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Strain-hardening influence on iodine induced stress corrosion cracking of Zircaloy-4

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Abstract

The iodine induced stress corrosion cracking (SCC) of recrystallized Zircaloy-4 is first intergranular, and then turns to transgranular propagation, before leading to final ductile rupture. In order to progress in the identification of the factors enhancing transgranular propagation of SCC cracks, the effect of strain-hardening on SCC propagation modes is studied. Fractographic observations by SEM of as-received or pre-strained specimens, submitted to iodine methanol under constant load until rupture, show that strain-hardening enhances transgranular propagation of SCC cracks. This propagation mode is associated with a significant acoustic emission. On the base of these results and metallographic observations and texture measurements, the mechanisms associated with strain-hardening at grain scale and their potential consequences on transgranular initiation and propagation of SCC cracks are discussed.

1. Introduction

Zirconium alloys are used in nuclear power reactors as fuel rod cladding and also as structural material in the reactor core. Under power transient conditions, the fuel rod cladding is susceptible to stress corrosion cracking (SCC), induced by the iodine liberated during the nuclear fission of uranium. On a phenomenological point of view, iodine induced SCC failures of zirconium alloys are described in three steps: localization of iodine attack – intergranular development – transgranular propagation (Fig. 1) [1], before final ductile fracture. The proportions of intergranular to transgranular cracking depend on alloy composition and aggressive iodine environment nature [2]. Transgranular propagation occurs by cleavage-like on basal planes and fluting. It is the result of a competition between a plastic accommodation of the applied strain and the brittle fracture of basal planes by iodine assisted cleavage. For both intergranular and transgranular cracking, an iodine adsorption mechanism along the crack walls and at crack tip may be involved [3,4]. For intergranular crack development, adsorption can be assisted by either a dissolution mechanism or the formation of zirconium iodides [5–7]. On the other hand, for transgranular cracking, some calculations [4], confirmed by ab-initio modeling [8], show that iodine adsorption induces a reduction of the Gibbs surface energy, which affects preferentially the basal plane.

In general, crack velocity depends on environmental parameters such as electrochemical potential, nature and concentration or partial pressure of chemical species, temperature; on metallurgical parameters such as alloy composition, texture, yield strength; and on mechanical parameters such as nature, level and orientation of the applied stress, stress intensity factor, strain rate. For the particular case of iodine induced SCC of zirconium alloys, the critical parameters relative to each of the three steps involved in the cracks development are gathered in Table 1.

As far as transgranular cracking is concerned, the specimen texture appears to be the main controlling parameter for unirradiated Zircaloy-4 [9]. It is quantified by an angular parameter Φ^*, describing the variation in preferential orientation of the c-axis in the RT plane (Fig. 2). When

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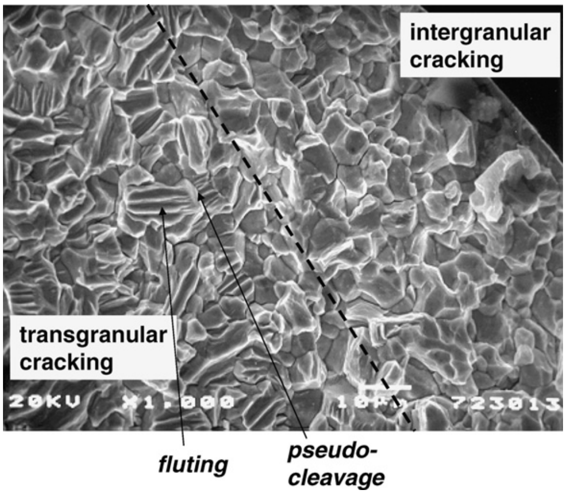

Fig. 1. Intergranular development of SCC cracks, followed by transgranular propagation with cleavage-like and fluting (SSRT on irradiated Zircaloy-4 in a 5×10^{-6} g/g iodine methanol solution at ambient temperature) [1].

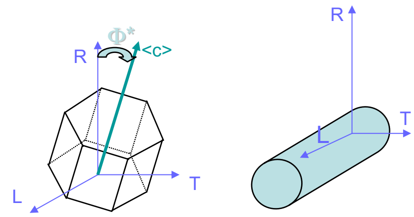

Fig. 2. Definition of angle Φ^*, representative of material texture effect on transgranular cracking (L: rolling direction, T: transverse direction, R: radial or normal direction).

the deviation from the preferential c-axis orientation is increased towards the radial direction, the threshold value being around 30° [9], transgranular cracking occurs as soon as the stress intensity factor overshoots a threshold value $K_{\text{I-SCC}}$ [6].

Yet, the effect of strain-hardening on iodine induced stress corrosion cracking of zirconium alloys, in particular on cracks propagation modes, was poorly studied. On the other hand, few studies deal with the use of acoustic emission to monitor zirconium alloys SCC [10,11], whereas this technique is widely used in the particular domain of materials embrittlement by SCC processes [12,13].

In that context, the purpose of that study is to gain insight in the effects of strain-hardening on cracks propagation modes, and more generally in the understanding of the mechanisms involved in SCC cracks development. A strain-hardening pre-treatment is applied on Zircaloy-4 samples. Resulting microstructures are characterized with attention paid to respective activation of twinning and gliding during strain-hardening pre-treatments. Pre-strained or

Table 1
Parameters influencing the different steps of iodine induced SCC of Zircaloy-4

	Initiation	Intergranular development	Transgranular propagation
Environmental parameters	Iodine concentration or partial pressure		
	Oxygen partial pressure		
	Temperature		
Mechanical parameters	Local plastic strain		Stress intensity factor
	Strain rate		
	Stress level and orientation		
Metallurgical parameters	Grain orientation		Texture

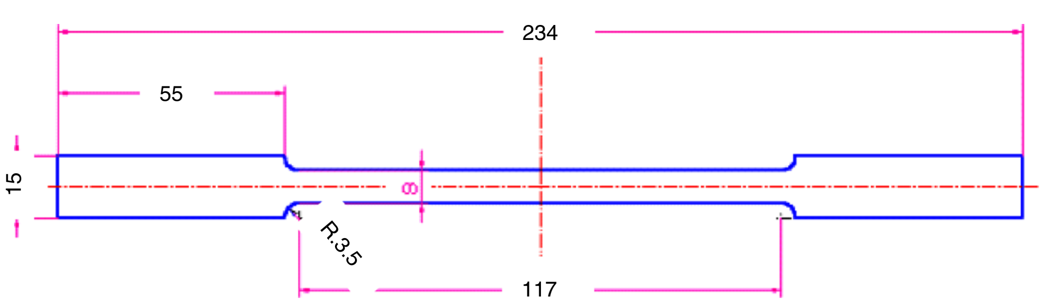

Fig. 3. Tensile specimens shape (dimensions in mm).