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Ratcheting Strain Accumulation Due to Asymmetric Cyclic Loading of Zircaloy-2 at Room Temperature

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Abstract

Asymmetric stress cycling leads to accumulation of plastic strain which is called as ratcheting strain. The problem is generally associated with nuclear fuel cladding materials used in nuclear power plants and in pressurized pipe lines. In the present investigation asymmetric stress controlled fatigue tests were conducted with three different parameters namely, mean stress, stress amplitude and stress rate (keeping two parameter constant and varying third parameter) to see the plastic strain accumulation and its effect on fatigue life of Zircaloy-2 at room temperature. The tests were conducted with mean stress varying from 80 to 150 MPa, stress amplitude varying from 270 to 340 MPa and stress rate varying from 30 to 750 MPa/s respectively. The experimental outcomes show that with increase in mean stress and stress amplitude, the ratcheting strain accumulation increases with reduction in fatigue life. However, increase in stress rate leads to improvement in fatigue life of the material due to small ratcheting strain accumulation. Cyclic softening is observed during initial cycles for lower values of mean stress and stress amplitude and cyclic hardening is predominant for higher values of mean stress and stress amplitude. However, cyclic hardening is observed with increase in stress rate.

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Keywords: Zircaloy-2; asymmetric stress cyclic loading; ratcheting strain; Mean stress; stress amplitude; stress rate and plastic strain.

1. Introduction

Zirconium and its alloys are widely used as structural material for components of nuclear reactors because of their inherent low neutron absorption cross section [Lin et al. (2004)], excellent mechanical properties [Mallipudi et al. (2012), Lee and Hong (2011)] and corrosion resistance [Guo et al. (2012)]. It has been observed that zircaloy-2 clad fuel tubes are subjected to cyclic loading with non-zero mean stress and hence cyclic accumulation of plastic strain occurs and causes yielding of the material [Gaudin and Feaugas (2004)], often known as ratcheting fatigue, or cyclic creep, proposed by [Hübel (1996)]. Fuel tubes are subjected to primary load in the axial and circumferential

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directions because of the pressure and a secondary cyclic bending moment due to cyclic thermal gradients. If the loads are high enough to make the structure yield, the plastic strain accumulates cycle by cycle until the whole structure collapses.

The ratcheting strain rate is defined as the increment of plastic strain in each cycle. It was observed that ratcheting strain rate is usually high during the initial few cycles and subsequently decreased from cycle to cycle, till failure. Deformation behavior of Zircaloy-2 has been investigated and the possible deformation modes have been characterized as prismatic, pyramidal and basal slip apart from twinning [Xiao and Bai (1999), Lin and Haicheng (1998)]. Several studies have been carried out to understand the complex cyclic plastic deformation behavior and cycle by cycle strain accumulation, termed as ratcheting in different materials such as steels, copper alloys etc [Paul et al. (2010), Zhang and Jiang (2005)]. However, no systematic study has been carried out on ratcheting behavior of Zircaloys, therefore the present investigation was undertaken to examine hardening/softening behavior of Zircaloy-2 during asymmetric cyclic loading at room temperature.

2. Material and Methods

Zircaloy-2, material of the present investigation was received from the Nuclear fuel complex, Department of atomic energy, Hyderabad, India, in annealed condition, in the form of rods of 14 mm diameter. It was processed by extruding billet of 150 mm diameter to 24 mm rod, followed by swaging and vacuum annealing at 730°C for 3 h. The chemical composition of the alloy is presented in Table 1.

Table 1. Chemical composition of the Zircaloy-2. (wt%).

Elements	Sn	Cr	Fe	Ni	Hf*	O*	C*	N*	H*	Zr
Amount (wt%)	1.3	0.09	0.15	0.04	<50	1040	64	40	8	Balance

* *ppm level*

Asymmetric stress cycling tests were conducted at different mean stresses (σ_m), stress amplitudes (σ_a) and stress rates (σ^*), at room temperature. Fatigue tests were conducted on 50 kN servo hydraulic MTS (Model 810), equipped with fully automatic Test Star IIs controller keeping two parameters constant and varying the third one. Test specimens were prepared with gauge length and gauge diameter of 15.5 mm and 5.5 mm respectively, threaded ends of 12 mm diameter and 30 mm length, shoulder radii of 25 mm. Gauge section of specimen was mechanically polished before testing. Plastic strain was measured by mounting an extensometer of 12 mm gauge length (Model: MTS 632.13C-20) in gauge section of the specimen.

