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# GROWTH OF CRACKS IN STEEL UNDER REPEATED THERMAL SHOCK IN A CHEMICALLY CONTROLLED ENVIRONMENT

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## ABSTRACT

Repeated thermal shock loading is common in many industrial situations including the operation of pressure equipment found in thermal power stations. Thermal shock can produce a very high stress level near the exposed surface that eventually may lead to crack nucleation. Further crack growth under the influence of repeated thermal shock is a very complex phenomenon due to both the transient nature of the highly non-linear thermal stresses and the strong influence of the environment. This paper describes an experimental analysis of crack growth in heated carbon steel specimens exposed to repeated thermal shocks using cold water. Analysis of the effect of steady state primary loads on the growth of the cracks is isolated using a unique test rig design. Environmental effects due to the aqueous nature of the testing environment are found to be a major contributor to the crack growth kinetics.

## KEYWORDS

Crack growth, environmental effects, fatigue, pressure equipment, primary load, thermal shock.

## INTRODUCTION

The growth and arrest of cracks due to repeated thermal shock loading is of interest in industrial applications where predictions can allow decisions to be made on the necessity of planned inspections and component replacements. Current methods for predicting repeated thermal shock (RTS) crack initiation lifetime and growth rates rely on standards and codes of practice such as the ASME Boiler and Pressure Vessel Code [1,2], and British Standard BS7910 [3], both of which use models based on isothermal fatigue tests and simplified stress profiles. The conservatism of these codes when analyzing RTS cracking is of concern, particularly when predicting crack growth rates after initiation has been observed. An over-estimation of this growth rate can lead to premature replacement of components that otherwise may have been left in service. A particular reference to the conservatism of the ASME code can be found in work by Czuck et al [4], where growth at the tip of a crack exposed to cyclic thermal shock loading was found to be an order of magnitude less than that predicted by using the code.

Cracking due to repeated thermal shock (RTS) is a particular problem in thermal power stations. Thermal shocks in boiler equipment are an inevitable side effect of normal operation with start-up and shut-down procedures thought to be especially damaging. Cyclic operation of traditionally base-loaded units only increases the severity of the problem. In this work, tests that closely simulate the real life conditions of thermal shock encountered in thermal power station pressure components are completed. These tests are intended to develop data that will provide for realistic determination of lifetime to crack initiation and crack growth rates for service components as well as allow for an estimation of the conservatism of the current codes.

Many influential external factors that are present in thermal power plant equipment are ignored in existing codes. Foremost is the combined effect of external primary loads and the environment in which the crack is growing. The external loads can be a direct result of the pressure or mechanical loading of the components, the effect of which is to open any cracks, exposing them to the environment. The environment is dependent on the process in which the component is being used, which in the case of thermal power station equipment is often aqueous in nature (including chemical treatment to control pH and oxygen levels) and will modify conditions at the crack tip.

In this paper, selected results from crack growth tests using a unique test-rig arrangement are presented. Comparisons of the actual results with empirical prediction methods from current design codes are made.

## EXPERIMENTAL TECHNIQUE

The testing completed in this investigation has been carried out on a thermal fatigue test rig that has been purpose built for the investigation of crack initiation and growth due to repeated thermal shock loading. Consisting of a convection furnace, static loading structure and quenching system it allows for the monitored growth of cracks for a wide variety of component geometries.

The key advantages of this rig over those used in previous studies are:

- The component is heated by convection, which means that there are no unwanted heat effects at the crack tip as may be the case for induction or resistance heating.
- The component is quenched by room temperature pH and $O_2$ controlled water.
- The specimen size is representative of typical industrial components.
- Large specimen size permits multiple simultaneous experiments.
- An unloaded “control” specimen can be used.
- Approximately one-dimensional conditions exist at any one crack because of the unique specimen design.

A thorough analysis of the development of the test rig and specimen design, including a review of previous trends in the experimental investigations of thermal shock cracking can be found in [5].

