Research Article

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In-phase thermomechanical fatigue studies on P92 steel with different hold time

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Abstract: The effect of hold time with 0, 20, and 40 s on in-phase thermomechanical fatigue (TMF) behavior and life of P92 steel is investigated in this study. TMF tests are carried out under mechanical strain control with strain amplitudes of 0.4, 0.6, and 0.8%, and temperature range of 550–650°C which is closely relevant to the operating condition in power plant. TMF tests are performed in a mechanical strain ratio of $R = -1$ and cycle time of 120 s. The fatigue life variation follows the sequence of $N_f^{0s} < N_f^{20s} < N_f^{40s}$ for the same mechanical strain amplitude. In addition, the influence of hold time on fatigue life decreases with the increasing strain amplitude. A continuous softening can be observed from the cyclic stress response under all test conditions. Fractographic and microstructural tests indicate that the fracture surfaces are characterized by a multi-source cracking initiation and an oxidation phenomenon. Furthermore, a modified Ostergren model is used to predict the fatigue life and achieves a good predicted result.

Keywords: P92 steel, in-phase thermomechanical fatigue, hold time, fatigue life, modified Ostergren model

1 Introduction

In the process of thermal power generation, with the continuous addition of temperature and pressure, a new type of heat-resistant material with high performance is one of the key points to assure the safety and stable working of the unit. In the process of frequent startup and shut-down in power plant, the unit components are subjected to temperature change and mechanical load at the same time, which is a typical (thermomechanical fatigue, TMF) condition. The new martensitic heat-resistant steel P92 is widely used to replace P91 in power station for its better high-temperature properties [1–3]. Instead of using isothermal low cycle fatigue experiments to replace TMF tests, more and more researchers have begun to conduct the TMF test directly, with the development of advanced test technology and equipment.

In recent years, the characterizations of low cycle fatigue performance of P92 steel are discussed in various aspects. Considering the effect of strain amplitude, some studies have shown that P92 steel exhibits obvious cyclic softening characteristics under cyclic loading [4–7]. Effects of various temperatures on the low cycle fatigue behavior of P92 steel have been compared, which reported that the cyclic softening of materials is more obvious, and the crack propagation rate is faster along with the increase of temperature [8]. Meanwhile, issues relevant to creep have been widely reported and interaction between fatigue and creep was adequately studied on fatigue mechanism, fatigue life, and cyclic deformation under various conditions [9–12].

Generally, the study of creep–fatigue interaction of high-temperature materials is achieved by adding hold time in continuous low cycle fatigue tests [13]. Moreover, the addition of tensile hold in low cycle fatigue tests at elevated temperature results in lower fatigue life of the material, which is even less than that with the compressive hold under the same conditions. The results show that the cycle life with the compressive hold and symmetric hold is equivalent to that of the continuous low

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cycle fatigue tests [14–17]. However, some materials are of different results. The fatigue life of both the Rene80 and IN738 super nickel-base alloys increases with the addition of tensile protection [18]. It is also generally known that high-temperature environment or corrosive environment seriously affects fatigue fracture behavior of materials [19,20].

The present paper aims at understanding the influence of hold time varying from 0, 20 and 40 s on in-phase (IP) TMF behavior and life of P92 power station steel with strain amplitudes of 0.4, 0.6, and 0.8%, and temperature range of 550–650°C. In addition, the material behavior under different hold time is compared by fractographic and microstructural tests.

2 Experimental

2.1 Chemical composition and mechanical properties of P92 steel

The investigated material is P92 steel, which is one type of 9–12% Cr steel alloys. Specimens were cut from a pipe, whose dimensions are approximately $\Phi 350 \text{ mm} \times 90 \text{ mm}$. The chemical composition of the material used in this paper and the tensile properties at ambient temperature are shown in Tables 1 and 2, respectively. IP TMF tests are accomplished on cylindrical specimens (6 mm diameter and 20 mm gauge length) and the integrated size of specimen is shown in Figure 1.

2.2 Experimental procedure for TMF

TMF tests are carried out under mechanical strain control with strain amplitudes of 0.4, 0.6, and 0.8%, respectively, and temperature range of 550–650°C. Meanwhile, TMF testing is carried out with hold time of 0, 20, and 40 s for each strain amplitude. TMF tests are performed in mechanical strain ratio of $R = -1$ and the cyclic period is 120 s for the continuous strain cycling tests. A TMF test machine (MTS809), which utilizes an induction coil heating, is

Table 2: Mechanical properties of P92 steel at ambient temperature

Temperature (°C)	R_{eL} (MPa)	R_m (MPa)	A (%)	E (MPa)
Ambient temperature	437.00	611.20	25.75	207100.00

R_{eL} : yield strength, R_m : maximum strength, A: ductility in elongation, E: modulus of elasticity.

used to conduct all experiments. Besides, the specimens are cooled by the compressed air. Three types of waveforms are described in Figure 2.

