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A study of life prediction differences for a nickel-base Alloy 690 using a threshold and a non-threshold model

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A R T I C L E I N F O

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A B S T R A C T

In this paper we compare and contrast the crack growth rate of a nickel-base superalloy (Alloy 690) in the Pressurized Water Reactor (PWR) environment. Over the last few years, a preponderance of test data has been gathered on both Alloy 690 thick plate and Alloy 690 tubing. The original model, essentially based on a small data set for thick plate, compensated for temperature, load ratio and stress-intensity range but did not compensate for the fatigue threshold of the material. As additional test data on both plate and tube product became available the model was gradually revised to account for threshold properties. Both the original and revised models generated acceptable results for data that were above 1×10^{-11} m/s. However, the test data at the lower growth rates were over-predicted by the non-threshold model. Since the original model did not take the fatigue threshold into account, this model predicted no operating stress below which the material would effectively undergo fatigue crack growth. Because of an over-prediction of the growth rate below 1×10^{-11} m/s, due to a combination of low stress, small crack size and long rise-time, the model in general leads to an under-prediction of the total available life of the components.

1. Introduction

Nickel-base superalloys are chosen and used in the polycrystalline form in gas turbine engines and a spectrum of other applications of relevant use in the nuclear industry. One of the most critical applications for this material is the high pressure turbine disk. For this particular application fatigue crack propagation under high cycle fatigue conditions is of interest and need. Alloy 690 is a nickel-base superalloy that offers resistance to corrosion and was developed as a viable replacement to the widely used alloy IN 600. The problems with the most widely used nickel-base superalloy IN 600 were that it suffered from environmental degradation such as stress-corrosion cracking (SCC), intergranular attack, and pitting [1]. To facilitate the actual usage of alloy IN 690 in steam generators, a better understanding of mechanical properties and proven fatigue reliability are required. Driven by their promise, recent years have seen several studies on alloy IN 690, which have focused in entirety on understanding microstructural influences on corrosion properties [2–9] and tensile deformation [10,11].

Studying and understanding fatigue crack growth behavior is an important issue in the service life reduction and maintenance of key structural components of a nuclear power plant. Further, since structural components intrinsic to the nuclear plant are exposed to varying environments during operation, designing for enhanced fatigue resistance is an important consideration in the nuclear power industry. Therefore, a precise determination of the fatigue endurance and crack growth characteristics in key structural components of a power plant is essential for the design of safe, reliable and economical structures.

The purpose of this paper is to use the fatigue crack growth rate superposition model (developed at Argonne National Laboratory (USA)) for comparing the predictions of life both with incorporating and without incorporating a fatigue threshold into the model. The Alloy 690 material had a composition (in weight percent) of 61.01% Ni, 28.05% Cr, 10.24% Fe, 0.016% C, 0.22% Mn, 0.22% Si and 0.24% Cu.

2. Background

A simple model for corrosion-fatigue is based on the superposition approach. This model assumes the total crack growth rate in a given environment to be the sum of the rate due to mechanical fatigue plus the rate due to stress-corrosion cracking [12–14]. This basic model is given in Eq. (1) as:

$$\left(\frac{da}{dt}\right) = \left(\frac{da}{dt}\right)_{\mathrm{F}} + \left(\frac{da}{dt}\right)_{\mathrm{SCC}} \tag{1}$$

In this equation (da/dt) represents the total crack growth rate and $(da/dt)_{\mathrm{F}}$ represents the crack growth rate due to mechanical fatigue, while $(da/dt)_{\mathrm{SCC}}$ represents the crack growth rate due to

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stress-corrosion cracking. One of the key assumptions made in this model is that the maximum stress intensity during cyclic loading has to be greater than the initiation stress intensity for stress-corrosion cracking ($K_{\max} > K_{\mathrm{ISCC}}$) before any contribution of the stress-corrosion cracking rate is made to the total rate. Although this assumption is valid for the model, during preliminary experiments on low strength materials, an actual enhancement in corrosion was seen for values of $K_{\max}$ significantly less than K_{ISCC}. To overcome this, a term was added to the above equation [1] to account for material – environment interactions during fatigue. This term accounts for the contribution due to corrosion-fatigue [15–17]. The revised model is now expressed as:

$$\left(\frac{da}{dt}\right) = \left(\frac{da}{dt}\right)_{\mathrm{F}} + \left(\frac{da}{dt}\right)_{\mathrm{SCC}} + \left(\frac{da}{dt}\right)_{\mathrm{CF}} \tag{2}$$

