HCF AND LCF FRACTURE MECHANISM OF A COMMERCIAL-PURITY ZIRCONIUM

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ABSTRACT

Both reversed bending tests under stress control at RT(298K) and symmetric push-pull fatigue tests under strain control at RT and 673K were conducted to study the HCF and LCF behaviours of a commercial-purity zirconium in casting and annealed conditions, respectively. The cyclic deformation behaviour of zirconium is characterized with three stages of cyclic hardening, saturation and softening. SEM examination reveals that there exist a lot of regular facets and microcracks on the fracture surfaces of HCF specimens, whereas many striations accompanied by secondary cracks and tire marks on the fracture surfaces of LCF specimens. TEM studies show that the predominant structure in HCF specimens are straight and curved dislocation lines, loops and stacking faults in casting condition, while band dislocation in annealed condition; However, the typical structure in LCF specimens are irregular bands and embryonic cells at RT, and cells of dislocations at 673K. All these results are rationalized in terms of fatigue fracture modes of hcp metal.

KEYWORDS

Zirconium, fatigue, cyclic hardening, cyclic softening, dislocation structure

1. INTRODUCTION

Zirconium and its alloys are used extensively in nuclear reactors for fuel sheathing due to their low neutron absorption cross-section, excellent mechanical properties and good resistance to corrosion. The continuing trend of operation of nuclear reactors is towards power cycling as a means of running the systems more efficiently. This fact has led to reversed plastic deformation subjected by fuel sheathing and then fatigue failure finally during their lifetime. The fatigue properties of zirconium are therefore important to ensure performance, safety and reliability of fuel rods operated in severe loading conditions. Up to now, some researches in the field of fatigue for zirconium and zircaloy have been done[1-6]. The objectives of the present paper were to study the cyclic deformation behaviour and dislocation structures in a commercial-purity zirconium.

2. EXPERIMENTAL PROCEDURE

The material used in this investigation was a commercial-purity zirconium (99. 98%) but in two conditions; casting condition with extremely coarse grains and annealed at 1173K × 6h to obtain more homogeneous grain size.

Both reversed bending tests and symmetric push-pull fatigue tests were conducted to study the HCF and LCF behaviours of zirconium, respectively. In the reversed bending tests, symmetric bending cyclic loading was employed under load control at a frequency of 12HZ. A sine waveform loading signal was selected. Displacement/deflection, which are for the outside fibers of specimens only, versus cyclic number were measured with strain gauges and registered on a digitizing memory oscilloscope. LCF tests were conducted on an electro- servohydraulic Mayes machine fitted with a radiation furance. The LCF specimens with gauge dimensions of Φ5mm × 10mm were machined from the annealed zirconium. The LCF tests were performed with a triangular wave function at a strain rate of $4 \times 10^{-3} s^{-1}$ with strain ratio of R=-1. Each fracture surface of fatigued specimens were examined with JSM-35C scanning electron microscope. TEM foils were cut from HCF and LCF specimens, and dislocation structures were studied using JEM-200CX transmission electron microscope operated at 200KV.

3. RESULTS

3. 1 High cycle fatigue

3. 1. 1 Cyclic deformation behavior. The variation of strain amplitudes on the outside fibers of fatigued specimens as a function of the cyclic numbers is shown in Fig. 1 for zirconium in casting condition. Under testing conditions with constant stress, the strain amplitudes of specimens decrease as cyclic number increasing, and this is followed by strain amplitudes increase subsequently. The result indicates that zirconium exhibits initial cyclic hardening, which is followed by cyclic softening. The variation of strain response is significant at high stress ranges and diminishs quickly as constant stress ranges decrease, i. e. this phenomenon of fatigue hardening/ softening is pronounced at high cyclic stress ranges, however it is fading at low cyclic stress range below 40MPa. The cyclic hardening/softening behaviour of zirconium in annealed condition is similar to that in casting condition. Therefore its curve is omitted here.