3. Results and Discussion

3.1 Variation of plastic strain

As mentioned above asymmetric stress cycling leads to accumulation of plastic strain. Hardening/softening behavior of the material was assessed from the width of the hysteresis loops by conducting fatigue test with different combinations of mean stress, stress amplitude and stress rate. Figure 1 shows the translation of hysteresis loop for mean stress of 80 MPa at stress amplitude of 270 MPa and stress rate of 150 MPa/s. It may be seen that the hysteresis loop of the first cycle, with tensile loading, shows maximum plastic strain.

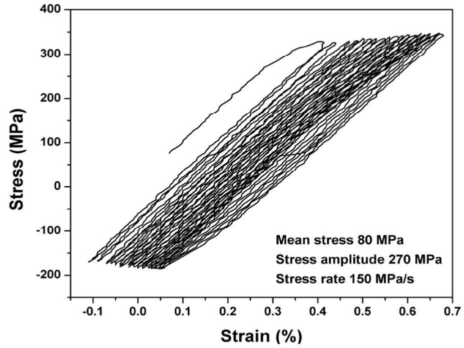

Fig. 1 Variation of plastic strain at mean stress 80 MPa, stress amplitude 270 MPa and stress rate 150 MPa/s.

3.2 Effect of mean stress on hardening/softening behavior during asymmetric cyclic loading.

Hysteresis loops resulting from different combinations of mean stress, stress amplitude and stress rate were compared in terms of their width at different number of cycles for a particular combination of three variables. The effect of the mean stress from 80 to 150 MPa at constant stress amplitude of 300 MPa and stress rate of 150 MPa/s is brought out by the hysteresis loops at different number of cycles: 5, 50 and 500 in Figure 2.