Tests conducted with this rig have concentrated on identifying the effects of environment and primary loads on crack initiation and growth during repeated thermal shock. This was completed by simultaneously testing sets of two low carbon steel flat plate specimens (grade AS 1548-1995 [6]) placed side by side. One specimen is subjected to a 90MPa (13ksi) uniform tensile stress and the other left unloaded. The specimens, with a combination of 0.25mm and 0.1mm radius notches machined into the quenched faces, were fitted vertically in the furnace. The upper specimen temperature was limited to 370°C to remove any creep effects. Dissolved oxygen levels (D.O.) were varied between tests, while the pH was held steady at around 8.0. The first set of tests used fully oxygenated tap water with a D.O. level of around 8ppm. This water was vigorously pre-boiled in the second set of tests, driving off excess oxygen and reducing the D.O. level to around 2ppm.

Each thermal cycle consisted of a slow heat to a central specimen temperature of 330°C followed by a 7s water quench. Cycle time was around 15 minutes. Due to the fact that the specimens were positioned vertically, the thermal gradient in the furnace prevented a uniform temperature from being achieved along the whole specimen length. Rather the temperature from top to bottom of the specimen varied linearly from 370°C to 290°C.

After each period of 500 thermal cycles, the specimens were removed from the furnace and investigated for cracking at a low magnification (10 to 60x). A rough estimate of crack initiation lifetime was defined as when a full-face hairline crack was visible at the base of the notch. Extrapolations of the long crack growth data were used to further refine when initiation was to have occurred. Any subsequent crack growth after initiation was measured on each side of the specimen. Through crack depth was taken as the average of these two measurements.

## TEST RESULTS

Times to crack initiation in the notched specimens are shown graphically in figure 1. Unlike the authors' previous work [5], where elastic stress amplitude was used, times to crack initiation are plotted against the Neuber pseudostress amplitude ($S'_a$). The pseudostress is defined as the local strain amplitude at the notch ($\varepsilon_a$) multiplied by Young's Modulus ($E$).

$$S'_a = \varepsilon_a E \tag{1}$$

When the behaviour of the material remote from the notch is predominantly elastic, the pseudostress amplitude can be related to the nominal stress amplitude ($S_n$) and the local stress amplitude ($\sigma_a$). The final relationship, outlined in work by Prater and Coffin [7], is reproduced below:

$$S'_a = \frac{(k_f S_n)^2}{\sigma_a} \tag{2}$$

Here $k_f$ is the notch fatigue factor, determined from a notch sensitivity analysis as used in [5]. A maximum value of 5.0 has been established for $k_f$ in accordance with a "worst case notch" analysis. Use of equation (2) also requires knowledge of the cyclic stress strain relationship for the material. Prater and Coffin [7] provide data for carbon steel that has been adapted for use in this investigation.

Figure 1 also shows a curve based on ASME *fatigue* data. This curve is slightly different to the published *design* curve as shown in Section VIII of the ASME Code [2]. The design curve has a built-in conservatism of 2 times on stress and 20 times on lifetime on the fatigue data, whichever is the most conservative.

Crack growth results are shown on figure 2. Stress intensity factors have been plotted against the crack growth rate using the *R*-ratio to categorise the data. Both water and air environment crack growth curves for carbon steel, taken from the ASME Boiler and Pressure Vessel Code [3], are also plotted for comparison.

## DISCUSSION

### *Crack Initiation*

As shown in Fig. 1 and reported in [5], the application of a primary load displays little or no effect on crack initiation lifetime within the limitations of experimental variance. The same can be said for reducing the dissolved oxygen level from 8ppm to 2ppm.

In all of the test cases, the ASME *fatigue* curve seems to provide a good approximation of the relation between number of cycles to crack initiation and notch pseudostress amplitude. However, any attempt to use the ASME curves to predict crack initiation should be approached with care. This is because the ASME fatigue curves are based on uniaxial strain controlled testing of small cylindrical specimens. Failure in one of these specimens is defined as when complete fracture occurs. It is then assumed that the failure of these small specimens is equivalent to the initiation of a small crack in a larger structure.