3. 1. 2 SEM observation. SEM examination reveals that HCF process consists of microcrack nucleation along the persistent slip bands (PSBs) and the twin-matrix boundaries, then coalescence of cracks to fracture finally. Fig. 2(a) and (b) show the typical micrographs of cracking along PSBs and twin-matrix boundaries. In Fig. 2(a) the distribution of PSBs is heterogeneous from one grain to another, and fatigue damage is highly localized. Deformation twins frequently appear on the fracture surfaces of zirconium, and fatigue crack is formed at the tip of twin or along twin-matrix boundary (Fig. 2(b)). It is worthwhile to note that some regular facets and cyclic cleavage features appear on the surfaces of fatigued specimens in hcp metal, as shown in Fig. 2(c) and (d).

3. 1. 3 Dislocation structure. TEM studies show that the predominant structures of fatigued specimens in casting condition are straight and curved dislocation lines, loops, twins and stacking faults. Photographs of these structures are shown in Fig. 3(a)-(c). In Fig. 3 (a), there still appear groups of free dislocations of the opposite sign. The test result in this investigation offers an evidence of stacking faults presence in the commercial-purity zirconium (Fig. 3(b)). Twinning is an important deformation mode of hcp zirconium (Fig. 3(c)). In difference with the casting specimens, the typical structure in fatigued specimens in annealed condition is bands of dislocations, which are intersected with the long dislocation lines in another direction (Fig. 3(d)).

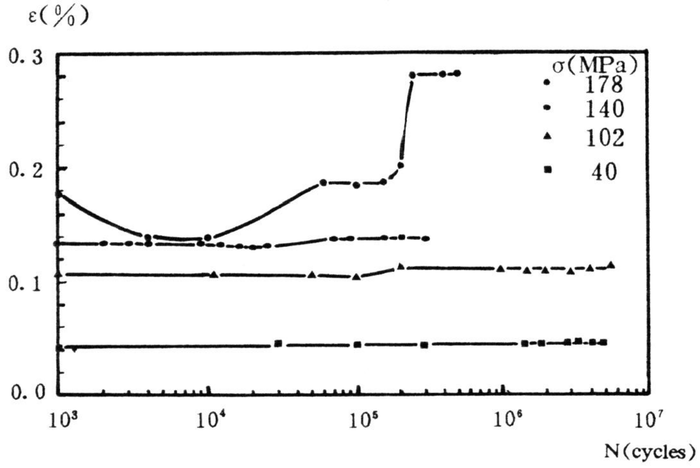

Fig. 1 Strain response of zirconium cycled under constant stress condition

3. 2 Low cycle fatigue

3. 2. 1 Cyclic deformation behavior. The amplitude from peak tensile stress to peak compressive stress for zirconium at RT (298K) and 673K under constant strain amplitude was plotted as a function of the logarithm of the number of cycles in Fig. 4(a) and (b). Zirconium exhibits a marked initial hardening followed by well-defined saturation stages and finally cyclic softening occurs. This fact is in accordance with that of HCF, i. e. the initial hardening is followed by softening at high stress ranges. For all strain amplitudes, there exists obvious fatigue softening stages before fatigue failure occurs at 673K (Fig. 4 (b)).

3. 2. 2 Fractography. SEM examination of fracture surfaces reveals that the specimens fatigued at RT under strain control condition have many striations and numerous subsidiary cracks perpendicular with principal crack (Fig. 5(a)). Besides ductile striations, tire marks are also found on the surfaces of specimens fatigued at 673K, as shown in Fig.