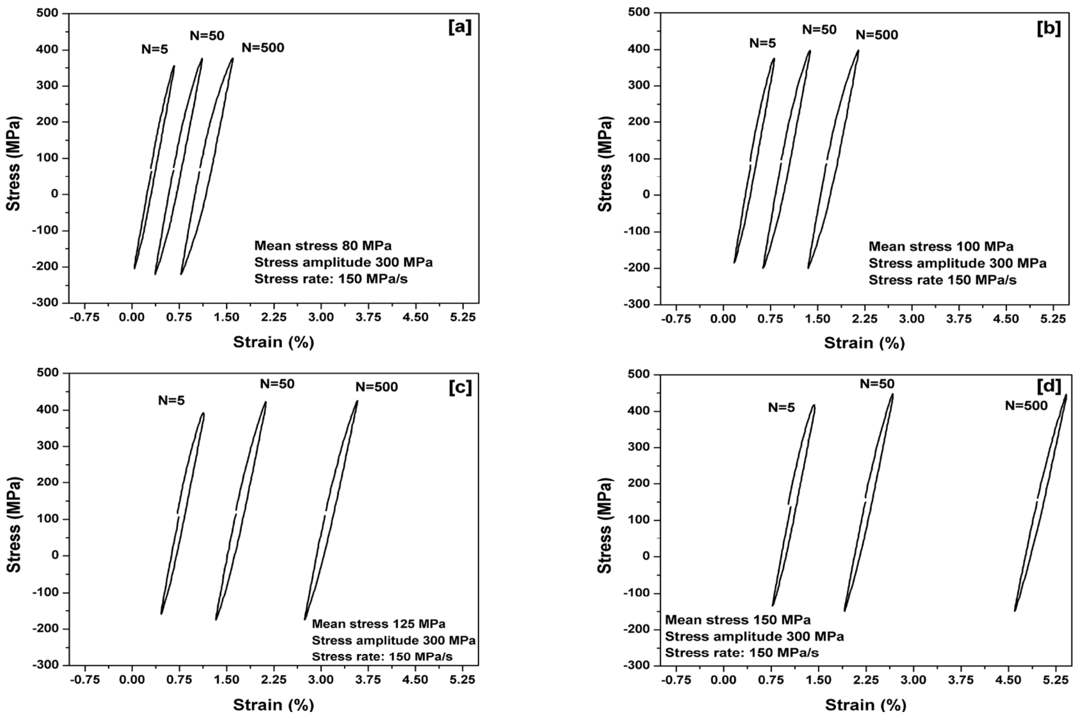

Fig. 2 Hysteresis loops corresponding to 5, 50 and 500 load cycles at different mean stresses: (a) 80 MPa, (b) 100 MPa, (c) 125 MPa and (d) 150 MPa, at stress amplitude of 300 MPa and stress rate of 150 MPa/s.

As shown in Figure 2 for constant stress amplitude and varying mean stress from 80 to 150 MPa, the width of hysteresis loop decreased. The decrease in width of hysteresis loops with increase in mean stress can be attributed to increase in cyclic work hardening of the material. Figure 3 shows variation of energy associated with hysteresis loops for different levels of mean stress. It is obvious that for less number of cycles (N=5) there is softening with increase in mean stress; however, there is softening upto 50 cycles and hardening at higher number of cycles. It is interesting to note that there is increasing hardening with increase in mean stress at higher number of cycles (N=500).

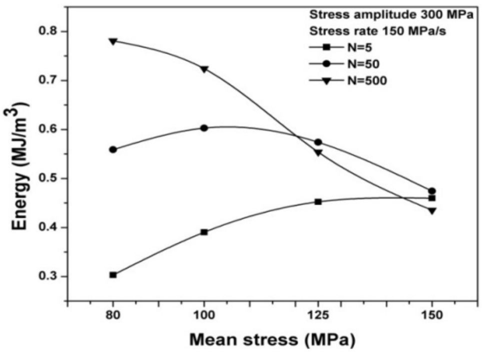

Fig. 3 Variation of hysteresis loop energy with mean stress at different number of cycles at constant stress amplitude of 300 MPa and stress rate of 150 MPa/s.

3.3 Effect of stress amplitude on hardening/softening behavior during asymmetric cyclic loading.

The effect of stress amplitude on hysteresis loops at mean stress of 80 MPa and stress rate of 150 MPa/s is shown in Figure 4. It may be seen that there is increasing softening with increase in stress amplitude.