The TMF test procedure is divided into two parts: TMF setup and TMF test. During the TMF setup, three K thermocouples are welded to the sample surface. The intermediate thermocouple is used to control the temperature, and the other two thermocouples are welded at the points which are about 6 mm from middle thermocouple to monitor the temperature deviation and thermal stability. Compared with the temperature values of the middle one, the temperature deviation at upper and lower points is within 2% maximum cyclic temperature. Strains are measured using high-temperature extensometer with a gauge length of 15 mm. The total strain can be measured directly by high-temperature extensometer, and the mechanical strain based on thermal strain compensation can be used to simulate the relation between temperature and time, seen in equation (1).

$$\varepsilon_{\text{mech}}(t) = \varepsilon_{\text{tot}} - \varepsilon_{\text{th}}(T) \quad (1)$$

where $\varepsilon_{\text{mech}}(t)$ is mechanical strain at time of t , ε_{tot} is total strain measured by high temperature extensometer, and $\varepsilon_{\text{th}}(T)$ is thermal strain at temperature of T .

2.3 Criterion of fatigue life

To reduce the inaccuracy of fatigue life for the uncertain fatigue criteria, scholars have obtained different fatigue life criteria for different materials. Shankar et al. [21] reduced the cycles of steady stress by 20% as the fatigue life of P91 steel. Fournier et al. [22] defined the number of cycles corresponding to a 50% reduction in maximum peak stress of the P91 steel during the cycle as the fatigue

Table 1: Chemical composition of P92 steel (wt%)

Element	C	Si	Mn	Cr	W	V	Nb	N	Ni	Mo	Ti
wt%	0.121	0.191	0.418	8.83	1.60	0.195	0.074	0.048	0.339	0.462	0.007

Figure 1: The geometry of specimen used in the test (dimensions in mm).

Figure 2: TMF test waveforms: (a) IP 0 s, (b) IP 20 s, and (c) IP 40 s.

life of various 9–12% Cr steels. Figure 3 shows the typical cyclic softening response curve of P92 steel. The cyclic softening response curve can be obviously divided into

three stages, stage 1 is rapid softening stage, stage 2 is linear softening stage, where peak stress shows a linear change trend with the increase of cycle time, the final stage corresponds to the initiation and expansion of fatigue crack until the specimen fails. To obtain the TMF life of P92 steel as accurately as possible, according to the cyclic deformation characteristics of P92 steel, the fatigue criterion proposed by Marmy and Kruml [23] is adopted in this paper, described in Figure 3.

Figure 3: Definition of fatigue life N_f .

- A dotted black line fits the linear softening stage of the cyclic softening response curve of P92 steel.
- The dotted black line is intersected with the ordinate axis with a cyclic number of $N = 0$, and the cross point is marked as σ .
- A parallel red dotted line is drawn 20% σ away from the black one, the number of cycles at the intersection of the black line and the cycle softening response curve is defined as the TMF life N_f of P92 steel.

Table 3: Summary of TMF experiments results

Specimen number	At mid-life cycle				Fatigue life N_f
	Plastic strain amplitude $\Delta\epsilon_p/2$, %	Maximum tensile stress $\sigma_{\max}$, MPa	Mean stress σ_m , MPa	Stress amplitude $\Delta\sigma/2$, MPa	
IPTMF0.4, 0 s	0.29	120.07	-35.22	155.29	1,112
IPTMF0.4, 20 s	0.31	120.24	-38.43	158.67	1,330
IPTMF0.4, 40 s	0.30	140.59	-38.69	179.28	1,479
IPTMF0.6, 0 s	0.49	144.97	-35.64	180.61	496
IPTMF0.6, 20 s	0.51	156.53	-36.52	193.05	605
IPTMF0.6, 40 s	0.53	153.03	-38.13	191.16	724
IPTMF0.8, 0 s	0.67	171.54	-36.52	208.06	337
IPTMF0.8, 20 s	0.71	148.85	-36.71	185.56	364
IPTMF0.8, 40 s	0.69	175.26	-36.86	212.12	375

IPTMF0.4, 20 s: the TMF test under IP condition with 20 s hold time with a mechanical strain amplitude of 0.4%.