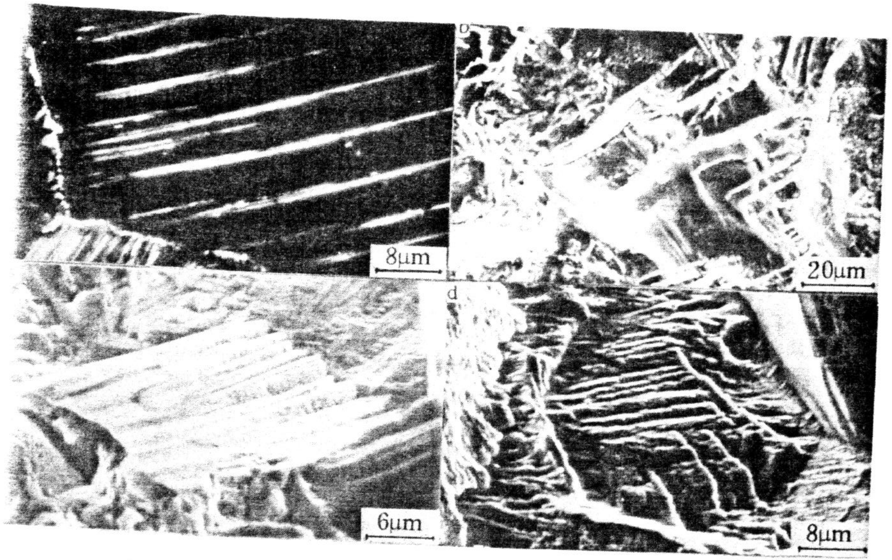

Fig. 2 SEM photographs of zirconium fatigued at constant stress
(a) cracking along PSBs (b) cracking along twin-matrix boundary
(c) regular facets (d) cyclic cleavage

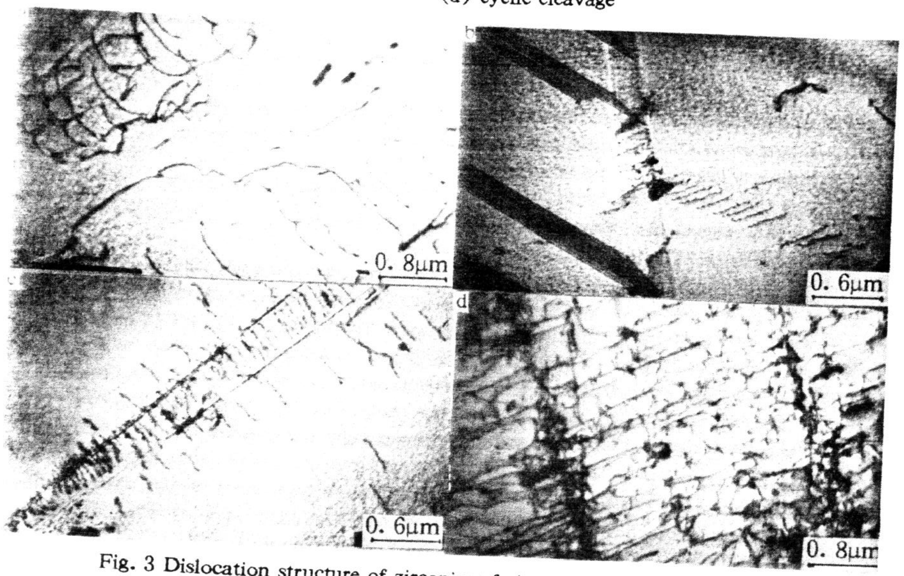

Fig. 3 Dislocation structure of zirconium fatigued at constant stress range
(a) dislocations in casting specimens (b) stacking faults
(c) twin (d) dislocations in annealed specimens

5(b) and (c). The presence of clear striations, tire marks and subsidiary cracks are the typical morphologies of fracture surfaces for LCF specimens at RT and 673K.

3. 2. 3 Dislocation structure. Fig. 6(a) and (b) show the general dislocation arrangement in zirconium specimens fatigued to fracture under constant strain ranges at RT. The dislocation structures are mainly loops, lines and debris. This structure exhibits a low dislocation density, and the dislocations are distributed more or less homogeneously in many regions (Fig. 6(a)). As the cyclic strain ranges increase, these tangles of dislocations tend to form an embryonic cell (Fig. 6(b)), and the dislocation density increases. The dislocation structure in specimens fatigued at 673K is shown in Fig. 7(a) and (b). The predominant features are cells of dislocation that are separated by regions relatively free of dislocations (Fig. 7(a)) at small strain ranges. As the cyclic strain range increasing, the cell boundaries become more distinct and the interior of cell appears more "clean", containing less dislocations (Fig. 7(b)).