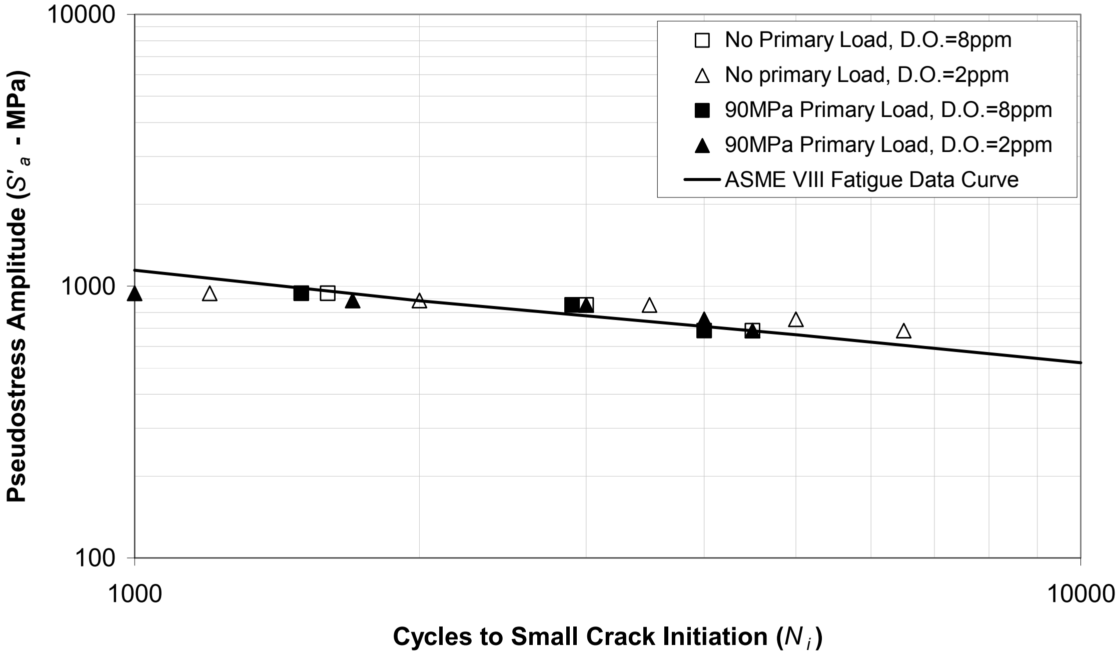

**Figure 1:** Effect of primary load and dissolved oxygen Level (D.O.) on small crack initiation lifetime.

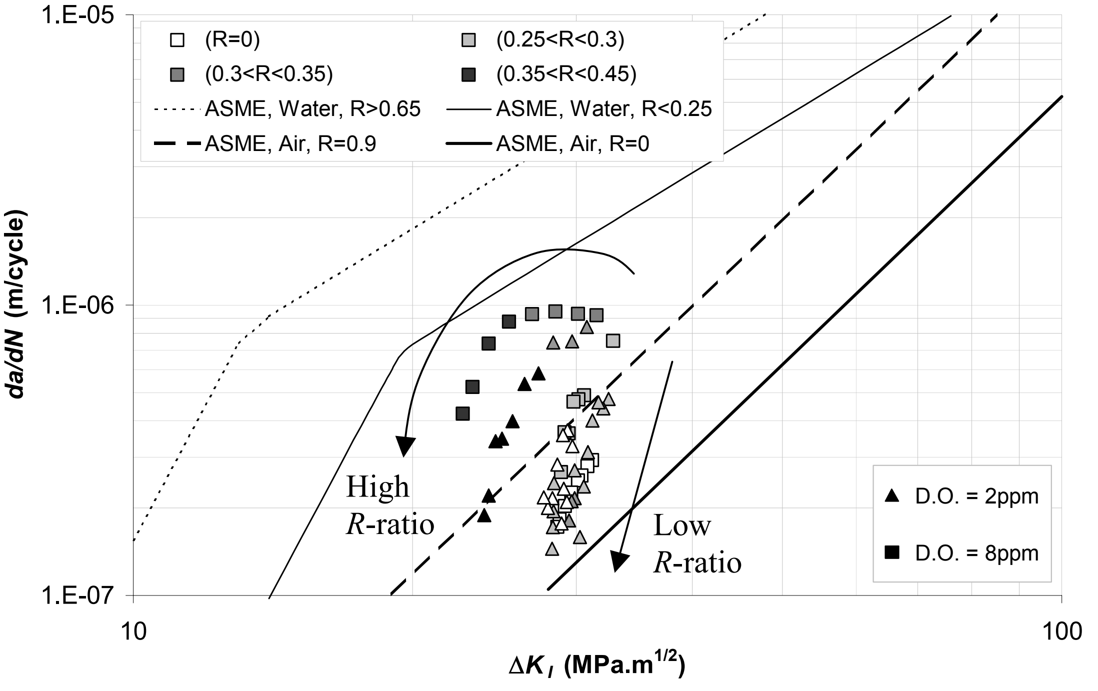

**Figure 2:** Crack growth rates as a function of stress intensity factor. Squares correspond to measurements made during testing with D.O.≈8ppm, triangles correspond to D.O.≈2ppm. The large arrows indicate only trends for individual crack growth – no curve fitting is implied.

Referring to ASTM E 8M – 96 [8], the standard small cylindrical specimen size for tensile tests is 12.5mm in diameter. Depending on the stress amplitude during fatigue testing and the presence of mean stresses, a small amount of crack growth will occur before specimen failure, probably in the order of a few millimetres. This means however that no exact "initiation" size can be known to allow comparison with experimental data from large specimens. Therefore, any correlation between the ASME code and the experimental work presented here must remain purely qualitative. Namely, the pseudostress developed at a notched carbon steel specimen exposed to RTS can be related to number of cycles to initiation in a linear manner similar to that shown by the ASME fatigue curve. Reciprocally this means the ASME fatigue curve can be used as a guideline for determining approximate times to develop small (<1mm) deep cracks in carbon steel exposed to RTS.

### *Crack Growth*

A number of observations can be made from the crack growth data obtained by relating the change in stress intensity factor $\Delta K$ to the propagation rate *da/dN.*

- For all of the plotted points, the ASME water curves provide a conservative result (see Fig. 1). For some points this conservatism is more than an order of magnitude.