3 Results and discussion

3.1 Results of fatigue life

The summary of TMF test results is presented in Table 3. As shown in Figure 4a, the fatigue life of the IP TMF with different hold time is drawn as a function related to the mechanical strain amplitude. Along with the increasing

mechanical strain amplitude, the fatigue life of all experiments shows significant downward trends. Considering the effect of hold time, the fatigue life increases with the hold time for a same mechanical strain amplitude. However, the influence of hold time decreases with the growth of strain amplitude. With the increase of strain amplitude up to 0.8%, the existence of symmetrical hold time has little effect on the fatigue life. Therefore, the fatigue life variation follows the sequence of $N_f^{0s} < N_f^{20s} < N_f^{40s}$.

Figure 4: Relation between fatigue life and (a) mechanical strain amplitude, (b) plastic strain amplitude, (c) net tensile hysteresis energy, and (d) total deformation energy with different hold time.

In Figure 4b, the relation between plastic strain amplitude and fatigue life is shown. A straight line can be fitted approximately to describe the relation between plastic strain amplitude and fatigue life with different hold time. The fitted straight line with 0 s hold time has lower plastic strain amplitude and shorter fatigue life compared with the other two lines, which can be inferred that there is no linear relation between the plastic strain amplitude and the fatigue life with different hold time. Moreover, as seen in Table 3, the variation of plastic strain amplitude with different hold time is very small for the same strain amplitude, which indicates that there is more than one factor that affects the fatigue life.

The product of plastic strain range and maximum tensile stress is called net tensile hysteresis energy, and the product of plastic strain range and stress range is called total deformation energy. In Figure 4c and d, net tensile hysteresis energy and total deformation energy are used to evaluate the fatigue life of material, and establish a double logarithmic linear relationship with the fatigue life. However, there is no monotonous linear relationship with different hold time at the same mechanical strain amplitude, and higher total deformation energy or net tensile hysteresis energy can sometimes correspond to longer fatigue life. The above results once again prove that the TMF life behavior of P92 steel with different hold time cannot be comprehensively evaluated only by fatigue

alone, among which creep and oxidation are also key factors affecting the fatigue life of material.

3.2 Analysis of cyclic stress response

As presented in Figure 5a, a continuous cyclic softening (maximum stress $\sigma_{\max}$ and mean stress σ_m) is observed under IP tests with different hold time at a mechanical strain amplitude of 0.4%. Under all circumstances, the $\sigma_{\max}$ keeps dropping along with the cyclic life which presents a clear cyclic softening characteristic without hardening phenomenon. Figure 5b explains the relation between stress amplitude and fatigue life, in which the same phenomenon can be found that P92 steel is one type of cyclic softening material [24]. It can also be noted from the cyclic $\sigma_{\max}$ response curve that as the hold time increases, stage 3 of the cycle softening curve appears later, which leads to a longer fatigue life. The compressive mean stress is produced during the process of all IP TMF tests, seen in Table 3 and Figure 5a. As seen in Figure 5c, the same cyclic softening phenomenon is observed under IP tests at different mechanical strain amplitudes with a hold time of 40 s. As the mechanical strain amplitude increases, the $\sigma_{\max}$ increases as an obvious trend and stage 3 of the cycle softening curve appears earlier, which leads

Figure 5: Cyclic response of (a) maximum stress $\sigma_{\max}$ and mean stress σ_m and (b) stress amplitude with different hold time, (c) maximum stress $\sigma_{\max}$ and mean stress σ_m , and (d) stress amplitude with different mechanical strain amplitudes.

to a shorter fatigue life. It can also be observed that the cyclic σ_m response curve at three mechanical strain amplitudes is almost coincidence, which indicates that mechanical strain amplitude has little effect on σ_m at the same temperature range. Figure 5d shows the relation between stress amplitude and fatigue life, in which the same law can be found compared with the $\sigma_{\max}$ cycle response in Figure 5c. In order to describe cyclic response under different hold time, a conception of cyclic softening factor J_ε is raised as [25]:

$$J_\varepsilon = \frac{\Delta\sigma_i - \Delta\sigma/2}{\Delta\sigma_i}, \quad (2)$$

where $\Delta\sigma_i$ is stress amplitude at each cycle and $\Delta\sigma/2$ is stress amplitude at mid-life cycle. The variation of the softening factor with a mechanical strain amplitude of 0.4% is shown in Figure 6a. The variation trend of softening factors is same under different hold time and the difference of softening factor is not significant, which indicates that the cyclic response owns a hold time independent characterization of the cyclic softening behavior. The variation of the softening factor under hold time of 40 s with different strain amplitudes is shown in Figure 6b. As presented in Figure 6b, with the increase of mechanical strain amplitude, its cyclic softening of stage 3 is more notable and the change rate is faster, which leads to a shorter fatigue life.

