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Impacts of weld residual stresses and fatigue crack growth threshold on crack arrest under high-cycle thermal fluctuations

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HIGHLIGHTS

- For crack growth analysis, weld residual stress field must be considered through its SIF in presence of a crack.
- Presence of cracks of same depth proves their arrest, where equal depth is because mean stress acts only on crack opening.
- Not considering amplitudes under a fatigue crack growth threshold (FCGT) does not compensate the lack of FGCT in Paris law.
- Propagation rates are close for axisymmetric and circumferential semi-elliptical cracks.

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ABSTRACT

High cycle thermal crazing has been observed in some residual heat removal (RHR) systems made of 304 stainless steel in PWR nuclear plants. This paper deals with two types of analyses including logical argumentation and simulation. Crack arrest in networks is demonstrated due to the presence of two cracks of the same depth in the network. This identical depth may be proved assuming that mean stress acts only on crack opening and that cracks are fully open during the load cycle before arrest.

Weld residual stresses (WRS) are obtained by an axisymmetric simulation of welding on a tube with a chamfer. Axisymmetric and 3D parametric studies of crack growth on: representative sequences for variable amplitude thermal loading, fatigue crack growth threshold (FCGT), permanent mean stress, cyclic counting methods and WRS, are performed with Code_Aster software using XFEM methodology. The following results are obtained on crack depth versus time: the effect of WRS on crack growth cannot be determined by the initial WRS field in absence of crack, but by the associated stress intensity factor. Moreover the relation between crack arrest depth and WRS is analyzed.

In the absence of FCGT Paris's law may give a significant over-estimation of crack depth even if amplitudes of loading smaller than FCGT have not been considered. Appropriate depth versus time may be obtained using different values of FCGT, but axisymmetric simulations do not really show a possibility of arrest for shallow cracks in contrast with logical argumentations.

1. Introduction

Thermomechanical crazing (shallow and dense unidirectional or multidirectional crack networks), was discovered (Molinie et al., 2002; Robert, 2004) in some nuclear power plants in different areas of RHR systems made of 304 ASS (Fig. 1a). The crack nucleation has been attributed to high cycle variable amplitude thermal load in the mixing zones of cold and hot water flows of RHR systems. Fig. 1b gives 10 s of temperature variation in the fluid on a location on Father mock-up of a RHR systems (Le Duff et al., 2011; Courtin, 2013). This is a broad band thermal loading where significative values of DSP are obtained between 0.1 Hz and about 6 Hz in the fluid (Vincent et al., 2009). Several detrimental factors impact crack nucleation in RHR systems such as stress singularities at welding toe, surface slope change, and surface roughness. But pre-hardening (Taheri et al., 2015a) (due to surface treatment under high compression) and weld tension residual stresses are also detrimental factors on which less attention has been paid. The effects of these factors are amplified due to the dispersion on

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Nomenclature

AC	all cycles
ASS	austenitic stainless steel
EDF	Electricite De France
FCGT	fatigue crack growth threshold
FCGR	fatigue crack growth rate
FEM	finite element method
XFEM	extended finite element method
RSE_M	French nuclear maintenance code for nuclear plants
NO-FCGT	Paris law parameter identification without FCGT
RHR	reactor heat removal
SIF	stress intensity factor
VA	variable amplitude
WRS	weld residual stress
2D	axisymmetric XFEM simulation
3D	tridimensional XFEM simulation
ΔK	stress intensity factor variation in mode I
ΔK_{th}	fatigue crack growth threshold for long cracks in mode I
σ_m	mean stress
K_I	SIF in mode I
ΔT	temperature variation
K_{mean}	mean value of SIF

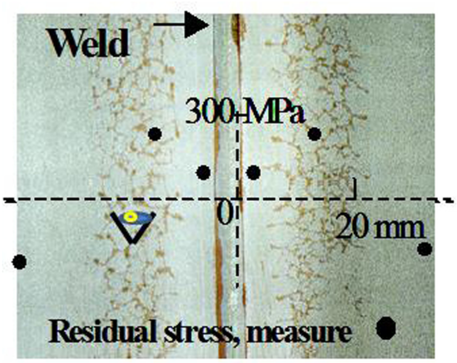

Fig. 1a. Crack networks near a weld seam in a RHR system.

