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Stress corrosion crack initiation in Alloy 690 in high temperature water

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ABSTRACT

Initiation of stress corrosion cracks in Alloy 690 in high temperature water is a rare occurrence and depends on the method by which the sample is loaded. Only in dynamic straining experiments is crack initiation consistently observed. Stress relaxation in constant deflection tests, and lack of a means of rupturing the oxide film in constant load tests are the principle reasons for the difficulty of initiating cracks in these tests. These observations, combined with those from the much more susceptible Alloy 600 form the basis for a mechanism stress corrosion crack (SCC) initiation of Alloy 690. SCC initiation is proposed to occur in three stages: an oxidation stage in which a protective film of Cr_2O_3 is formed on the surface over grain boundaries, an incubation stage in which successive cycles of oxide film rupture and repair depletes the grain boundary of chromium, and a nucleation stage in which the chromium depleted grain boundary is no longer able to support growth of a protective chromium oxide layer, resulting in formation and rupture of oxides down the grain boundary. The mechanism is supported by the available literature on oxidation and crack initiation of Alloy 690 in hydrogenated primary water conditions.

1. Introduction

Stress corrosion cracking (SCC) of Alloy 690 in high temperature water has been extensively studied since the 1970s as the Alloy was introduced into pressurized water nuclear reactor (PWR) steam generators as replacement tubing for Alloy 600 (N06600) in 1979, and later for vessel head penetration nozzles [1]. Given the past experience with the long incubation time to crack initiation in Alloy 600, there is concern that SCC could eventually occur in Alloy 690. There has been no evidence of primary water stress corrosion cracking (PWSCC) of Alloy 690 in steam generators since its introduction. Current regulations allow for a life extension of the 40-yr operating license of a PWR for an additional 20 yr to a total of 60 yr. With the prospect of a second life extension, operating lifetimes could approach 80 yr, emphasizing the need to understand degradation modes of materials that have shown excellent resistance to date.

Both crack initiation and crack growth are important in assessing the resistance of an Alloy to stress corrosion cracking. While crack growth rates (CGR) in pre-cracked Alloy 690 laboratory samples are generally extremely low [2,3], cold work has been observed to increase the crack growth rate significantly (by up to several orders of magnitude), especially in thermally treated (TT) condition [4,5]. The Electric Power Research Institute (EPRI) has an ongoing program to investigate the role of cold work in SCC of Alloy 690 in the form of an expert panel that meets annually to review ongoing research. For crack growth to be of significance, cracks must first nucleate. While Alloy 690 has proven to be very resistant to crack nucleation both in service and in laboratory studies, experience with Alloy 690 has shown that it can indeed, occur. It is the objective of this study to review what is known about crack initiation in this Alloy and to propose a mechanism for crack nucleation.

The difficulties associated with generating cracks in Alloy 690 have been an impediment to the study of the mechanisms of SCC initiation. Alloys of similar composition, such as the lower chromium nickel based Alloy 600, crack readily in high temperature water, allowing researchers to study the SCC behavior in depth and postulate mechanisms to explain the observed cracking behavior. The higher chromium content of Alloy 690 is believed to be the primary factor contributing to its resistance to IGSCC initiation. Thus, while it is not the objective of this paper to review SCC of Alloy 600, lessons learned in studying this Alloy will be employed here in an effort to elucidate the mechanism by which crack initiation occurs in Alloy 690. Techniques used for evaluating the SCC initiation susceptibility can be categorized as either constant strain, constant load, or constant extension rate tensile (CERT) tests. As will be shown, the nucleation of IGSCC in Alloy 690 is highly dependent on the test technique, and therefore, the following section will review crack initiation in Alloy 690 by technique. Results are summarized in Table 1.

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Table 1
Summary of SCC initiation work on Alloy 690 in simulated PWR primary water.