Figure 7 shows the stress–strain hysteresis loops of the second cycle and the half cycle of fatigue life with a mechanical strain amplitude of 0.4%. It can be noted that the minimum and maximum stress at mid-life cycle is obviously smaller than that at the second cycle, which also suggests that P92 steel is a cyclic softening material. For IP loading, the change of mechanical strain and temperature is the same, and the values reach maximum and minimum at the same time. However, stress and strain are not always kept in sync. As shown in Figure 7a, the tensile stress gets to its extreme value before the maximum tensile mechanical strain arrives. In addition, the phenomenon not only appears in tensile half cycle, which is plotted

with blue dotted square but also occurs in the compressive half cycle for the existence of symmetrical hold in Figure 7b and c. As described in Figure 7d, with the increase of hold time, the creep relaxation is more obvious, which leads to lower equivalent stress.

For IP condition, as shown in Figure 2, the tensile stress half cycle is under high temperature and the compressive stress half cycle is under low temperature. It is generally known that the modulus of elasticity decreases with temperature, which represents that it needs higher stress at low temperature compared with that at high temperature for the same strain amplitude. Therefore, the compressive mean stress is found during the process of all tests. The compressive mean stress is beneficial to fatigue life, which can retard crack nucleation and propagation [26]. In Table 3, it can be noted that the mean stress decreases with the growth of hold time, leading to a longer fatigue life. Besides, with the addition of hold time, the creep relaxation is more obvious. Due to the same cyclic period, the more obvious creep relaxation can drop equivalent stress, which may explain its longer fatigue life. Under the TMF loading, the material is subjected to a certain plastic deformation every cycle and the accumulation of plastic deformation is the main cause of material damage. As seen in Table 3, with the growth of strain amplitude, the plastic strain amplitude increases obviously, meanwhile, the fatigue life is significantly reduced for same hold time.

3.3 Mechanism of crack nucleation and propagation

Figure 8 shows a comparison of fracture morphologies with the strain amplitude of 0.4% and the hold time of 40 s. Under IP hold loading, as illustrated in Figure 8a–e, the fracture is characterized by multi-source cracking initiation. The existence of hold load causes vertical

Figure 6: The change of softening factor with fatigue life (a) under different hold time and (b) at different mechanical strain amplitudes.

Figure 7: Typical hysteresis loops at the mechanical strain amplitude of 0.4% with dwell time of (a) 0 s, (b) 20 s, (c) 40 s and (d) comparison of the three hysteresis loops.

cracks perpendicular to the fracture surface and parallel to the loading direction at the edge of the fatigue fracture. Moreover, the hold time increases the exposure time of P92 at a high temperature, and the prolonged high-temperature environment may cause the existence of a significant oxide layer on the surface of fracture. Meanwhile, some obvious secondary cracks expand in many directions in Figure 8a. Compared with Figure 8a, less secondary cracks are found in Figure 8b and there is almost no evident secondary cracks in Figure 8c at a magnification scale of 1 mm. The fracture surfaces in Figure 8a and b have many stepped irregularities compared to that in Figure 8c–e.

Figure 9 shows the typical three regions in the final stage of fatigue life. Figure 9a shows the cracking initiation region at 0.6% mechanical strain amplitude with 40 s hold time, in which a main crack and some secondary cracks develop in different orientations are noted. Figure 9b shows the propagation region with severe oxidation phenomenon and some cavities, and in which the fatigue striation is the typical observations for fatigue fracture. In Figure 9c, a larger number of cavities and dimples can be seen in the fracture region, which shows typical ductile fracture characteristics. Considerable creep holes are generated near the fracture, and the creep holes

are located between the fatigue striations, as observed in Figure 9d.

As shown in Figure 8, the fracture with shorter hold time and lower strain amplitude has a more obvious multi-source cracking initiation characteristic and secondary cracks compared with the others. With the growth of hold time, the fracture presents a relatively smooth characteristic for the compression of negative mean stress. Compared with higher strain amplitude, the fracture with lower strain amplitude shows a more significant oxidation phenomenon, which indicates that the effect of strain amplitude is more obvious than hold time on the fatigue life. The effect of strain amplitude and hold time on fatigue life has also been compared in Figure 10. As presented in Figure 10a, with the mechanical strain amplitude increases from 0.4 to 0.8, the fatigue life decreases by about 70% at the same hold time. Figure 10b shows the effect of hold time on fatigue life, as hold time increases from 0 to 40 s, the increase of fatigue life is less than 50% with the same mechanical strain amplitude. Furthermore, the influence of hold time is little when the mechanical strain amplitude increases to 0.8%. To compare the variation of effect on fatigue life in Figure 10a and b, it is clearly showing that the effect of strain amplitude is more obvious than hold time. As shown in Figure 9, the oxidation phenomenon

