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Dynamic strain aging in stress controlled creep–fatigue tests of 316L stainless steel under different loading conditions

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ABSTRACT

Stress controlled fatigue–creep tests were carried out for 316L stainless steel under different loading conditions, i.e. different loading levels at the fixed temperature (loading condition 1, LC1) and different temperatures at the fixed loading level (loading condition 2, LC2). Cyclic deformation behaviors were investigated with respect to the evolutions of strain amplitude and mean strain. Abrupt mean strain jumps were found during cyclic deformation, which was in response to the dynamic strain aging effect. Moreover, as to LC1, when the minimum stress is negative at 550 °C, abrupt mean strain jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process. While the minimum stress is positive, mean strain only jumps once at the end of deformation. Similar results were also found in LC2, when the loading level is fixed at −100 to 385 MPa, at higher temperatures (560, 575 °C), abrupt mean strain jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process. While at lower temperature (540 °C), mean strain only jumps once at the end of deformation.

1. Introduction

Type 316L stainless steel is a prospective material for the reactor vessels and piping systems in nuclear power plants because of a good combination of its excellent high-temperature tensile and creep strength, corrosion resistance and enhanced resistance to sensitization [1]. Generally, the service temperature range for 316L stainless steel is from 450 to 600 °C, which is right in its Portevin–Le Chatelier (PLC) effect regime [2,3].

The Portevin–Le Chatelier effect [4], occurring in many dilute alloys under appropriate conditions, is one of the most prominent examples of plastic instabilities. In monotonic tensile tests, this effect manifests itself in stress–strain curves as serrated flow under strain control mode [5,6] or staircase jump under stress control mode [7]. Since discovered a century ago, the PLC effect has attracted much attention from experimental and theoretical researchers [8–10]. As an intrinsic property of materials, the PLC effect is generally attributed to the dynamical strain aging (DSA) [11] associated with the interactions between mobile dislocations and diffusing solute atoms.

On microscopic scale, the dislocation glide is intermittent, which has been proved by both acoustic emission measurements and numerical simulations [12]. As one type of defects in crystal, dislocation distorts the surrounding lattice and therefore causes an elastic stress field, which acts on the solute atoms nearby. After a mobile dislocation being impeded by obstacles such as forest dislocations, precipitates, and grain boundaries, etc., solute cloud may form around it in response to solute segregations by preferred pipe diffusion, and the mobile dislocation is effectively pinned. With the aid of effective stress, obstacles can be conquered by thermally activated dislocation motion, and this unpinning process of dislocation may cause a sudden material softening. Therefore, DSA is in response to dynamic repeated pining and unpinning processes between mobile dislocation and solute atoms.

In strain controlled low cycle fatigue tests, DSA manifests during cyclic deformation in the form of serrations in stress–strain hysteresis loops, which has been reported by Mannan [2]. Moreover, the influence of DSA on the strain controlled LCF behavior of 316L stainless steel has also been reported by Hong and Lee [3], namely the existence of plateau or the peak in the variation of cyclic peak stress with temperature and the negative temperature dependence of plastic strain amplitude or softening ratio etc. However, under stress control mode, characterization of DSA in fatigue or creep–fatigue tests was not so many up to now.

Recently, some work has been presented by us about the influence of DSA pre-treatment on creep–fatigue behavior of 316L steel [13]. It was found that, under stress control mode, DSA manifests itself macroscopically as displacement or mean strain abrupt jumps during cyclic deformation. In this paper, creep–fatigue tests

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Table 1
Creep–fatigue test results under different loading levels at 550 °C.

σ_{max} (MPa)	σ_{min} (MPa)	σ_a (MPa)	σ_m (MPa)	N_f (cycles)	δ (%)
385	−150	267.5	117.5	690	40.44
385	−100	242.5	142.5	776	39.72
385	−50	217.5	167.5	1483	39.7
385	0	192.5	192.5	5881	35.84
385	50	167.5	217.5	8731	37.01
385	100	142.5	242.5	2330	37.16
385	150	117.5	267.5	993	35.84

were systemically carried out for 316L stainless steel under different loading conditions. Cyclic deformation behaviors were investigated with respect to the evolutions of strain amplitude and mean strain. Moreover, manifestation of DSA was also discussed under different loading conditions.