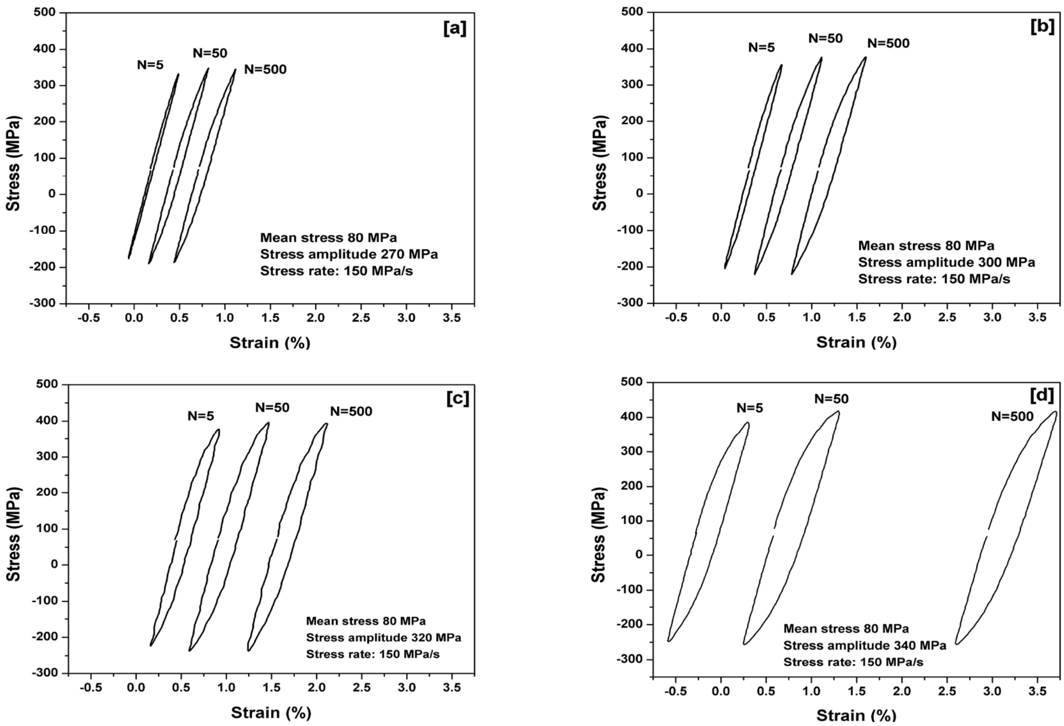

Fig. 4 Hysteresis loops corresponding to 5, 50 and 500 load cycles at different stress amplitudes: (a) 270 MPa, (b) 300 MPa, (c) 320 MPa and (d) 340 MPa; at mean stress of 80 MPa and stress rate of 150 MPa/s.

As shown in Figure 4, with variation of stress amplitude from 270 to 340 MPa the width of hysteresis loop increased. The increase in width of hysteresis loops with increase in stress amplitude can be attributed to increase in cyclic softening of the material. This observation of increase in width of hysteresis loops happens without any plastic shake down and can be related to pseudo-softening, as explained earlier [Dutta et al. (2010), Bassim (1989), Majumdar and Ray (2006)]. Dislocation cells which are formed during initial plastic deformation are low energy dislocation cells. These dislocation cells can accommodate large dislocation density in them. Therefore, all the newly generated dislocations get easily re-distributed at the cell walls and as a result lowering of internal stresses facilitates further deformation. This whole phenomenon contributes to pseudo-softening and the material shows continuous softening with increase in stress amplitude. This can also be seen from Figure 5 which shows variation of energy associated with hysteresis loops for different levels of stress amplitude. It is obvious that energy of hysteresis loops keeps on increasing with stress amplitude. Continuous softening may also lead to earlier failure of the material. Therefore, increase in stress amplitude has more damaging effect.

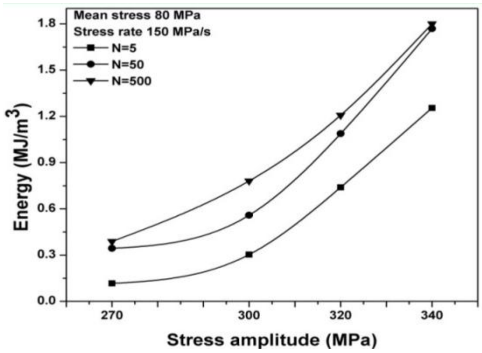

Fig. 5 Variation of hysteresis loop energy at constant mean stress of 80 MPa and stress rate 150 MPa/s with stress amplitudes, at different number of cycles.

3.4 Effect of stress rate on hardening/softening behavior during asymmetric cyclic loading.

The effect of stress rate on hysteresis loops at mean stress of 80 MPa and stress amplitude of 300 MPa is shown in Figure 6. It shows that there is increasing hardening with increase in stress rate.