To make use of Eq. (2), the expressions for the three crack growth rate terms on the right hand side of Eq. (2) must be determined independently. For the candidate nickel-base superalloy 690 in an environment containing low dissolved oxygen (DO), the crack growth rate due to pure stress-corrosion cracking is taken to be equal to zero. This is essentially attributed to the environment not being able to corrode the grain boundaries of the material so as to initiate intergranular attack. The observed lack of intergranular attack due to pure stress-corrosion cracking can be attributed to the presence of second-phase particles, i.e., chromium-carbide (Cr_2C), decorating the grain boundaries coupled with the absence of a chrome-depleted zone immediately adjacent to the grain boundaries. In general, it has been found that heat treating can and does lead to chromium depletion at the grain boundaries in precipitation hardened nickel-base alloys as a result of grain boundary chromium-carbide precipitation. This condition should be highly susceptible to stress-corrosion cracking [SCC]. The term or contribution due to corrosion-fatigue can still manifest itself at stress intensity values less than K_{ISCC}. Thus, for this nickel-base superalloy 690 the model reduces to the following expression:

$$\left(\frac{da}{dt}\right)_{690} = \left(\frac{da}{dt}\right)_{\mathrm{F}(690)} + \left(\frac{da}{dt}\right)_{\mathrm{CF}(690)} \tag{3}$$

This expression was subsequently revised at the Argonne National Laboratory (ANL) to reflect the behavior of nickel-base alloys [18,19]. The form of equation that is generally accepted in the nuclear engineering community is given by the Eq. (4) [18].

$$\left(\frac{da}{dt}\right)_{690} = \left(\frac{da}{dt}\right)_{F(690)} + A_{690}\left[\left(\frac{da}{dt}\right)_{F(690)}\right]^{m} \tag{4}$$

In this expression the corrosion-fatigue rate is modeled by an enhanced pure mechanical fatigue rate. This model is now used as the basis for the current study. The fatigue crack growth rate in ambient air and the model parameters are discussed in the following section.

Over the past few years, test data has been generated and gathered on Alloy 690 in both the plate stock and tubing stock. The original model was based on a small data set for the thick plate and compensated for temperature; load ratio and stress-intensity range but not compensated for fatigue threshold of the material. As additional test data, on both plate stock and tubing stock, became available the model was revised to account for threshold properties. Both the original and revised models generated acceptable results for crack growth test data that was above 1×10^{-11} m/s. However, the crack growth data at the lower growth rates was over-predicted by the non-threshold model. Since the non-threshold model does not take into account the fatigue threshold value it tends to predict no operating stress below which the material would not undergo crack growth during fatigue. By an over-prediction of the crack growth rates below 1×10^{-11} m/s, due to synergism of low stress, small crack size and long rise-times, the model in general lead to an under-prediction of the total available life of the components.

3. The models

The Argonne superposition model published for Alloy 690 for Pressurized Water Reactor environment or Low Dissolved Oxygen (DO) water can be described by the expressions:

$$\left(\frac{da}{dN}\right)_{\mathrm{air}} = \left(\frac{1}{t_r}\right)\left[D(1-bR)^{p}(\Delta K)^{n}\right] \tag{5}$$

$$\left(\frac{da}{dN}\right)_{\mathrm{env}} = \left(\frac{da}{dN}\right)_{\mathrm{air}} + A\left(\frac{da}{dN}\right)_{\mathrm{air}}^{m} \tag{6}$$

$$D = (5.423 \times 10^{-14}) + (1.83 \times 10^{-16})T + (-1.725 \times 10^{-18})T^2 + (5.490 \times 10^{-21})T^3 \tag{7}$$

In these three equations D, b, p and r are empirical parameters; T is the temperature; A and m are environmental fitting parameters; t_r is the rise-time of the test waveform in seconds; R is the stress ratio defined as minimum stress intensity to maximum stress intensity $[K_{\min}/K_{\max}]$ and $\Delta K = K_{\max} - K_{\min} = K_{\max}\ (1 - R)$. The specific parameter values are summarized in Table 1. As shown in Table 1 the corrosion-fatigue term is identically zero for Alloy 690 in the low DO environment, suggesting that the fatigue crack growth rate in ambient air can be used to represent the crack growth rate in low DO environment. Eq. (5) does not contain a fatigue threshold, thus predicting a finite value of fatigue crack growth rate at an infinitesimal stress-intensity range. It is also shown to over-estimate the crack growth rate in the range of flow crack growth rate. Anderson gave credit to Lucas and Klensil for the modified Paris Law, which took into account the possibility of a fatigue threshold [20]. This can be expressed as:

$$\frac{da}{dN} = C(\Delta K)^{n} - \left(\frac{da}{dN}\right)_{\mathrm{th}} \tag{8}$$

Using this concept a simple expression for fatigue crack growth rate is developed. The modified expression takes into account the fatigue threshold of the material. The threshold fatigue crack growth rate is determined to be 1.74×10^{-10} m/cycle.

$$\left(\frac{da}{dN}\right)_{\mathrm{air}} = \left(\frac{1}{t_r}\right)D(1-bR)^{p}(\Delta K)^{n} - \left(\frac{1}{t_r}\right)\left(\frac{da}{dN}\right)_{\mathrm{th}} \tag{9}$$

In Table 2 are summarized the parameters of this model. The actual benefit in using the threshold model is depicted in Fig. 1. In this figure are shown test data for crack growth rates less than 10^{-10} m/s, where better correlation between the experimental data and model prediction is obtained using the threshold model.

