Isothermal, Thermo-Mechanical and Bithermal Fatigue Life of Ni Base Alloy HR6W for Piping in 700°C USC Power Plants

Yasutaka Noguchi, Hirokazu Okada, Hiroyuki Semba, Mitsuru Yoshizawa

Abstract

Three types of high temperature fatigue tests are carried out for HR6W, which is one of the candidate materials for piping in an advanced ultra super critical (A-USC) power boiler operating over 700°C steam condition. The first test is the isothermal fatigue test at 700°C, the second one is the thermo-mechanical fatigue (TMF) test between 100°C and 700°C under in-phase and out-of-phase conditions, the final one is the bithermal fatigue (BTF) test at 100°C and 700°C. The relations between the partitioned inelastic strain range determined by the strain range partitioning method and the life in those tests show good agreement, while the relations between the total strain range and the life show some differences.

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1. Introduction

An A-USC (advanced ultra super-critical) power boiler, which is operated over 700°C steam condition, has been developed to reduce CO₂ emissions. In this temperature range, the strength of conventional ferritic and austenitic steels is insufficient for the use in boiler tubes and pipes. Therefore, Fe-Ni base or Ni base alloys are used when making the A-USC boiler. Since these alloys have higher coefficient of thermal expansion than conventional ferritic steels, it is expected to increase the thermal stress generated in the thick section parts of the boiler. This shows some concern about increasing thermal fatigue damage.
because the boiler is repeatedly started-up and shut-down.

In order to evaluate the fatigue life of the material under thermal cycles, a thermo-mechanical fatigue test is often made. This test is carried out under both temperature and strain controlled conditions and can simulate those cycles in the service loading. However, the thermo-mechanical fatigue test is more complex and difficult than the isothermal fatigue test, which is carried out under a strain controlled condition at a constant temperature. This complexity and difficulty cause that the thermal fatigue life is estimated by the results of the isothermal fatigue test. It is reported that the thermal fatigue life is nearly the same as the isothermal fatigue life at the maximum temperature, if the fracture morphology does not change. [1]

With these points as background, the fatigue properties of Fe-Ni base and Ni base alloys for A-USC boiler have been evaluated by the isothermal fatigue test.[2] However, the thermal fatigue properties of these alloys are not known clearly due to the lack of the test data. In this study, the thermal fatigue properties of Ni base alloy HR6W, which is one of the candidate materials for the piping in the A-USC boiler, are investigated and compared to the isothermal fatigue properties.

2. Experimental

The test material is a pipe made of Ni base alloy HR6W. The outside diameter of the pipe is 355.6mm and the pipe thickness is 37.5mm. Table 1 and Table 2 show the chemical compositions and the mechanical properties of the alloy, respectively. The elongation and the reduction of area measured by tensile tests from room temperature to 750°C are shown in Fig.1. Fatigue test specimen is cylindrical with diameter of 12mm and thickness of 1.45mm. The specimen is cut parallel to the axial direction of the pipe.

Table 1. Chemical compositions of test alloy. (mass%)

| C   | Si  | Mn  | Ni  | Cr  | W   | Ti  | Nb  | Fe  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.08| 0.20| 1.02| 45.0| 23.6| 7.1 | 0.10| 0.21| bal.|

Table 2. Mechanical properties of test alloy.

| Temperature | 0.2% proof stress (MPa) | Tensile strength (MPa) | Elongation (%) | Reduction of area (%) |
|-------------|-------------------------|------------------------|---------------|----------------------|
| R.T.        | 280                     | 670                    | 46            | 64                   |
| 700°C       | 190                     | 440                    | 48            | 52                   |

Fig. 1. Tensile ductility of tested alloy.
In order to evaluate the fatigue properties of HR6W at high temperature, the isothermal fatigue test, the thermo-mechanical fatigue (TMF) test and the bithermal fatigue (BTF) test [3] were carried out. The isothermal fatigue test was carried out under strain controlled condition at 700°C. Strain waveforms were PP (fast-fast), CP (slow-fast) and PC (fast-slow). Fast strain rate and slow strain rate were 1.0%/s and 0.01%/s, respectively. Inelastic strain range, $\Delta e_{in}$ was measured from the stress-strain hysteresis loop at the middle of the fatigue life. In CP and PC test, creep strain generated in a cycle was measured by the rapid load method [4].

The TMF test was carried out under temperature and strain controlled conditions. Maximum and minimum temperatures were 700°C and 100°C, respectively. The heating time from 100°C to 700°C was 85s, the cooling time from 700°C to 250°C and from 250°C to 100°C were 85s and 110s, respectively. The total time per cycle was 300s. The thermal and the strain cycles were applied in both in-phase and out-of-phase conditions. In the in-phase condition, a tensile mechanical strain was applied in the heating period and a compressive one was applied in the cooling period to synchronize the thermal cycle and the strain cycle. Conversely, in the out-of-phase condition, a compressive one was applied in the heating period and a tensile one was applied in the cooling period.

