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Effects of remedial actions on small piping reliability

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Abstract

This article describes probabilistic calculations that address intergranular stress corrosion cracking of stainless steel piping; a degradation mechanism of major concern to nuclear pressure boundary integrity. The objective is to simulate the cracking of stainless steel piping under intergranular stress corrosion cracking conditions, and to evaluate the structural reliability using remedial actions for intergranular stress corrosion cracking that are limited to benefits of in-service inspections and the induction heating stress improvement process. The results show that an effective in-service inspection requires a suitable combination of flaw detection capability and inspection schedule, and it has been suggested that the residual stresses could be altered to become favorable, thereby improving the reliability piping.

Keywords

Probabilistic fracture mechanics, stress corrosion cracking, structural reliability, in-service inspection, Monte Carlo simulation

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Introduction

One of the important degradation mechanisms to be considered for alloyed steels is stress corrosion cracking (SCC). This mechanism causes cracking in the material owing to the combined action of a susceptible material, a tensile stress, and a corrosive environment. In boiler water reactor (BWR) piping, the susceptible material is usually AISI 304 stainless steel in a sensitized condition next to weldments. The susceptibility of this material to intergranular SCC (IGSCC) is owing to chromium carbide precipitation in the grain boundaries, which leaves the regions immediately adjacent to these grain boundaries low in corrosion-resistant chromium.[1] The precipitation occurs most commonly under the thermal conditions encountered during welding. The stress is primarily owing to weld shrinkage during fabrication, and the corrosive environment results from coolant oxygen and low impurity levels according to the operating specifications.[2]

The purpose of this article is to apply probabilistic fracture mechanics (PFM) to analyze the influence of remedial actions on austenitic stainless steels piping structural reliability. PFM provides a technique for estimating the probability of failure of a structure or one of its components when such failures are considered to occur as the result of the sub-critical and catastrophic growth of an initial crack-like defect. Such techniques are inherently capable of treating the influence of nondestructive inspections.[3–6] Several articles in the literature[7–11] addressed the probabilistic failure analysis of components subjected to IGSCC. Failure probabilities of a piping component subjected to IGSCC, including the effects of residual stresses, were computed by Guedri et al.[12–13] using Monte Carlo simulation (MCS) techniques.

IGSCC in the heat-affected zones of stainless steel welds is much more difficult to detect by ultrasonic testing (UT) inspection techniques. The IGSCC tends to be extremely tight, and is often highly branched at the crack tip. It is also difficult to distinguish between UT echo signals from cracks and from the weld root. Thus it is very hard to detect IGSCC, and even more difficult to determine the depth accurately.[14] As a result, UT in-service inspection (ISI), conducted in accordance with the minimum requirements of Section XI of the ASME boiler and Pressure Vessel Code, tends to be of little value for this problem.

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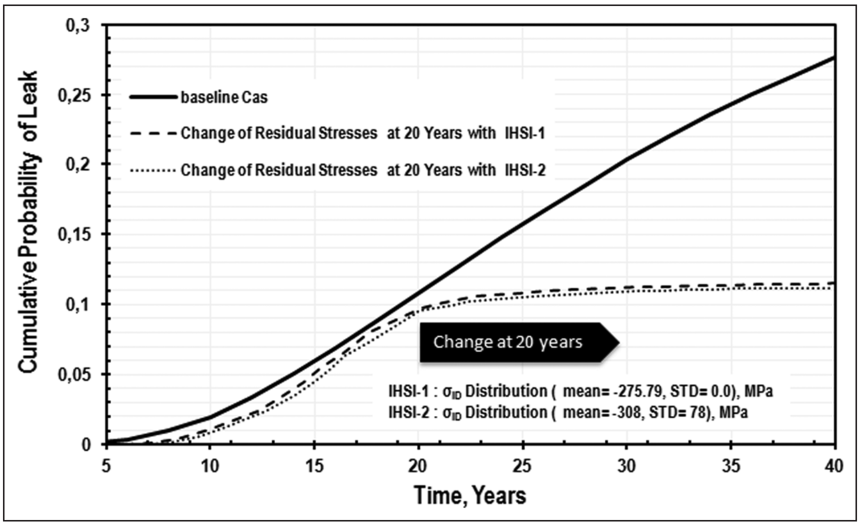

Figure 19. Effect of reducing residual stress at midlife with IHSI process.
IHSI: induction-heating stress improvement.

provide a useful basis to generalize results for piping-leak probabilities. This article has also discussed POD curves and the benefits of ISI in the framework of reductions in the leak probabilities for nuclear piping systems subjected to IGSCC based on Dσ. The results for typical NDE performance levels indicate that low inspection frequencies (one inspection every 10 years) can provide only modest reductions in failure probabilities. More frequent inspections appear to be even more effective. However an "advanced" NDE reliability can achieve a factor of 10 improvements in preventing IGSCC leaks at typical operating conditions even when inspections occur approximately every 10 years; this can be increased to a factor even greater than 10 if the inspection interval is decreased sufficiently. Finally the recommended post-IHSI residual stress has a large effect on reducing the leak probabilities and the lower benefits of ISI for IGSCC can be explained in terms of long incubation periods for stress-corrosion cracking followed by a period of rapid crack growth.

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Appendix I

Notation

a	crack depth
A_{0-6}	coefficients computed from the table given in ASM Handbook
A_{cr}	area of crack
A_p	area of cross-section of pipe
b	one-half of crack length
C_1–C_9	material dependent constants
C_{12}, C_{13}, C_{15}	material dependent constants

C_{14}	material dependent random variable
d	spacing between two cracks
D_σ	damage parameter
E	modulus of elasticity
f_1	sensitization term
f_2	environmental term
f_3	loading term
F	material dependent random variable
G	material dependent constant
h	pipe wall thickness
J	material dependent random variable
K	stress intensity factor
K_a	stress intensity factor in the depth direction of crack
K_{ap}	stress intensity factor for applied stress
K_b	stress intensity factor in the length direction of crack
K_{res}	stress intensity factor for residual stress
l, l_1, l_2	crack length
n	number of possible initiation sites in the pipe
N	number of simulations
N_T	total number of simulations
N_f	number of failure cases
O_2	oxygen concentration
Pa	degree of sensitization
P_f	probability of failure
Q	leak rate
Ri	internal radius of pipe
t_I	time to initiation of stress corrosion cracking
T	temperature
v_1	initiation crack growth velocity
v_2	fracture mechanics based crack growth velocity
W	width of the plate
γ	water conductivity
δ	crack opening displacement
ε	smallest possible PND for very large cracks
σ	applied stress
σ_f	flow stress
σ_{ID}	stress at ID
σ_{LC}	load-controlled component of stress
σ_{net}	net-section stress
σ_{OD}	stress at OD
υ	Poisson's ratio
φ	parametric angle measured from the plate surface toward the centre of the crack