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Crack Growth Rate of Zirconium Alloys Under Sustained and Cyclic Loads

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1. Introduction

Considering that delayed hydride cracking (DHC) in zirconium alloys occurs consecutively by nucleation of hydrides at a crack tip, their growth to the critical length and their cracking, the crack growth rate (CGR) should be governed by the slowest process among the above-mentioned three processes. However, this kind of kinetic approach has never been considered before. The aim of this study is to demonstrate that the CGR in zirconium alloys is governed by hydride nucleation than the other two processes. Given that the hydride nucleation rate is very effectively affected by crack tip stress states, this study investigated the CGR of Zr-2.5Nb tubes by applying cyclic and sustained loads at a constant temperature of 250°C. Given that the cyclic loads and sustained loads create compressive and tensile stresses, respectively, at a crack tip especially upon unloading [1], the CGR would decrease under the cyclic loads when compared to that under the sustained loads.

2. Experimental Methods

17 mm compact tension (CT) specimens taken from a heat-treated Zr-2.5Nb tube were used to measure the CGR in the axial direction. They were pre-charged to the same hydrogen concentration of 60 ppm H using an electrolytic method. DHC tests were conducted at the constant temperature of 250°C under either constant loads or cyclic loads so as to change the load ratio R from 0.13 to 1. In case of cyclic loads, loading frequency was set at 1 cycle/min. Details of the DHC test methods under cyclic loads are given elsewhere [2].

3. Results and Discussion

To identify the effect of crack tip stress states on the CGR, the tension-tension cyclic loads with the load ratio of R changing from 0.13 to 1 were applied to a heat-treated Zr-2.5Nb tube in the DHC tests at 250°C. As expected, the CGR decreased linearly with decreased R, as shown in Fig. 1. To assess the effect of the cyclic loads on the hydride cracking rate, the striation spacing was investigated with R. It was found that the striation spacing decreased with decreasing R. Considering that the striation spacing represents the critical hydride length above which hydrides start cracking, it is clear that cyclic loads promote hydride cracking, increasing the hydride cracking rate with decreasing R. Nevertheless, the CGR was reduced with decreasing R although hydride cracking was enhanced with

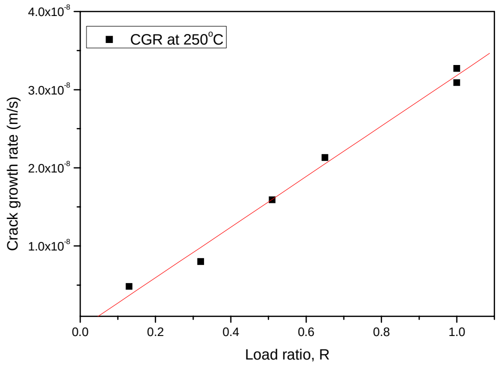
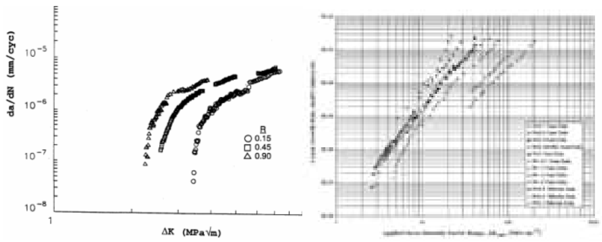


Fig. 1. Crack growth rates at 250°C of a heat-treated Zr-2.5Nb tube under cyclic loads with the load ratio, R changing from 0.13 to 1.



(a) (b)

Fig. 2. Crack growth rate da/dN of (a) AERMET 100 steel [3] and Ti-6Al-4V [4] with R.

decreasing R. This finding demonstrates that the rate-controlling step for the CGR is not the enhanced hydride cracking rate under the cyclic loads but the hydride nucleation rate. It should be noted that the hydride growth rate governed only by hydrogen diffusion is disregarded at a fixed temperature. Thus, we suggest that the decreased CGR under cyclic loads when compared to under sustained loads is due to compressive stresses arising upon unloading under cyclic loads, lowering the hydride nucleation rate. In support of this hypothesis is Sun's experiment[1] where compressive strains occurred ahead of a crack tip of CT specimens of a Type 316 LN stainless steel under cyclic loading and furthermore they increased with decreasing R. Consequently, the decreased CGR with decreasing R shown in Fig. 1 is due to the deceased hydride nucleation rate caused by the presence of compressive stresses in the plastic zone ahead of a crack tip.

In most metals [3-5] including hydride-forming metals subjected to cyclic loads, the crack growth rate or da/dN also turns out to decrease with decreasing R as shown in Fig. 2 Thus, it seems that the decreased CGR with decreasing R is a general pattern of crack growth in metals under cyclic loads. Despite a hypothesis that crack closure is the cause of a slower crack growth rate at the lower R, this study suggests that the CGR is governed by nucleation of hydrides in the hydride forming metals or by nucleation of cracks by the formation of voids in the non-hydride-forming metals.

3. Conclusions

Under cyclic loads, the CGR and striation spacing decreased with decreasing load ratio, R when compared to those under sustained loads. In other words, the cyclic loads promoted cracking of the hydrides but decreased the CGR. This decrease of the CGR with decreasing R is due to compressive stresses (strains) at a crack tip, making the hydride nucleation rate slower than other processes. Consequently, it is demonstrated that under cyclic loads the CGR in zirconium alloys is governed by the hydride nucleation rate. Furthermore, it is suggested that the decreased crack growth rate, da/dN with decreasing R may be caused by nucleation of cracks or voids at a crack tip, not by crack closure.

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