Since the isothermal fatigue test, which needs only a strain control, is simpler than the TMF test, which needs a strain and a temperature control, the thermal fatigue life is often estimated by the results of the isothermal fatigue test at the maximum temperature. However, if a brittle temperature range exists below the maximum temperature, the effect of that can not be considered in the isothermal test. In order to overcome these defects, the BTF test was proposed. [3] In the BTF test, the tensile and compressive halves of the cycle are conducted isothermally at two different temperatures and the specimen is held at zero stress during the heating and cooling periods.

The BTF test was carried out under both temperature and strain controlled conditions. The maximum temperature and minimum temperatures were 700°C and 100°C, respectively. The mechanical strain was imposed only at the maximum and minimum temperatures. The heating and cooling time between 100°C and 700°C was 120s, the holding time at 700°C and 100°C was 30s, the total time per cycle was 300s. Table 3 shows the BTF test conditions. PP and CP test correspond to the in-phase condition in the TMF test, since tensile strain is imposed at the maximum temperature. PC test, in which compressive strain is imposed at the maximum temperature, corresponds to the out-of-phase condition in the TMF test. Creep strain generated in a cycle was measured by the rapid load method in CP and PC test. The maximum and the minimum temperatures in the BTF test were the same as those in the TMF test and the strain rate in the BTF test was the same as that in the isothermal fatigue test.

### 3. Results and discussion

#### 3.1. Fatigue life

| Phase      | Strain waveform | Total strain range, $\Delta e$ (%) | Straining at 100°C | Straining at 700°C |
|------------|-----------------|-----------------------------------|---------------------|---------------------|
|            |                 |                                   | Direction           | Rate                |
|            |                 |                                   |                    | Direction           | Rate                |
| In-phase   | PP              | 0.5, 1.0                          | Compression         | 1.0%/s              | Tension             | 1.0%/s              |
| In-phase   | CP              | 0.5, 1.0                          | Compression         | 1.0%/s              | Tension             | 0.01%/s             |
| Out-of-phase | PC             | 0.5, 1.0                          | Tension             | 1.0%/s              | Compression         | 0.01%/s             |
Comparison between isothermal fatigue test and TMF test

Fig.2(a),(b),(c) show the total strain range, $\Delta e_t$ versus the life, $N_f$ relation, the inelastic strain range, $\Delta e_{in}$ versus the life, $N_f$ relation and the partitioned inelastic strain range, $\Delta e_{ij}$ (ij=pp, cp, pc) versus the life, $N_{ij}$ relation determined by the strain range partitioning method [5], respectively. Partitioning $\Delta e_{in}$ into $\Delta e_{ij}$ was difficult in the TMF test, because the temperature was changed continuously during the test and the rapid loading method could not be used. Therefore, $\Delta e_{ij}$ versus $N_{ij}$ relation in the isothermal fatigue test and $\Delta e_{in}$ versus $N_f$ relation in TMF test were compared in Fig.2(c).

As shown in Fig.2(a), the out-of-phase TMF test and the isothermal PC test, which applied the compressive creep strain to the specimen, were close to life. In contrast, the in-phase TMF test and the isothermal CP test, which applied the tensile creep strain, were significantly different from the life. The life in the in-phase TMF test tended to be shorter than that in the CP test. In Fig.2(b), the plots of the $\Delta e_{in}$ - $N_f$ relation in the TMF test were located at the shorter life side than that in the isothermal fatigue test. On the other hand, in Fig.2(c), $\Delta e_{in}$, $\Delta e_{ij}$ - $N_f$, $N_{ij}$ relation in the isothermal PC and CP test corresponded well to those of the out-of-phase and in-phase TMF test, respectively. This result suggests that the TMF life can be predicted from the isothermal fatigue test by the partitioned inelastic strain range, $\Delta e_{ij}$.

Comparison between isothermal fatigue test and BTF test

Shown in Fig.3 are the $\Delta e_t$ - $N_f$ relation and $\Delta e_{ij}$ (ij=pp, cp, pc) - $N_{ij}$ relations. In both relations, the isothermal fatigue life and the BTF life were equivalent to each other. Generally, $\Delta e_{ij}$ - $N_{ij}$ relation correlates to the ductility of the material. The reason why the life in the isothermal fatigue test, which applied the strain at 700°C, and the BTF test, which applied the strain at 100°C and 700°C, are close is that the ductility of HR6W at 100°C and 700°C are not significantly different, as shown in Fig.1.