2. Material and test methods

The material used in our tests is hot rolled grade 316L stainless steel. Specimens were taken along the rolling direction and machined to cylindrical bar with 35 mm gauge length and 10 mm diameter. Tests were conducted in air using a servo-hydraulic machine MTS 809 equipped with a coil heating system whose accuracy is ±2 °C. Test temperature was in the range from 540 to 575 °C. A trapezoid waveform, i.e. 1 s for loading/unloading and 5 s for holding at the maximum/minimum stress, was used to introduce the creep–fatigue interaction in tests. To investigate the effects of stress amplitude σ_a and mean stress σ_m on creep–fatigue behavior simultaneously by only changing minimum stress σ_{min}, the maximum stress σ_{max} was keeping fixed at 385 MPa and σ_{min} was changing from −150 to 150 MPa. Details can be referred to [13].

3. Experimental results and discussion

Under stress control mode, fatigue property is mainly governed by stress amplitude σ_a and temperature, while creep property is mainly influenced by mean stress σ_m, holding stress σ_{max}, σ_{min} and temperature [14]. To investigate the effect of loading level and temperature on creep–fatigue behavior, respectively, two groups of tests were conducted under different test conditions, i.e. different loading levels at the fixed temperature and different temperatures at the fixed loading level.

3.1. Different loading levels at the fixed temperature

The test parameters and results under different loading levels at 550 °C are given in Table 1. With increasing σ_{min}, the stress amplitude σ_a decreases, the mean stress σ_m increases, while the material life N_f increases first and then decreases. When $\sigma_a = 167.5$ MPa ($\sigma_{min} = 50$ MPa), N_f reaches its maximum value.

Here, when $\sigma_a > 167.5$ MPa ($\sigma_{min} < 50$ MPa), the fatigue effect is dominant. With increasing σ_{min}, σ_a decreases gradually and so does the fatigue effect. Therefore, the material life will be getting longer with increased σ_{min}. When $\sigma_a \leqslant 167.5$ MPa, creep effect is dominant. Hence, with increasing σ_{min}, σ_m increases and the material life decrease.

Fig. 1 shows the cyclic strain amplitude $\Delta\varepsilon$ and mean strain ε_m responses under different minimum stress at 550 °C. According to Fig. 1(a), in all loading levels, $\Delta\varepsilon$ decreases with the development of cyclic deformation, which represents a cyclic hardening property in 316L stainless steel. Moreover, $\Delta\varepsilon$ is found to monotonically decrease with increased σ_{min}. Fig. 1(b) presents a nonlinear relationship between the evolution of mean strain and cycles. At the beginning of deformation, mean strain rises slowly and gradually. While at the last stage of deformation, it increases quickly and emergently till final fracture. Moreover, there is no distinct difference in the mean strain value for all the loading levels.

Additionally, abrupt jumps are found in ε_m–N curves during cyclic deformation under all loading levels, as shown in Fig. 1(b), which has been reported in [13]. Considering the test temperature, i.e. 550 °C, it happens to be in the DSA regime of 316L stainless steel. Hence, the above mentioned displacement or mean strain jumps should be associated with the dynamic strain aging during

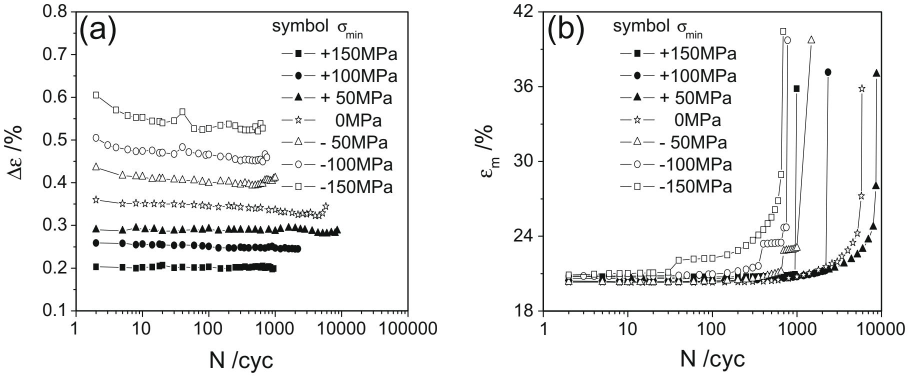

Fig. 1. (a) Cyclic strain amplitude and (b) mean strain responses under different minimum stress at 550 °C.

Table 2
Jump records for different loading levels at 550 °C.

