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Prediction of cleavage crack propagation path in a nuclear pressure vessel steel

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ABSTRACT

A propagation criterion based on maximum principal stress is proposed to predict the cleavage crack propagation in a nuclear vessel steel. Experiments are performed on three specimen geometries: standard Compact Tensile, precracked ring (mixed mode) and Extended Compact Tensile. Their crack paths are respectively directionally stable and straight, directionally stable and curved, directionally unstable and deflected. Numerical computations are performed by eXtended Finite Element Method. The propagation criterion, combined with a deterministic direction criterion based on the maximum hoop stress provides good predictions for directionally stable crack paths whereas predicting directionally unstable crack paths requires a probabilistic direction criterion.

1. Introduction

The safety demonstration of the PWR (Pressurized Water Reactor) vessel is based on the defect assessment of the vessel subjected to a pressurized thermal shock. In France, this demonstration is limited to the crack initiation: the crack extension is not considered, even if a crack arrest can be demonstrated using a specific criterion.

Therefore, the codified approach to predict the crack arrest in vessel steels, as proposed in the ASME code [1] is not considered for the demonstration performed in France. The ASME method is based on the crack arrest toughness K_{Ia}. This parameter, introduced by Irwin [2], is deduced from a static analysis. This crack arrest criterion is accepted in several countries such as US. It has been verified by the experimental evidence on mock-up tests [3]. However, its physical fundament is considered to be insufficiently understood. That's why a comprehensive work is needed to understand the phenomena involved in the crack arrest process. It can be helpful to consolidate the codified approach and furthermore, to propose a more physical criterion.

In fact, the standard codified approach based on crack arrest toughness K_{Ia} is questionable for at least two main reasons:

- K_{Ia} is evaluated by static analysis. However, some studies [4,5] highlight the important role played by dynamic effects during the cleavage crack propagation and arrest. The authors point out that there is a difference between the true dynamic Stress Intensity Factor (SIF) and SIF obtained by static analysis. More precisely, it can be summarized as follows:
  - o Immediately after the crack initiation, the dynamic SIF is smaller than the static SIF, because a part of elastic energy stored in the specimen is converted to kinetic energy after crack initiation.
  - o Then, the dynamic SIF exceeds gradually the static SIF. That is due to the conversion of kinetic energy to strain energy as the

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Nomenclature

a, $\dot{a}$	crack length, crack propagation speed
A,B	parameters in the critical stress formulation
B_0	thickness of specimen
da	increment of crack propagation
dt	increment of time
D,p	parameters in Cowper-Symonds law
K_{Ic}	crack initiation toughness
K_{Ia}	crack arrest toughness
r_c	critical distance in RKR model
r_p	radius of plastic zone at crack tip
T	temperature
W	width of specimen
$\dot{\varepsilon}$	plastic strain rate
ε^p	equivalent plastic strain at crack tip
$\dot{\varepsilon}^p$	equivalent plastic strain rate at crack tip
θ, θ_c	angle to descript the direction of crack propagation
σ_I	maximum principal stress
σ_{Ic}	dynamic critical stress in RKR model
σ_{Ic0}	static critical stress in RKR model
σ_y	yield stress
$\sigma_{\theta\theta}$	hoop stress

Principal abbreviations

CT specimen	compact tensile specimen
CT25 (or standard CT25) specimen	CT specimen with a 25 mm thickness
CMOD	crack mouth opening displacement
fps	frame per second, unit of framing rate of camera
FE method	finite element method
PWR	pressurized water reactor
RKR	Ritchie, Knott and Rice model
SEM	scanning electron microscopy
X-FEM	eXtended Finite Element Method

crack speed decreases down to arrest.

o After crack arrest, the dynamic SIF oscillates around the static SIF. This oscillation is strong in the beginning and it damps out with time.

Consequently, in order to depict properly the dynamic crack propagation, arrest and possible reinitiating events in real specimens, some authors find that it is important to take into account the inertial effects [6,7].

- The transferability of K_{Ia} from laboratory specimens to structural components is difficult to ensure. In fact, experimental results [3] show that the value of K_{Ia} depends not only on the materiel properties but also on the specimen geometry. Moreover, the values of K_{Ia} are dispersed especially at high temperature and this dispersion has not been yet explained because the phenomenon of crack arrest is complex due to the dynamic effects.

As an alternative, the local approach provides a better description of the phenomena at the crack tip, and it is more suitable to address transferability issues. The model proposed by Ritchie, Knott and Rice (or RKR model) is one of the first precursory models to predict crack initiation [8]. According to this model, the cleavage crack initiates as soon as the maximum principal stress (σ_I) reaches a critical stress (σ_{IC}) at a critical distance ahead of crack tip (r_c). The distance r_c depends only on the material microstructure. After that, some probabilistic models have been developed such as Beremin model [9]. This type of model is based on a probabilistic description of the phenomena involved in the cleavage fracture initiation.

Inspired by models dedicated to the crack initiation, some adaptions are proposed to extend these models to the cleavage crack propagation and arrest. For example, Iung and Pineau [10] evaluate the crack arrest toughness K_{Ia} by applying the Beremin model and the RKR model. In order to take into account the dynamic effects, the yield stress (σ_y) in their studies depends not only on the temperature (T), but also on the stain rate ($\dot{\varepsilon}$). Authors find that, contrary to crack initiation, the weakest link theory related to the Beremin model is not appropriate in case of cleavage crack propagation and arrest.

The local criterion of RKR type to predict crack propagation and arrest is defined by Eq. (1): the cleavage crack propagates as soon as the maximum principal stress (σ_I) attains a critical stress (σ_{IC}) at a critical distance ahead of crack tip (r_c), otherwise, the crack arrest occurs.

$$f(\sigma) = \sigma_I(r_c) - \sigma_{IC}(r_c) = 0\dot{a} > 0 f(\sigma) = \sigma_I(r_c) - \sigma_{IC}(r_c) < 0\dot{a} = 0 \tag{1}$$

where $\dot{a}$ is the speed of crack propagation.

Different criterions based on the critical stress (σ_{IC}) are developed in the following works:

- Hajjaj et al. [12,31] and Dahl et al. [3,13] propose that the critical stress (σ_{IC}) depends only on the temperature (T) and follows an exponential law similar to the well-known relationship between the cleavage toughness of ferritic low alloy steels and the temperature. This proposition is based on experiments performed on precracked discs subjected to an intense thermal shock (without mechanical load). The material used in their studies is a bainitic steel 18MND5.
- In order to evaluate the effect of local variation in the microstructural resistance, Berdin [14] introduces a Weibull distribution into the critical stress (σ_{IC}) proposed by Hajjaj et al. and Dahl et al. [12,13]. The author finds that this local variation in σ_{IC} affects neither the distance of crack propagation, nor the shape of crack front. This result shows that, contrary to crack initiation, the cleavage crack propagation and arrest are related to a collective behavior of grains.
- Meanwhile, Prabel et al. [15,16] and Bousquet et al. [17,18] propose that the critical stress (σ_{IC}) depends on the equivalent plastic