- From the trend of the data represented it seems that deceleration of all observed cracks is occurring.
- In specimens without steady state primary loaidng, crack growth rates begin decreasing immediately after crack initiation.
- In contrast, after initiation, cracks in the specimens with large steady state primary loading experience an increase in crack growth rate as the *R*-ratio increases. Then, after a period of rapid growth (at around 1 mm/1000 cycles), the rate decreases rapidly. It is possible that this high rate of crack growth, followed by the quick drop off may correspond to the start of an environmentally influenced diffusion controlled crack growth.

## CONCLUSIONS

Results obtained from a test program developed to simulate repeated thermal shock conditions produced in operating thermal power station have shown:

1. The application of a primary stress had little or no affect on crack initiation lifetime during repeated thermal shock below the creep range. A reduction of dissolved oxygen levels in the quenching water from 8ppm to 2ppm also did not significantly affect initiation times. ASME Boiler and Pressure Vessel Code, Section VII, Division 2 [2] fatigue data may be used as a guideline for determining approximate times to develop small (<1mm) deep cracks in notched carbon steel specimens exposed to repeated thermal shock.

2. Environmental and primary load interaction is highly influential in the growth of thermal shock cracks. Cracks with a low *R* ratio (no primary stress) show signs of rapid deceleration and cracks with high *R* ratio show signs of deceleration after a period of environmentally enhanced growth. The ASME provided crack growth curves for a water environment are conservative in all cases.

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