T (°C)	σ_{max} (MPa)	σ_{min} (MPa)	N_f (cycles)	Jump record (cycles)	Life fraction at 1st jump	Total jump times
550	385	−150	690	38/646/674	0.05507	3
550	385	−100	776	370/692	0.4768	2
550	385	−50	1483	680/1130/1200/1325/1463	0.45853	5
550	385	0	5881	5690	0.96752	1
550	385	50	8731	8580	0.98271	1
550	385	100	2330	2299	0.9867	1
550	385	150	993	986	0.99295	1

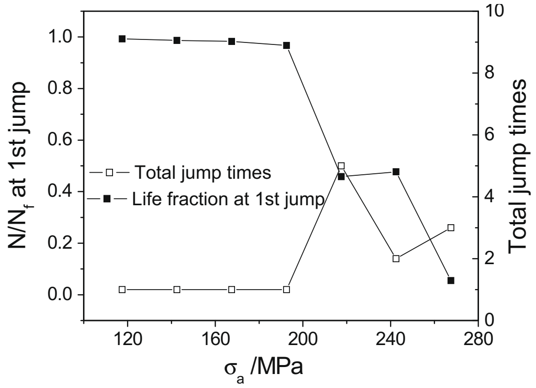

Fig. 2. Evolution of life fraction at the first jump and total jump times with stress amplitude.

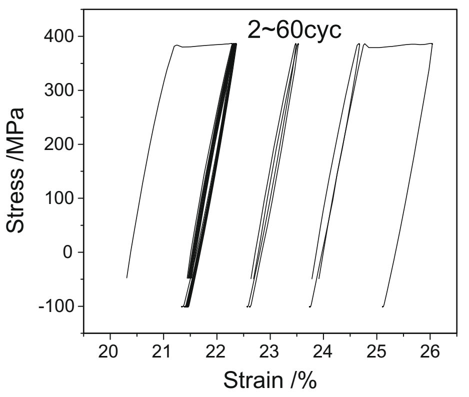

Fig. 4. Hysteresis loops at 575 °C when the loading level is −100 to 385 MPa.

Table 3
Creep–fatigue test results under different temperatures at the fixed loading level.

T (°C)	$\sigma_{\max}$ (MPa)	$\sigma_{\min}$ (MPa)	N_f (cycles)	δ (%)
575	385	−100	79	39.72
560	385	−100	567	41.57
550	385	−100	776	39.72
540	385	−100	3821	37.6

cyclic deformation. On micro scale, as dislocation density continuously increases with the development of plastic deformation, finite solute atoms will finally be unable to pin them effectively. That means the aging effect will get weaker with plastic deformation development. Therefore, when a critical deformation value is reached, mobile dislocation will escape from obstacles with the aid of applied stress. This unpinning process will further produce an avalanche-like dislocation multiplication causing material softening. For stress controlled tests, instant material softening will lead to a sudden strain increase, namely displacement or mean strain will jump abruptly in sample.

Table 2 presents the abrupt jump records for different loading levels at 550 °C. The evolution of life fraction at the 1st jump and total jump times with stress amplitude are shown in Fig. 2. It can be found that, when $\sigma_{\min} \leqslant 0$ MPa, abrupt displacement jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process; while $\sigma_{\min} > 0$ MPa, displacement only jumps once at the end of deformation.

Referring to the results in Fig. 1, as all the mean strain values at different loading levels are almost the same, then plastic deformation in material is mainly determined by the strain amplitude. As shown in Fig. 1(a), when $\sigma_{\min} > 0$ MPa, strain amplitude $\Delta\varepsilon$ is much smaller than those when $\sigma_{\min} \leqslant 0$ MPa, which means less plastic deformation and lower dislocation density is produced in one cycle. Therefore, when $\sigma_{\min} > 0$ MPa, it will take more cycles to reach that critical deformation value which DSA occurs, namely displacement will jump at a later cycle.

3.2. Different temperatures at the fixed loading level

The test parameters and results under different temperatures at the fixed loading level, i.e. −100 to 385 MPa, are given in Table 3. It can be seen that, with increasing temperature, the material creep–fatigue life decreases monotonically. Since the loading level is fixed, enhanced creep damage with increasing temperature should be responsible for the degradation of material life.

Fig. 3 shows the cyclic strain amplitude $\Delta\varepsilon$ and mean strain ε_m responses under different temperatures at the fixed loading level. As shown in Fig. 3(a), all $\Delta\varepsilon$ decrease with the development of cyclic deformation, which represents a cyclic, hardening property in 316L stainless steel at different temperatures. However, it should be noted that, although $\Delta\varepsilon$ is minimal at 540 °C, another three $\Delta\varepsilon$–N curves twist with each other at the rest temperatures. Fig. 3(b) also presents a nonlinear relationship between the evolution of mean strain and cycles. At the beginning of deformation, mean strain rises slowly and gradually. While at the last stage of deformation, it increases quickly and emergently till final fracture. Additionally, with decreasing temperature, the mean strain value is found to decrease monotonically.

