Journal of Nuclear Materials 503 (2018) 13–21

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

d*K*/d*a* effects on the SCC growth rates of nickel base alloys in high-temperature water

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A R T I C L E I N F O

Article history:
Received 26 October 2017
Received in revised form
8 January 2018
Accepted 20 February 2018
Available online 22 February 2018

Keywords:
d*K*/d*a*
Stress corrosion cracking
Crack growth rate
High temperature water

A B S T R A C T

The effect of d*K*/d*a* on crack growth behavior of nickel base alloys has been studied by conducting stress corrosion cracking tests under positive and negative d*K*/d*a* loading conditions on Alloys 690, 600 and X-750 in high temperature water. Results indicate that positive d*K*/d*a* accelerates the SCC growth rates, and the accelerating effect increases with d*K*/d*a* and the initial CGR. The FRI model was found to underestimate the d*K*/d*a* effect by ~100X, especially for strain hardening materials, and this underscores the need for improved insight and models for crack tip strain rate. The effect of crack tip strain rate and d*K*/d*t* in particular can explain the d*K*/d*a* accelerating effect.

1. Introduction

Nickel base alloys have been widely used for structural components in light water reactors (LWRs) due to their good high temperature mechanical properties, good weldability and low general corrosion rate [1–4]. However, after long term operation, many nickel base alloy, especially Alloy 600 (UNS N06600), Alloy 182/82 weld metals and Alloy X-750 (UNS N07750) exhibit high susceptibility to stress corrosion cracking (SCC). Alloy 690 (UNS N06690) was developed to replace Alloy 600, and laboratory tests show that Alloy 690 has superior SCC resistance. No instances of SCC in Alloy 690 components have been observed in nuclear power plants after more than 25 years of service.

Laboratory tests on SCC of nickel base alloy in high temperature water have been conducted by many institutions, and crack growth rates (CGR) were measured under various conditions. Large scatter exists in the CGR data, and cold work, inhomogeneity (such as banding) and sensitization are recognized to be major material factors, and load, temperature and water chemistry are mechanical and environmental factors that affect the CGR. Recent tests show medium to high SCC growth rates in cold-worked (CW) Alloy 690 in pressurized water reactor (PWR) [5]. Prediction models are by nature a weak fit to the scattered data. A better understanding of the SCC growth behavior in nickel base alloys is crucial to the safe operation and aging management of key reactor components.

For a growing crack, the stress intensity factor (K) at the crack tip is a major mechanical parameter that affects the crack growth rate. In almost all components, K changes only as the crack advances ($K \propto \sigma\sqrt{a}$), and increases rapidly at the initial and latter stages of crack growth (+dK/da) [6]. The heat affected zone (HAZ) of welds is an area where SCC is often observed because of the high residual stresses and strains that exists through wall. As the crack grows in the HAZ or weld metal, K can rise or fall, due to different through-wall weld residual stress profiles, which are typically U-shaped [6]. However, almost all SCC growth behavior has been studied under constant load or K conditions in laboratory tests, or under uncontrolled and small changes in K that are not representative of dK/da in components. For example, tests at constant load cause a slow increase in K that depends on the type of specimen and crack depth, but the dK/da is very small compared to what can exist in components.

The effect of changing K on SCC growth rate is important for both mechanistic understanding and field application. Andresen and Morra [6–9] reported very different crack growth response for rising vs. falling K conditions in their SCC tests on austentitic stainless steel and nickel base alloys in high temperature water

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https://doi.org/10.1016/j.jnucmat.2018.02.032
0022-3115/

environments. Relevant values of positive dK/da could increase the CGRs significantly, while negative dK/da had essentially no effect.

The only SCC data on dK/da effects relevant to plant components has been reported by Andresen and Morra [6–9]. Several researchers have performed theoretical and experimental efforts on the effect of K on SCC growth rates, but few addressed the importance of dK/da. Pettersson and Jenssen [10] evaluated small values of dK/da within the framework of slip-dissolution/oxidation theory using the FRI model and by finite element calculations of strain gradients at moving crack tips, and concluded there was no significant effect. The only observed dK/da accelerating effect (at low dK/da) was on an irradiated stainless steel, and the authors had little confidence in the result, attributing it to the effect of straightening the uneven crack front [11]. Konig et al. [12,13] observed mild dK/da effects when comparing the SCC response between actively loading and bolt loading techniques, where dK/da resulted from the small K increase with crack advance at constant load. These dK/da effects were limited due to the very small changes in K vs. crack length (e.g., in compact type (CT) specimens) comparing to the controlled and larger dK/da values used in this study and in Refs. [6–9], which are more directly relevant to components.

