 0.5 \right) \]

Where \( \sigma \) is apparent stress in the middle of wall, \( P \) is steam pressure, \( D \) is outer diameter and \( t \) is wall thickness. Since internal pressure creep specimens were welded by multi-pass weld, it was difficult to investigate the accurate relationship between welding thermal cycle and creep property degradation in the HAZ using only this test. Therefore single pass welded joint creep tests were carried out.

2.3. Single Pass Welded Joint Creep Tests

Figure 2 shows dimensions of single pass welded creep specimen. Firstly, a U groove was machined on the outer surface of an ASME P122 tube of diameter 350 mm and thickness 53 mm. A filler wire was fed by hot wire TIG and welding was performed with single pass to obtain a simple welding thermal cycle, which was measured during welding. Table 3 shows the welding condition for the single pass welded creep specimen. After weld, the tube was heated to 1018 K and kept for 4.5 h as PWHT. Finally, a series of specimens were cut from the tube and machined to single pass weld specimens. The creep tests were carried out at temperature of 923 K and applied stresses of 90 and 120 MPa. The creep tests of several specimens were interrupted at desired times but the other specimens were crept till fracture.

The reduction of area of the single pass welded specimen was measured by laser scanning micrometer. The analysis of creep void distribution was based on the microstructural observation. Elements of precipitates in creep voids were analyzed by AES.

3. Experimental Results

3.1. Determination of Type IV Cracking

Applied stresses of internal pressure specimens of ASME P92 were 116, 137 and 167 MPa and their rupture times were 1188.2, 561.7 and 68.5 h respectively. Figures 3(a) and 3(b) show ASME P92 specimens ruptured at 167 and 116 MPa. It can be found that the specimen ruptured at 167 MPa exhibited typical ductile failure with large diameter expansion and a crack in which the mouth largely opened. However, the specimen fractured at 116 MPa exhibited typical brittle failure with small deformation. At
low applied stress the crack occurred in the FGHAZ and was identified as Type IV cracking, but at high stress the crack occurred in the base metal and was identified as normal creep crack.

Internal pressure creep tests could not clarify the accurate relationship between welding thermal cycle and degradation of creep property in HAZ. Therefore, single pass welded specimen creep tests were performed. Figure 4 shows the specimen ruptured at 90 MPa after 2 763.2 h. It was found that the crack occurred in the FGHAZ and the fractured surface was smooth and parallel to the weld fusion line. This creep fracture could be clearly identified as Type IV cracking.

Figure 5 shows the change of specimen diameter along longitudinal direction. It was noticed that the diameter in the HAZ was slightly small compared to the diameter of the base metal and weld metal, indicating that the reduction of area was larger in the HAZ. A careful observation showed that the position in which the diameter was smallest corresponded to the FGHAZ.

3.2. Observation of Type IV Cracking

3.2.1. Creep Void Distribution

The specimen of the single pass welded joint of ASME P122 was observed using an optical microscope. Figure 6 shows the microstructure of the weldment. It can be seen that in the HAZ region whose distance was more than 1.5 mm away from the fusion boundary, many voids occurred and some of them coalesced, and micro fissures began to form. This region belonged to FGHAZ. However, few creep voids occurred in the HAZ region near the fusion boundary, which belonged to CGHAZ.

3.2.2. Comparison between Void Distribution and Peak Weld Temperature

Creep void distribution and peak weld temperature in the welded joint were measured as a function of the distance away from the fusion boundary and the results are shown in Fig. 7. According to the result reported by J. Hald, the equilibrium temperatures of $\text{Ac}_1$ and $\text{Ac}_3$ of ASME P122 were 1 078 and 1 177 K respectively. However, the heating rate during welding is so fast that its effect should be taken into account. It was considered that the real temperature of $\alpha \rightarrow \gamma$ transformation was about 80–140 K higher than that of equilibrium transformation due to the high heating rate in welding. The microstructure of single pass welded joint specimen was carefully observed using an optical micro-

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Fig. 3. Ruptured specimens of internal pressure test of ASME P92 at 923 K.

Fig. 4. Ruptured single pass welded specimen of ASME P122 (923 K, 90 MPa, tr: 2763.2 h).

Fig. 5. Reduction in specimen diameter along longitudinal direction.

Fig. 6. Microstructure of single pass welded joint.

Fig. 7. Distribution comparison between creep voids and peak weld temperature.
scope. According to the observation from the base metal to the HAZ continuously, the microstructure change was found in the region in which $\alpha \rightarrow \gamma$ transformation began to appear. This region was regarded as the apparent $\text{Ac}_1$ (app. $\text{Ac}_1$). On the other hand, when the same observation from the CGHAZ to base metal was done, the grain size decreased and a region whose grain boundaries were difficult to distinguish was found. This region was regarded as the apparent $\text{Ac}_3$ (app. $\text{Ac}_3$). Based on the microstructure observation and peak weld temperature distribution, the transformation temperatures of $\text{Ac}_1$ and $\text{Ac}_3$ during the welding were determined to be about app. $\text{Ac}_1$ (1160 K) and app. $\text{Ac}_3$ (1320 K). The region of peak weld temperature between app. $\text{Ac}_1$ and app. $\text{Ac}_3$ is intercritical zone and is simply regarded as a part of FGHAZ in this study.