Ref.	Material condition	Water chemistry	Test technique	Test duration	Result
Constant deflection test					
[6]	MA and TT	316–360 °C oxygenated or deaerated water in static autoclave	Double U-bend	Up to 10,080 h	No cracking
[7]	MA and TT	360 °C water with 3.8 ppm H_2 and, 1200 ppm B + 2 ppm Li or 200 ppm B + 0.5 ppm Li	Reverse U-bend	Up to 16,000 h	No cracking
[8]	MA and TT	360 °C water with 30 cc H_2/kg H_2O and 500 ppm B + 1–2 ppm Li,	Reverse U-bend	12,000 h	No cracking
[9]	MA and TT, aged at 500 °C for 24 or 100 h	330 °C hydrogen saturated water with 1000 ppm B + 2 ppm Li, renewed every 250 h	Reverse U-bend	3000 h	Max IG crack depth of 70 µm
[10]	TT	340 °C pure deaerated water	C-ring test	1800 h	No cracking
[11,12]	MA and TT	365 °C water with 4–6 ppm H_2 in once-through autoclaves	Reverse U-bend	Up to 33,000 h	No cracking
[13]	20% pre-strained Alloy 690TT	360 °C water with 30 cc H_2/kg H_2O and 500 ppm B + 2 ppm Li, or 280 ppm B + 2 ppm Li, or1600 ppm B + 2 ppm Li, or 1600 ppm B + 3.5 ppm Li in refreshed autoclave	Reverse U-bend	Up to 10,015 h	No cracking
[14]	As received	350 °C water with 1200 ppm B + 2.2 ppm Li, or 1800 ppm B + 3.5 ppm Li, and 40 ppb Zn in once-through autoclave	Reverse U-bend	15,000 h	No cracking
[15]	MA and TT	365 °C pure water with 50 cc H_2/kg H_2O	Reverse U-bend	Up to 33,000 h	No cracking
[16]	TT	360 °C PWR primary water with 23–35 cc H_2/kg H_2O in static autoclave	Reverse U-bend	Up to 90,000 h	No cracking
[17]	TT	360 °C pure water with 3 bar H_2, or PWR primary water with 0.16–0.5 bar H_2 and 1000 ppm B + 2 ppm Li	Reverse U-bend	Up to 46,000 h	No cracking
[18]	MA and TT	360 °C water with 1000 ppm B, 2 ppm Li, 167 cc H_2/kg H_2O in static autoclave	Reverse U-bend	Up to 60,000 h	No cracking
[19]	Hot-extruded + TT, hot-rolled	360 °C water with 30 cc H_2/kg H_2O, and 1000 ppm B + 2 ppm Li	C-ring test	Up to 3600 h	No cracking
[20]	TT	380 °C hydrogenated steam, H_2/H_2O ratio ≈ 0.04 in static autoclave	Reverse U-bend	Up to 13,824 h	One heat cracked
[1]	TT	400 °C hydrogenated steam, H_2/H_2O ratio ≈ 0.0055	Reverse U-bend	Up to 9720 h	No cracking
Constant load test (CLT)					
[8]	MA and TT	360 °C water with 30 cc H_2/kg H_2O, and 500 ppm B + 1–2 ppm Li	Constant load (414–621 MPa)	7000 h	No cracking
[13]	20% pre-strained Alloy 690TT	360 °C water with 30 cc H_2/kg H_2O and 500 ppm B + 2 ppm Li, or 280 ppm B + 2 ppm Li, or1600 ppm B + 2 ppm Li, or 1600 ppm B + 3.5 ppm Li in refreshed autoclave	Constant load (586 MPa)	10,000 h	No cracking
[17]	TT	360 °C primary water	Constant load at 684 or 580 MPa	10,900 h at 684 MPa, 18,500 h 580 MPa	No cracking
[21]	TT	360 °C water with 30 cc H_2/kg H_2O and 1000 ppm B + 2 ppm Li,	From 603 to 684 MPa	11,000 h	Crack depth <10 µm
[22]	TT	360 °C water with 500 ppm B + 2 ppm Li	Constant load (~300 to ~550 MPa)	123,000 h	No rupture
[23,24]	TT + Cold worked	320–360 °C water with 0–45 cc H_2/kg H_2O and 500 ppm B + 2 ppm Li in refreshed autoclave or 360–460 °C air, or H_2 in argon	Constant load on BNT (30 $MPa{\cdot}m^{1/2}$)	Up to 34,484 h	No cracking in water
			Constant load on precracked CT(23–40 $MPa{\cdot}m^{1/2}$)	Up to 26,576 h	IG cracks with cavities in both water and gas
[25,26]	TT + Cold worked	360 °C water with 1000 ppm B, 2 ppm Li, 25 cc H_2/kg H_2O	Constant load on tensile bars (510 to 700 MPa)	Up to 9950 h	IG cracks with cavities
			Constant load on BNTs with dynamic loading (27.5–37 $MPa{\cdot}m^{1/2}$)	Up to 11,816 h	IG cracks with cavities
Constant extension rate tensile (CERT) test					
[17]	TT	360 °C primary water with0.16–0.5 bar H_2 and 1000 ppm B + 2 ppm Li	Strain rate 5×10^{-8}/s	Up to necking	5–65 µm deep IG cracks
[18]	MA and TT	360 °C water with 25–30 cc/kg H_2O and 1000 ppm B + 2 ppm Li in static autoclave	Strain rate 5×10^{-8}/s	Up to failure	20–120 µm deep IG cracks
[19]	Aged, Hot-extruded + TT, hot-rolled + cold rolled	360 °C water with 5–60 cc H_2/kg H_2O, and 1000 ppm B + 2 ppm Li	Strain rate 4×10^{-8}/s	20% elongation	One heat cracked with depth up to 18 µm
[21]	TT	360 °C water with 30 cc H_2/kg H_2O, and 1000 ppm B + 2 ppm Li	Strain rate 5×10^{-9}-2.5×10^{-7}/s		40–225 µm deep IG cracks

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