Hall [14–16] provided an alternative crack tip strain rate equation, which predicted the effect of variable K, dK/dt and dK/da reasonably well. However, the author thought that the creep and creep rate controlled the crack growth rate, which contradicts commonly accepted thinking (and data on creep resistant materials) [17–21] that the crack tip strain rate controls crack growth rate. Hashimoto and Koshiishi [22] modified the FRI equation. The calculated crack growth rates for negative dK/da conditions were in good agreement with the data from Andresen [6]. However, the authors only considered negative dK/da effects (where there is little or no effect) and chose to ignore the positive dK/da accelerating effect in Andresen's results.

In summary, the accelerating effect of dK/da has only recently been considered. Constant K laboratory data can be very non-conservative, since dK/da is the fundamental way K changes in components. Thus, it is essential that dK/da effects be accounted for in the crack growth behavior of materials.

Although Andresen and Morra [6–9] identified the importance of dK/da effects, more systematical studies and reliable data are needed to understand dK/da effects and to improve the prediction of their effect on the remaining life evaluation of components. The purpose of this work is to evaluate the +dK/da accelerating effect on SCC growth rate of nickel base alloys in high temperature water environments, and to evaluate and improve existing models of SCC.

2. Experiment

2.1. Materials and specimens

Three nickel base alloys were obtained from General Electric Global Research Center (GE-GRC) for use in this study: Alloy 690, Alloy 600 and Alloy X-750. Their chemical compositions are listed in Table 1. Before testing, Alloy 690 was cold worked to 30% reduction in thickness by one press forging, and the Alloy 600 was cold forged to 15% reduction in thickness. The cold work broadly simulates the residual strain in the weld HAZ [23,24]. Alloy X-750 is rarely welded and hence was tested in as-received condition.

Three standard 12.7 mm thick compact tension (CT) specimens with 5% side grooves were machined in the S-L orientation (both vs. product form and vs. the plane of deformation) from the test materials. Table 2 lists the ID, alloy, heat, cold work level and heat treatment of the specimens.

2.2. Experimental procedure

The crack length was measured by a reversing direct current potential drop (DCPD) method using platinum current and potential wires spot welded on the CT specimen [25]. The specimens were first pre-cracked by about 1 mm in room temperature air at a cyclic loading frequency of $f = 1$ Hz and a sequence of increasing load ratios R (K_{min}/K_{max}) = 0.1, 0.3, 0.5, 0.7 to reduce ΔK and the cyclically hardened plastic zone. The pre-cracked specimen was subsequently installed in the autoclave for SCC testing. Before acquiring SCC growth rates, transitioning from the fatigue crack to an SCC crack was perfomed by decreasing the loading frequency to 0.001 Hz, then introducing an increasing hold time at K_{max} of 1000–20000 s. Apart from the dK/da test segments, constant K was maintained during measurement of the SCC growth rates by decreasing load as the crack advanced. All parameters, including load, temperature, autoclave pressure, water chemistry parameters, crack length and DCPD potentials were recorded digitally. Crack length and K were calculated based on the load and DCPD (crack length) signals, and their values were used to automatically control the loading machine. For the K-changing phases of the test, ASTM E647 [26] defines a normalized K-gradient C:

$$C = \frac{1}{K}\frac{dK}{da} \tag{1}$$

C was positive in the K-increasing tests, and negative in the K-decreasing tests. During a dK/da test, C is set as a constant, and an ending K is given. Sophisticated control software updated the K and load either after very small increases in crack length (typically < 1%) or after a certain time (usually 2000 s). For example, for $C = 1$ mm^{-1} and $K = 25$ MPa$\sqrt{m}$, the load was automatically adjusted to yield $K = 25.25$ MPa$\sqrt{m}$ after a 0.01 mm increase in crack length according to Equation (1). Sometimes the DCPD readings exhibited higher noise that might exceed the 1% change in crack length threshold usually used. In these cases, the updating of K and load was manually switched to be based on time. The software averaged the crack length over 2000 s, then updated the K and load according to Equation (1). During + dK/da tests, K was often increased from 15 MPa$\sqrt{m}$ to 45 MPa$\sqrt{m}$, with the maximum K designed to ensure that the K dependency on SCC was not altered by excessive plasticity. Andresen and Morra [6–9] conducted dK/da tests by using constant dK/da values, rather than constant C values. These two techniques are similar in that they both update K values only as crack length changes.

Specimens CK1 and CK2 were tested in 360 °C high purity water with a dissolved hydrogen (DH) content of 2.32 mg/kg (26 cc/kg at room temperature and pressure), corresponding to the Ni/NiO

Table 1
Bulk compositions of the three nickel base alloys used in this study (wt%).

Alloy	Ni	Cr	Fe	Ti	Al	Nb	Si	Mn	C	Co	S	P
690	60.4	29.3	9.2	0.37	0.26	–	0.06	0.22	0.034	0.006	<0.003	0.006
600	75.0	15.6	8.4	0.25	0.2	–	0.20	0.19	0.04	0.02	0.001	0.004
X-750	70.8	15.0	7.8	2.4	0.8	1.0	0.25	0.20	0.04	0.73	0.002	<0.005