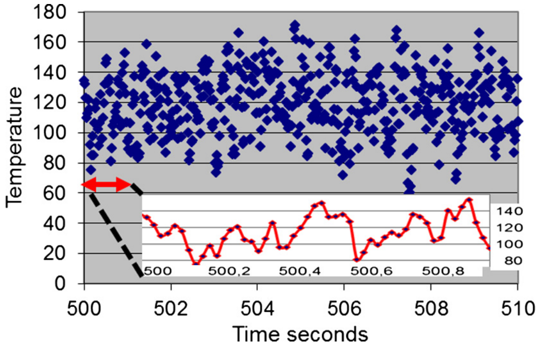

Fig. 1b. A portion of the thermal loading sequence revealed on the mock-up Father of a RHR system (500 points).

fatigue life as the thermal load amplitude is close to the fatigue limit of a 304 stainless. All affected RHR systems were changed in French power plants by improving the inner surface, e.g. by polishing and eliminating stress concentration zones such as weld toes. Research work has been undertaken to study the conditions of nucleation and crack arrest in high-cycle variable amplitude thermal fatigue in RHR systems.

From the operational feedback on different areas of RHR systems of 900, 1300 and 1450 MWa plants, it was deduced (Molinie et al., 2002; Robert, 2004) that maximum crack depth after 3000 h of operation is smaller than about 2.5 mm for all cracks in networks (Fig. 1c). This has suggested the possibility of crack arrest when cracks have a maximal depth about 2.5 mm (Kamaya and Taheri, 2008; Sbitti and Taheri, 2010). Axisymmetric and 3D simulations (Taheri, 2007) for a tube under constant amplitude thermal loading on the internal face have shown that for fully circumferential cracks the stress intensity factor variation (ΔK) as a function of crack depth may become decreasing at a certain depth. Parametric studies (Kasahara et al., 2002; Taheri, 2007) on thermal load amplitude, thermal exchange coefficient, and the frequency of thermal loading show the particular importance of frequency of thermal loading on decreasing of the ΔK. A decreasing ΔK is obtained for high frequencies of loading as the stress amplitude vanishes quickly in the depth. Due to the existence of a FCGT for a 304 ASS (Lesur, 2005; Le-Roux and Akamatsu, 2002) the crack may stop propagating when ΔK becomes equal to FCGT. As cracks stop propagating, but nucleation at different locations continues, crack density increases and thermal crazing appears. This analysis on the possibility of crack arrest is a proposition and not a proof of crack arrest before replacing RHR systems. A proof of crack arrest will be given in Section 2.

It is moreover shown that the deepest cracks of the same depth in a network have not been submitted to a mutual shielding effect (Sbitti and Taheri, 2010), so only single cracks may be considered for FCGR study.

To determine FCGR under elasticity hypotheses the French maintenance code for nuclear power plants RSE_M [RSE_M] uses Paris's law without any FCGT where amplitudes of loading under FCGT obtained by cycling counting are not considered in the methodology. However, as will be presented in this paper, simulations performed in the absence of FCGT in Paris's law with a commonly used mean stress of 50 MPa show that for Father loading, too conservative results on crack depth are obtained (predicted depths are much larger than crack depths observed on components). But the simulation of ΔK under a constant amplitude loading $\Delta T = 100\,^{\circ}\mathrm{C}$ which is higher than amplitudes obtained from Father experiment, with a zero mean stress may give a good order of crack depth at arrest about 2 mm (Sbitti and Taheri, 2010). This is why in this paper extensive analyses on FCGT and mean stresses and WRS are performed.

An important difference has to be noticed between the study of crack arrest and obtaining a validated FCGR by numerical modelling. For the first one (in axisymmetric case) only comparison between variation of SIF and ΔK_{th} of long cracks is needed, as maximal crack depths are sufficiently large in both RHR systems and Father mock-up. For the second one validation on a structure is more difficult, as for example in Father experience, 300 h of experimentation includes nucleation time, short crack propagation and long crack propagation time. In this case only qualitative analysis of simulations results on cracks depths may be proposed.

The impact of WRS is another outcome of this work where its effect on crack nucleation has been proved on RHR systems (Taheri, 2007; Lei et al., 2014; Taheri et al., 2015b). Moreover maximum crack depths in networks are larger in the vicinity of welds