Moreover, abrupt jumps are also found in ε_m–N curves during cyclic deformation at all test temperatures. In Fig. 4, it happens to record two abrupt jumps in hysteresis loop at 575 °C when

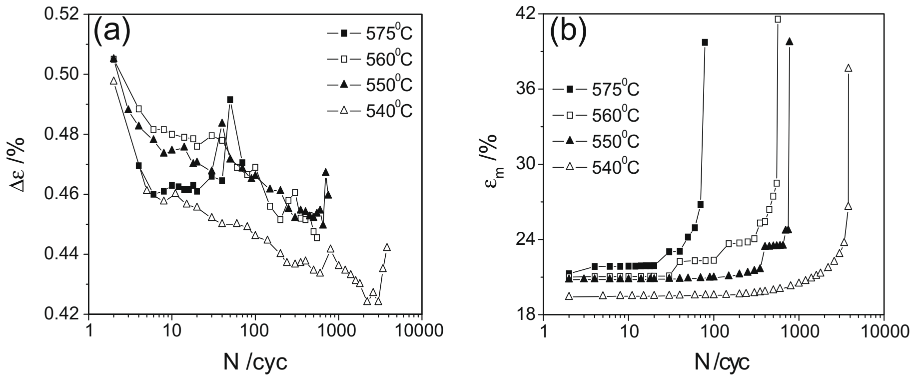

Fig. 3. (a) Cyclic strain amplitude and (b) mean strain responses under different temperatures at the fixed loading level.

Table 4
Jump records for different temperatures.

T (°C)	$\sigma_{\max}$ (MPa)	$\sigma_{\min}$ (MPa)	N_f (cycles)	Jump record (cycles)	Life fraction at 1st jump	Total jump times
575	385	−100	79	2/22/48/60/69/75	0.02532	6
560	385	−100	567	38/140/310/400/485	0.06702	5
550	385	−100	776	370/692	0.4768	2
540	385	−100	3821	3793	0.99267	1

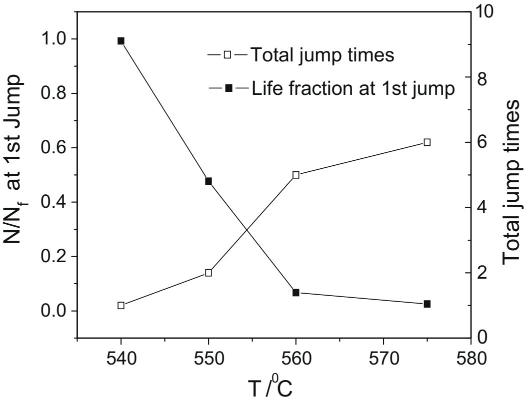

Fig. 5. Evolution of life fraction at the 1st jump and total jump times with testing temperature.

the loading level is −100 to 385 MPa. The strain jump is much larger than the deformation amplitude in one cycle, which means a large deformation occurs during this jump. It should be noted that, there are also such jumps at other temperatures but they were missed by the unequal-interval sampling method.

All the abrupt jump cycles were recorded in Table 4 for different temperatures. Fig. 5 presents the evolution of life fraction at the 1st jump and total jump times with testing temperature. It can be found that, at higher temperature (560 and 575 °C), abrupt mean strain jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process, while at lower temperature (540 °C), mean strain only jumps once at the end of deformation.

In this group of tests, the loading level is fixed. Therefore, higher is temperature, softer is material and larger is deformation, as shown in Fig. 3(b). On micro scale, larger plastic deformation will induce more mobile dislocations. Hence, at higher temperature, DSA, namely abrupt mean strain jump will emerge earlier.

4. Conclusions

(1) For both loading conditions, i.e. different loading levels at the fixed temperature and different temperatures at the fixed loading level, dynamic strain aging was found to manifest itself macroscopically as mean strain abrupt jumps during cyclic deformation under stress control mode.

(2) When $\sigma_{\min} \leqslant 0$ MPa, abrupt displacement jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process. While $\sigma_{\min} > 0$ MPa, displacement only jumps once at the end of deformation.

(3) At higher temperature, abrupt displacement jumps occur at the early stage of cyclic deformation and there are many jumps during the whole process. While at lower temperature, displacement only jumps once at the end of deformation.

Acknowledgements

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