From Fig. 7, it can be seen that the largest number of creep voids occurred in the region of peak weld temperature between app. $\text{Ac}_1$ and app. $\text{Ac}_3$. The fracture position of the specimens was 2.8–2.9 mm away from the fusion boundary and was just located in this region. It is also obvious that the region of peak temperature between app. $\text{Ac}_1$ and app. $\text{Ac}_3$ showed the maximum degradation of material property during creep and finally led to Type IV cracking.

3.3. Dependence of Creep Deterioration on Creep Time

3.3.1. Diameter Reduction during Creep

As shown in Fig. 5, the diameter of the FGHAZ in the single pass welded creep specimen was small compared to the other regions. The creep tests of two specimens were interrupted after 200 and 308.2 h and the other two specimens were creeped until creep fracture. For a ruptured specimen, there are two HAZs on the both sides of the WM but the creep fracture occurred in one of the HAZs. The diameter change in the HAZ without creep fracture was analyzed. Figure 8 shows the maximum diameter reduction as a function of creep time for the specimens. It can be found that the reduction in diameter increased with creep time and it seems to be accelerated after a creep time of about 300 h.

3.3.2. Creep Void Distribution during Creep

Figure 9 shows creep void distributions in the side without fracture for all specimens. It can be seen that for the specimens creeped for 200 and 308.2 h (Figs. 9(a) and 9(b)), few creep voids occurred and there was no apparent peak number of creep voids. After creep testing for 407.1 and 686 h, many creep voids occurred in the region of peak weld temperature between app. $\text{Ac}_1$ and app. $\text{Ac}_3$, but the increase of void number in the base metal and CGHAZ was not obvious (Figs. 9(c) and 9(d)). It is apparent that the time from 308.2 to 688 h was the important stage for creep void occurrence in the FGHAZ.

3.3.3. Precipitation Behaviour during Creep

Figure 10 shows the quantitative analysis of the number

Fig. 8. The maximum reduction in diameter during the creep.

Fig. 9. Creep void distributions after different creep times at 923 K and 120 MPa for ASME P122.
and area fraction of precipitates in creep void region and in base metal during creep. It can be seen that after welding the area fraction of precipitates was lower in the creep void region than in the base metal, but the number of precipitates was almost the same for both regions. Further, for these two regions, the area fraction of precipitates increased with creep time due to coarsening but the number of precipitates decreased. It can be seen that after 686 h the creep void region had the much lower precipitate number but the same precipitate area fraction than the base metal. This phenomenon indicated that the coarsening process of precipitates was more in the creep void region than in the base metal. Based on this result, it can be considered that the coarsening of precipitates in HAZ is an important factor that leads to the degradation of creep strength in HAZ.

4. Discussion

4.1. Two Factors Affecting Creep Void Occurrence

4.1.1. Relationship between Creep Stage and Void Occurrence

Figure 11 shows the variation of creep rate and number of creep voids with testing time. It should be noted that the variation of creep rate in this figure is for the specimen ruptured after 686 h but the number of creep voids is for all the specimens. The creep process of the specimen ruptured after 686 h can be apparently divided into three stages, the primary stage of decelerating strain rate from 0 to 200 h, the secondary stage of steady strain rate from 200 to 500 h, and the tertiary stage of accelerating deformation from 500 to 686 h. Further, it can be seen the number of creep voids was low for the specimens interrupted at 200 and 308.2 h but high for the specimens ruptured at 407.1 and 686 h, the creep void occurrence exhibited an accelerating rate during the creep. Many creep voids occurred in secondary and tertiary stages but few voids occurred in the primary creep stage. However, it should be noted that it is difficult to accurately distinguish the difference of void number for secondary stage and tertiary stage because the creep curves of these specimens were different. Since creep voids can represent the extent of micro damage, it is apparent that the creep damage increased at an accelerating rate during creep.

4.1.2. Relationship between Precipitate and Creep Void

The precipitates in specimens were identified as Laves phase (Fe₂W), M₂₃C₆, MX and so on based on the X-ray analysis for extraction residue of specimens. Figure 12 shows AES analysis for precipitates in a creep void of the single pass welded specimen fractured at 120 MPa after 686 h. It was found that the protruding points of void were precipitates and most of them seemed to be M₂₃C₆ and Laves. The result strongly suggested that precipitates were the nucleation sites of creep voids.