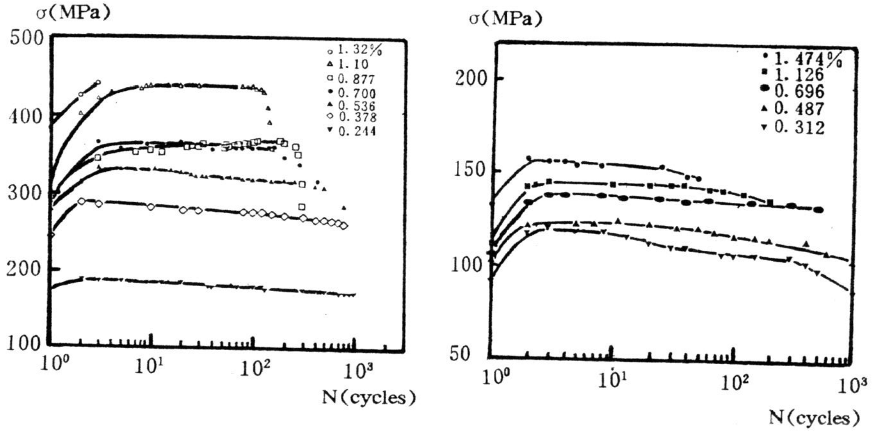

Fig. 4 Stress response of zirconium cycled under constant strain condition
(a) at RT (b) at 673K

4. DISCUSSION

Studies of the correlation between cyclic deformation behaviour and dislocation structure developed during reversed cyclic deformation are one of the main objects of this investigations. Dislocation structures produced in hcp metals are associated with many factors such as stacking fault energy, testing temperature, stress/strain ranges and cyclic numbers etc. In materials with a low stacking fault energy, cell structure occurs at very high cyclic stress/strain amplitudes or at high testing temperature. The presence of stacking fault in

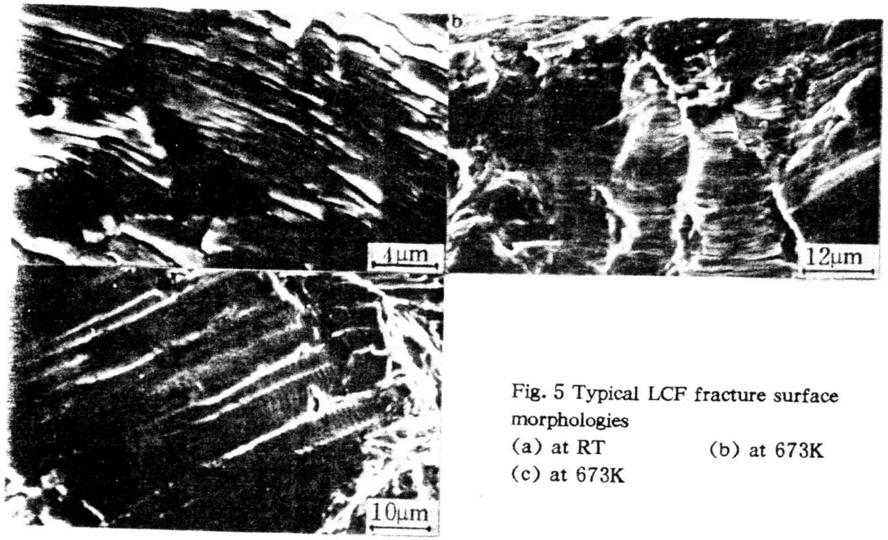

Fig. 5 Typical LCF fracture surface morphologies
(a) at RT (b) at 673K
(c) at 673K

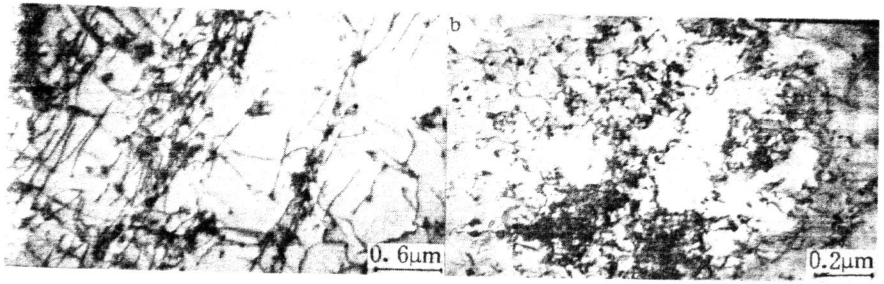

Fig. 6 Dislocation structure of LCF at RT
(a)$\triangle\varepsilon_t/2=0.244\%$ (b)$\triangle\varepsilon_t/2=0.700\%$