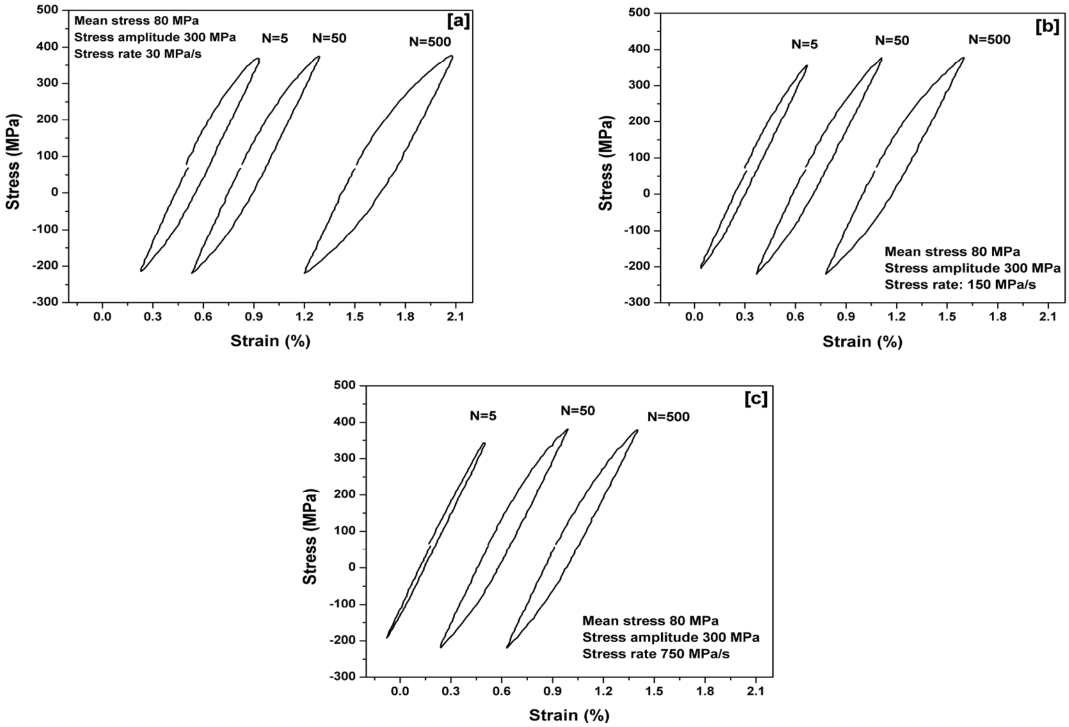

Fig. 6 Hysteresis loops corresponding to 5, 50 and 500 load cycles at different stress rates: (a) 30 MPa/s, (b) 150 MPa/s and (c) 750 MPa/s; at mean stress of 80 MPa and stress amplitude of 300 MPa.

As the stress rate increased the width of hysteresis loop decreased. The decrease in width of hysteresis loops with increase in stress rate can be attributed to increase in cyclic work hardening of the material due to increase in stress rate. Figure 7 shows continuous reduction in energy level associated with hysteresis loops of the material and thus reflects strengthening and increase in fatigue resistance. It is evident that there is increasing hardening with increase in rate of hardening with increasing number of cycles. Thus, there is decrease in damaging effect with increase in stress rate.

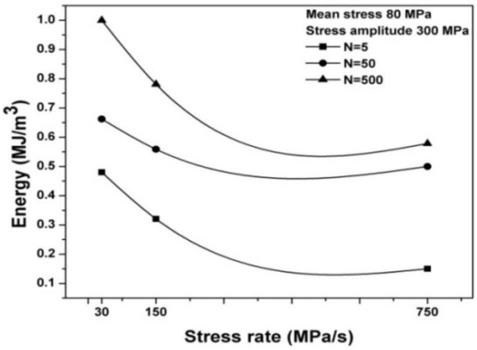

Fig. 7 Variation of hysteresis loop energy at constant mean stress of 80 MPa and stress amplitude of 300 MPa, with stress rate, at different number of cycles.

4. Conclusions

Following conclusions are drawn from this investigation.

1. There was cyclic softening with increase in mean stress during initial cycles (N=5 cycles), softening was followed by hardening at 50 cycles and continuous hardening in the later stage of cycling (N= 500 Cycles).

2. There was continuous softening with increase in stress amplitude from 270 MPa upto 340 MPa from initial cycles (N=5 cycles) to even later stage of cycling (N=500 cycles).

3. There was continuous cyclic hardening with increase in stress rate from 30 MPa/s upto 750 MPa/s and the rate of hardening increased with increasing number of cycles.

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