Comparison between TMF test and BTF test

Fig.4(a),(b) show the $\Delta e_t$ - $N_f$ relation and the $\Delta e_{in}$, $\Delta e_{ij}$ - $N_f$, $N_{ij}$ relation. The lives in both tests corresponded well, especially the $\Delta e_{in}$, $\Delta e_{ij}$ - $N_f$, $N_{ij}$ relation.

Comparison of inelastic strain range and fatigue life relation in all tests

Fig.5 shows the inelastic strain range, $\Delta e_{in}$, $\Delta e_{ij}$ - life, $N_f$, $N_{ij}$ relation in all tests. Fig.5(a) is the result of the PC test and the out-of-phase test, which applied the compressive creep strain, and Fig.5(b) is the result of the CP test and the in-phase test, which applied the tensile creep strain. The $\Delta e_{in}$, $\Delta e_{ij}$ - $N_f$, $N_{ij}$ relations in both figures correspond well and are approximated by a line in Fig.5.

The $\Delta e_{ij}$ - $N_{ij}$ relations in all tests can not be compared in Fig.5, because it is difficult to partition the

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**Fig. 2.** Comparison of life between isothermal and thermo-mechanical fatigue tests. (a) Total strain range $\Delta e_t$ - life $N_f$ relation, (b) Inelastic strain range $\Delta e_{in}$ - life $N_f$ relation, (c) Inelastic strain range $\Delta e_{ij}$, $\Delta e_{in}$ - life $N_{ij}$, $N_f$ relation.
Fig. 3. Comparison of life between isothermal and bithermal fatigue tests. (a) Total strain range $\Delta \varepsilon$ - life $N_f$ relation, (b) Inelastic strain range $\Delta \varepsilon_i$ - life $N_i$ relation.

Fig. 4. Comparison of life between thermo-mechanical and bithermal fatigue tests. (a) Total strain range $\Delta \varepsilon$ - life $N_f$ relation, (b) Inelastic strain range $\Delta \varepsilon_i$, $\Delta \varepsilon_n$ - life $N_i$, $N_f$ relation.

Fig. 5. Comparison of the inelastic strain range - life relation between isothermal, thermo-mechanical and bithermal fatigue tests. (a) PC and in-phase condition, (b) CP and out-of-phase condition.
inelastic strain, \( \Delta \varepsilon_{ij} \) into \( \Delta \varepsilon_{ij} \) in the TMF test, as mentioned above. However, if the large portion of inelastic strain in the TMF test is creep strain, the relations between \( \Delta \varepsilon_{ij} \) and \( N_{ij} \) in all tests are corresponding. This indicates the possibility to predict the TMF life of HR6W by the \( \Delta \varepsilon_{ij} - N_{ij} \) relation obtained from the isothermal or the BTF test results.

3.2. Fracture morphology

Fig. 6 shows the fatigue cracks observed in the longitudinal section of the specimen. The intergranular fracture mainly occurred in the CP test and the in-phase TMF test, while the transgranular fracture was dominant in the PC test and the out-of-phase TMF test. Thus, the fracture morphology of the test that there was a correlation in the fatigue life was equal. The reason why the difference in the fracture morphology did not appear in the TMF test and the isothermal fatigue test may be that there was no temperature region where the ductility decreases.

4. Conclusion

The isothermal fatigue test, the thermo-mechanical fatigue test and the bithermal fatigue test of Ni base alloy HR6W, which is one of the candidate materials for the piping in the A-USC boiler, were investigated, the results of which were compared to each other. In each test, the relations between the partitioned inelastic strain range determined by the strain range partitioning method and the life showed good agreement, while the relations between the total strain range and the life showed some difference. This indicates the possibility to predict the fatigue life under temperature variation of HR6W, as well as conventional boiler steels, by the isothermal or BTFT test results.

|                  | Isothermal | Thermo-mechanical | Bithermal |
|------------------|------------|-------------------|-----------|
| CP or In-phase   |            |                   |           |
| PC or Out-of-phase|           |                   |           |

Fig. 6. Fatigue crack path observed on the cross section of the tested specimen.

References

[1] A.Nitta, K.Kuwabara, T.Kitamura, Proceedings of the 1983 Tokyo International Gas Turbine Congress, 1983;3:765-772
[2] Y.Noguchi, M.Miyahara, H.Okada, M.Igarashi, K.Ogawa, Proceedings of CREEP8, PVP2007-26471; 2007
[3] G.R.Halford, M.A.McGaw, R.C.Bill, P.D.Fanti, Low Cycle Fatigue, ASTM STP 942, 1988: 625-637
[4] S.S.Manson, G.R.Halford, A.C.Nachtgall, NASA TM X-71737, 1975
[5] S.S.Manson, G.R.Halford, M.H.Hirschberg, Proceedings of Symposium on Design for Elevated Temperature Environment; 1971;12-28