Figure 8: Scanning electron microscope (SEM) fractography of specimen under (a) IPTMF0.4, 0 s, (b) IPTMF0.4, 20 s, (c) IPTMF0.4, 40 s, (d) IPTMF0.6, 40 s, and (e) IPTMF0.8, 40 s conditions.

and cavity fracture contribute a lot in all tests. The fracture morphologies show that the crack nucleation under low cycle fatigue load is mainly the result of local plastic deformation cracking during cyclic deformation.

In order to further study the causes of crack initiation, longitudinal sections under the above different load conditions are shown in Figure 11, in which the crack morphology near the fracture can be seen. As seen in the figure, Figure 11b shows the thinner and smaller cracks compared with Figure 11a, leading to a longer fatigue life. Figure 11c shows the smallest and least crack.

In Figure 11c–e, it also can be noted that with the increase of strain amplitude, the number and size of cracks both increase, which leads to a sharp decline in fatigue life.

3.4 Life prediction

Pan et al. [27] investigated the influence of phase angles on TMF behavior and life prediction of P92 steel, meanwhile, a modified Ostergren model is proposed to predict the fatigue life. To predict the fatigue life of the

Figure 9: SEM fractographs of specimen of $\Delta\epsilon_{\text{mech}}/2 = 0.6\%$ with 40 s hold time at (a) cracking initiation region, (b) propagation region, (c) fracture region, and (d) creep holes.

thermal–mechanical fatigue of P92 steel under different conditions more accurately, both data under different hold time and different phase angles are used to predict the life by modified Ostergren model.

Considering the effect of σ_m and $\sigma_{\max}$ on fatigue life for all conditions, a modified Ostergren model is presented in equation (3) [27].

$$C = N_f^\beta \Delta\epsilon_p \sigma_{\max} \left(1 + \frac{\sigma_m}{\sigma_{\max}} \right)^\eta, \quad (3)$$

where $\Delta\epsilon_p$ is the plastic strain range, $\sigma_{\max}$ is the maximum tensile stress in the mid-life cycle, N_f is the fatigue cycle, and the remaining are constants related to material.

Through regression analysis, $C = 5.7070 \times 10^4$, $\beta = 1.0284$, and $\eta = 0.01562$.

The values of predicted fatigue life and observed experimental fatigue life using modified Ostergren model are compared in Figure 12a. As can be seen, the data points under all conditions are within a factor of 1.5 error band and nearly 1/3rd points are located in the middle line, meanwhile, a few points are located in the top half of the error band. Modified Ostergren model not only considers the effect of plastic strain amplitude and tensile stress, but also considers σ_m and $\sigma_{\max}$ which are affected by hold time and phase angles, leading to a good predicted result.

Figure 10: Comparison of the effect on fatigue life of (a) strain amplitude and (b) hold time.

Figure 11: Optical photographs of surface cracks in cross-sectional view under (a) IPTMF0.4, 0 s, (b) IPTMF0.4, 20 s, (c) IPTMF0.4, 40 s, (d) IPTMF0.6, 40 s, and (e) IPTMF0.8, 40 s conditions.

Figure 12: Comparisons between predicted fatigue life and observed fatigue by modified Ostergren model life under different loading conditions.

To investigate whether the prediction results of life prediction model are conservative or non-conservative, the parameter R is used as shown in Figure 12b. The expression for R is as follows:

$$R = N_e/N_p, \quad (4)$$

where N_e is the observed fatigue life and N_p is the predicted fatigue life. When $R > 1$, the predicted values tend to be conservative, and when $R < 1$, the predicted values tend to be nonconservative. As seen in Figure 12b, the predicted results of modified Ostergren model have more conservative points under lower strain amplitude, which means that the predicted results of modified Ostergren model overestimate the cycle life of the material with the increase of strain amplitude. In general, all predicted points are close to the experimental value and showing a good predicted result.

4 Conclusion

The main conclusions are drawn as follows:

- (1) The hold time has a significant effect on cyclic deformation and fatigue life behavior, where $N_f^{0s} < N_f^{20s} < N_f^{40s}$ and the influence of hold time on fatigue life decrease with the increase of strain amplitude.
- (2) The cyclic response of P92 is characterized by a continuous softening, and the modified Ostergren model can predict the fatigue life very well.

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