The observation of creep specimen showed that coarsened precipitates in the FGHAZ played an important role in Type IV cracking. Normally coarsened precipitates can cause creep property deterioration by decreasing the effects of solid solution strengthening and precipitation strengthening. In addition, the phenomenon that many large precipitates were observed inside creep voids implied that the precipitates also played an important role as nucleation sites of creep voids.
the creep voids.

Goods et al.\textsuperscript{15} have found that cavities are usually associated with inclusions or second phase particles. A cavity can be induced by particle fracture or by separation of the particle/matrix interface. This behavior was commonly observed in both ferrous and non-ferrous systems. Many of the observations of homogeneous and grain boundary nucleation can be explained by the presence of small, unresolved particles. However, the mechanism of role of precipitate as nucleation site of void is complex. Since hard particle has large influence on the cavity nucleation, it can be thought that if cavity nucleation could be delayed or suppressed, the creep lifetime of structure can be expected to become longer. Therefore it is important for the design of high Cr ferritic steel to investigate the role of large precipitate as nucleation site of creep void.

4.2. Simulation about Void Occurrence in Welded Joint

In order to investigate the occurrence of creep voids in the single pass welded joint from strain/stress viewpoint, the simulation of single pass welded joint was performed. Figure 13 shows the FE model of creep test of single pass welded joint model of Fig. 13 was introduced in this model. It should be pointed out that this is a simple model based on macro material properties and doesn’t include many complex factors, such as diffusion, grain boundary, the material property of interface and so on.

When the applied stress was 100 MPa, the stress distribution in welded joint was calculated and the 3-D stress in the mesh with largest equivalent strain was chosen and introduced into the precipitate-matrix model as an applied stress. The stress condition varied with creep time. Figure 15 shows the contour map of equivalent strain field of precipitate-matrix model after 600 h. The highest magnitude of equivalent strain occurs at the interface in matrix at angle about 45° from the tensile loading direction. Therefore, this equivalent strain is used as a criterion of initiation of creep void in the following discussion.

Figure 16 shows the equivalent strains as a function of creep time with and without precipitate in the FGHAZ matrix. It can be seen that the equivalent strain with precipitate is more than twice of the condition without precipitate. This result indicates that precipitate facilitates void nucleation.

4.3. Simulation of Effect of Precipitate on Void Occurrence

In order to investigate the role of precipitate in the initiation of creep void, FEM simulation of a micro model was performed. This model assumed that the hard precipitate was embedded in a matrix. The matrix represented the FGHAZ, CGHAZ or base metal. The matrix crept but precipitate didn’t. The radius of spherical precipitate was assumed to be 0.2 μm and matrix size was 4×4×4 μm. The Poisson’s ratio and Young’s modulus of precipitate were assumed to be 0.22 and 600 GPa. Further, in order to investigate the effect of stress condition in the welded joint on the micro model, the stress results calculated by the welded joint model of Fig. 13 was introduced in this model. It should be pointed out that this is a simple model based on macro material properties and doesn’t include many complex factors, such as diffusion, grain boundary, the material property of interface and so on.

Table 4. Material properties used in simulation.

|                | Creep properties | Tensile properties |
|----------------|------------------|--------------------|
|                | A (MPa·h\(^{-1}\)) | N | Yield stress (MPa) |
| ASME P122 (923 K) | 3.37×10\(^{-1}\) | 24.0 | 106 | 91 | 0.3 |
| CGHAZ          | 6.97×10\(^{-1}\) | 10.2 | 99  | 135 | 0.3 |
| FGHAZ          | 2.80×10\(^{-1}\) | 9.8  | 77  | 82  | 0.3 |
| BM             | 3.76×10\(^{-1}\) | 15.6 | 103 | 104 | 0.3 |

The causes of Type IV cracking in weldment of high Cr ferritic steel were investigated by creep tests and simulations. The following conclusions can be drawn:

5. Conclusions

The causes of Type IV cracking in weldment of high Cr ferritic steel were investigated by creep tests and simulations. The following conclusions can be drawn:
(1) The degradation of creep strength in FGHAZ was considered to be induced by welding thermal cycle of peak weld temperature between app. Ac1 (1 160 K) and app. Ac3 (1 320 K).

(2) The creep void number and specimen necking increased at an accelerating rate during creep. The largest void number and maximum necking occurred in the FGHAZ.

(3) AES point analysis showed that many precipitates existed in the creep voids. Coarsening of precipitates was more in creep void region than in base metal. It appeared that these large precipitates led to the deterioration of creep property in FGHAZ.

(4) The welded joint model showed that FGHAZ has the highest equivalent strain and largest deformation. There is a good agreement between distribution of equivalent strain and that of creep voids.

(5) The precipitate/matrix model showed that precipitate is easy to induce the initiation of creep void by acting as nucleation site in creep void occurrence. Creep void initiation is easy to occur in the FGHAZ compared with the CGHAZ and base metal.

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