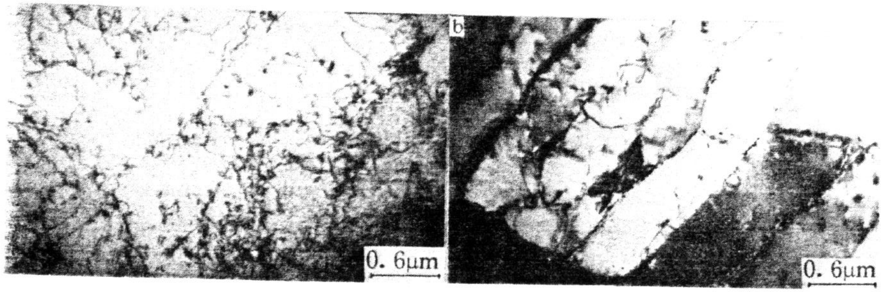

Fig. 7 Dislocation structure of LCF at 673K
(a)$\triangle\varepsilon_t/2=0.312\%$ (b)$\triangle\varepsilon_t/2=1.474\%$

the fatigued specimens indicates that the stacking fault energy of zirconium is low and cross-slip is difficult in this investigation. This fact is further confirmed by the test results of high cycle fatigued specimens having no cell structure at all. Thus planar arrays of dislocations and dissociated dislocations were acknowledged to be characteric dislocation structure of HCF specimens in casting specimens, and band dislocations were typical features of dislocation structure of HCF specimens in annealed condition. It is different from that in HCF specimens , the dislocation structure is mainly loops and debris in LCF specimens at RT, and dislocation cells tend to develop as increasing of cyclic strain range. The dislocation structure is well defined cells in fatigued specimens at 673K. At even higher cyclic strain ranges, the elongated and sharper cell wall forms. This cell structure formation is associated with the larger cyclic strain ranges and higher testing temperature during LCF testing. No cells of dislocation in high cycle fatigued specimens are attributed to lower cyclic strain range. The cell formation of low cycle fatigued specimens at RT is correlative with the imposed higher cyclic strain range. It seems that cell formation in LCF specimens at 673K is triggered by the thermal activated process at high testing temperature, because the formation of cells always requires more than one active slip systems[7].

In contrast with cubic and face-centre metals, the mechanical properties of the hexagonal (hcp) metals are highly anisotropic, because its slip systems fewer than the required five independent ones are operative. The cyclic hardening behaviour of metals may probably be correlated with the number of operative slip systems and the imposed strain amplitude[8]. A limited actived slip systems for zirconium at RT results in a pronounced initial fatigue hardening stage, which is not marked for zirconium at 673K due to the number of operative slip systems increased by thermal active action.

5. CONCLUSIONS

(1) The cyclic peak strain/stress versus cyclic number curves during HCF and LCF testing shows that the cyclic deformation behaviour of zirconium is characterized with three stages *viz*; cyclic hardening, saturation and softening, the proportion of which depends on cyclic stress/strain ranges and testing temperatures. The larger cyclic stress/strain ranges, the more pronounced of initial hardening stages; the higher test temperature, the more marked of final softening stages.

(2) Based on SEM examination it can be confirmed that the HCF failure process consists of microcrack nucleation along the persistent slip bands and the twin/matrix boundaries followed by their coalescence. Cyclic cleavage features are also found on the fracture surfaces. Whereas on the fracture surfaces of LCF specimens, there appear to be many fatigue striations accompanied by numerous subsidiary cracks. The tire marks are frequently obtained in the specimens fatigued at 673K.

(3) The predominant substructures of HCF spcimens are straight and curved dislocation lines, loops, twins and stacking faults in casting conditions, while band dislocations in annealed condition. The typical dislocation structures of LCF are vein, irregular bands fatigued at RT, and these tangles of dislocations tend to form an embryonic cell at high cyclic strain ranges. Whereas it is well defined cell of dislocations at 673K.

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