Table 1
Values of the Argonne model parameters.

Parameter	Value
D (m/s)	Varies with temperature
b	0.82
p	−2.20
n	4.10
A (low DO)	Not applicable
m (low DO)	Not applicable

Table 2
Values of the threshold model parameters.

Parameter	Value
D (m/s)	Varies with temperature
b	0.82
p	−2.20
n	4.10
(d_a/d_n) threshold	1.74×10^{-10} (m/cycle)

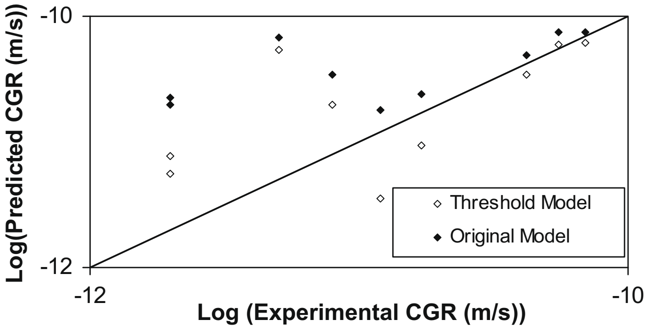

Fig. 1. A comparison of the statistical results in ambient temperature laboratory air environment.

4. A prediction of life using fracture mechanics

The American Society of Mechanical Engineers (ASME) has over the years adopted various crack growth models for both the ASME Code and for the various ASME Code cases. Most recently, a standardized comparison between the standard code models and code case models has been attempted [21]. In the ASME Code, no model for the nickel-base Alloy 690 exists, and a similar approach for a comparison of the threshold and non-threshold model is used. Five unique block loading sequences were used to compare the two models. The block loading histories are summarized in Tables 3–7 .

Using the fatigue crack growth model outlined in the preceding section, the number of loading blocks needed to predict crack propagation from an initial crack length (a_0) to a final crack length (a_f) can be easily predicted. Here we assume the initial crack length (a_0) to be 5.08 mm and the final crack length (a_f) to be 6.35 mm. The stress intensity factor is expressed as:

$$K = C\sigma\sqrt{\pi a} \tag{10}$$

In this equation, the value of the constant C is taken to be equal to 1. This provides sets of results that are summarized in Table 8. For the threshold model the number of cycles for a load ratio (R) of 0.98 does not affect the predicted number of blocks to propagate the crack from initial crack length (a_0) to final crack length (a_f). This is because the stress intensity factor ranges (ΔK) for this R-value is so small that the resultant fatigue crack growth rate is below the threshold value.

Table 3
The loading history 1.

Cycles	Maximum stress (MPa)	R-ratio	Rise-time (s)
1	344.75	0	1000
10	344.75	0.9	10
100,000	344.75	0.98	0.1

Table 4
The loading history 2.

Cycles	Maximum stress (MPa)	R-ratio	Rise-time (s)
1	344.75	0	1000
10	344.75	0.9	10
100,000	344.75	0.98	1

Table 5
The loading history 3.

Cycles	Maximum stress (MPa)	R-ratio	Rise-time (s)
1	344.75	0	1000
10	344.75	0.9	10
10,000	344.75	0.98	0.1

Table 6
The loading history 4.

Cycles	Maximum stress (MPa)	R-ratio	Rise-time (s)
1	344.75	0	1000
10	344.75	0.9	10
1000	344.75	0.98	0.1

Table 7
The loading history 5.

Cycles	Maximum stress (MPa)	R-ratio	Rise-time (s)
1	344.75	0	1000
10	344.75	0.9	10
100	344.75	0.98	0.1

Table 8
Number of blocks to propagate from initial crack length (a_0) to final crack length (a_f) for Alloy 690.

	History 1	History 2	History 3	History 4	History 5
Non-threshold model	1447	1447	1927	1993	2001
Threshold model	2007	2007	2007	2007	2007
% Variation	38.7	38.7	4.2	0.7	0.3

5. Conclusions

Based on this study the following are the key findings:

1. As test data on both plate and tube product forms of nickel-base superalloy 690 became available the original model was revised to account for threshold properties.
2. Both the original model and the revised model generated acceptable results for test data that was well above 1×10^{-11} m/s.
3. For the test data at the lower growth rates there was an over-prediction of fatigue life by the non-threshold model.
4. Since the original model did not take into account the fatigue threshold, this model fails to predict an operating stress below which the material would effectively undergo no fatigue crack growth.
5. By an over-prediction of the growth rate below 1×10^{-11} m/s, due to a combination of low stress, small crack size and long rise-time, the revised model in general leads to an under-prediction of the total available life of the components.

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