Cyclic thermo-mechanical testing of 316 stainless steel

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1   Abstract

Materials used for components such as power plant steam pipes, gas turbines discs and die forming machinery can be subject to combinations of extreme loading and temperature conditions. In addition, the materials can contain or develop cracks. Once a crack has initiated, the conditions under which the components operate can cause these cracks to propagate. This paper is concerned with the experimental testing of 316 stainless-steel, corner-cracked samples under thermo-mechanical-fatigue conditions, and the measurement of the crack propagation during testing using alternating-current-potential-difference readings. Fracture mechanics (Paris Law) methods have been used in the processing of the experimental data.

Keywords: Thermo-Mechanical Fatigue, Crack Growth, 316 Stainless Steel, High Temperature, Fracture Mechanics.

2   Introduction

This study concentrates on 316 Stainless Steel as it is heavily used in the Nuclear Industry for parts that are subject to both thermal and stress cycling in superheated steam systems. The stress cycling in these systems can be large due to significant thermal strains on start-up and shutdown. This cycling can lead to fatigue damage and cracking. As these

are very large systems it is very costly to do remedial work, therefore useful to understand crack growth rates in these conditions to evaluate risk and plan necessary maintenance as well as informing the design.

Square cross-section samples were manufactured with a sharp starter notch in the middle of the gauge length to control the location of the crack. The samples were then cycled at high rate on a servo-hydraulic testing machine to initiate the crack and grow a steady pre-crack before moving over to the TMF machine.

A state-of-the-art uniaxial TMF machine[1-2] which employs induction heating was modified to give good thermal stability and dynamic response on the square cross-section samples. An external air cooling system was designed and added to the system to decrease cycle times. An Alternating Current Potential Drop (ACPD) crack measurement system was also integrated into the system, allowing crack propagation monitoring during the test. The ACPD was incorporated into the system in such a way to allow data acquisition simultaneously with all the other measurements during the test.

To achieve reliable and repeatable potential drop (PD) measurements all the variable need to be controlled. Good thermal and mechanical control is required as well as robust and repeatable instrumentation for PD measurements.

Fracture mechanics[3-5] (Paris Law) was used to analyse the results obtained from the tests. Crack growth rates for both isothermal and TMF tests were calculated.

3   Experimental Setup

3.1 The Test Specimen

A parallel section of 7mm by 7mm square cross-section specimen was chosen giving and initial cross-sectional area of 49mm^2. In the centre of this 15mm parallel length a notch was machined to a depth of 1mm, measured across the diagonal of the parallel section. From the parallel length the sample gently flared out through a gentle radius to the required dimensions for gripping. See Figure 1 of an image of the sample.

7x7mm Cross-Section Parallel Length

Corner Notch

ACPD Measurement Wires

Thermocouples
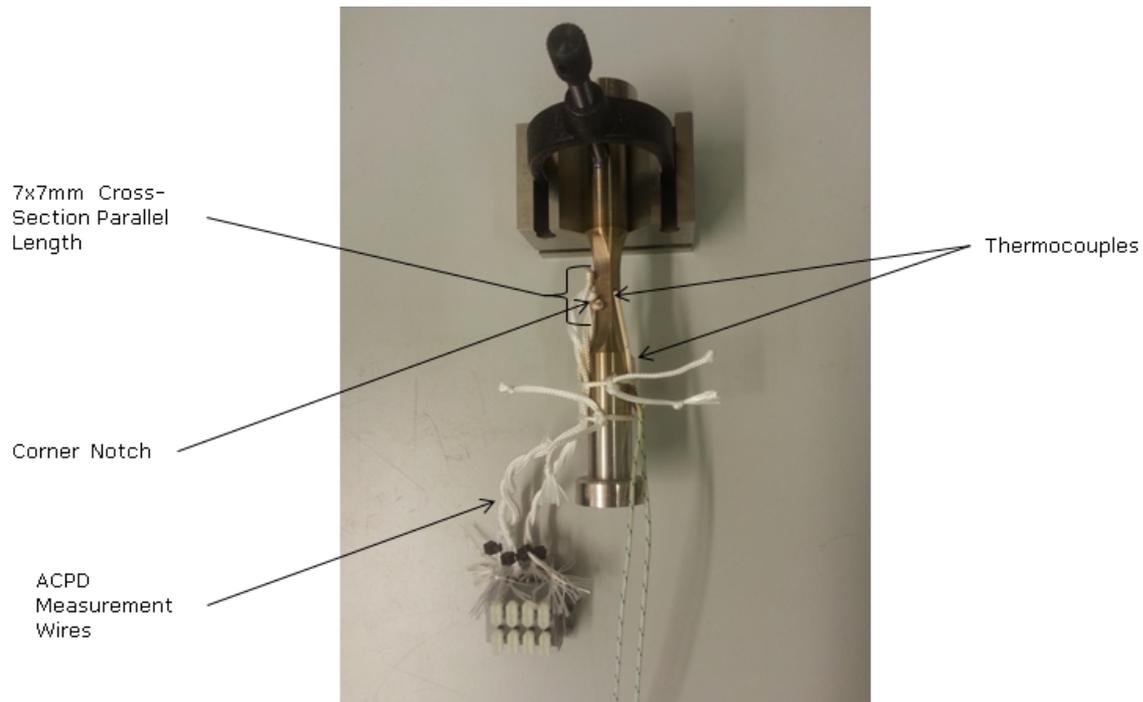
Figure 1 – Instrumented Sample

3.2 Thermal Control

This machine uses induction heating and can pass air through the centre of a hollow specimen to achieve high heating and cooling rates. Modifications were required to accommodate square cross section solid samples.

A new induction coil was designed and made to accommodate the instrumentation needed for the potential drop measurements. Extensive work was done to ensure good thermal stability and dynamic response. This was achieved by coil design as well as the control of positioning and power of the air cooling jets around the specimen.

3.3 ACPD system

Reliable potential drop measurements require good repeatable electrical connection on both the supply and measurement wires. Great care is required to achieve reliable positioning of connections and these need to have low impedance and not affect the behaviour of the sample under test. Two pairs of wires were connected (see Figure 1), one across the starter notch to measure the voltage change across the crack and another reference pair were connected close to the end of the parallel section of the sample. The reference pair are used to account for any spurious

voltage change which would be due to something other than the crack changing length.

3.4 Pre-crack

The crack was initiated at room temperature from a 1mm deep starter notch. The samples were cycled at 20Hz with an R-ratio of 0.1 on an Instron servo-hydraulic testing machine. The initial maximum stress in the pre-cracking was close to the ultimate tensile stress for the material, once the crack was initiated the stress was ramped down and the crack grown further at the stress lower than the stress level in the TMF phase to ensure that the crack would continue to grow under the subsequent TMF conditions. The length of the pre-crack was monitored optically by measuring the location of the crack tip on the surface of the sample.

3.5 Instrumentation

3.5.1 Thermocouple instrumentation

K-type thermocouples were spot-welded at the centre of the parallel length of the sample (see Figure 1). These give excellent temperature measurement and as these measure DC voltages are unaffected by the AC signals from the induction furnace and the ACPD equipment.

3.5.2 ACPD Instrumentation

Spot welding was used for attaching the ACPD instrumentation to the test specimen (see Figure 1). The samples were held on a linear table to allow accurate positioning of the measurement wires either side of the starter notch. This was also used to ensure that the reference wires where attached at the same separation as they need to measure over the same area as the gauge wires so that any changes in voltage reading that were not due to the crack would be the same in both sets of wires.

4   Tests

The temperature range of 400°C to 600°C was chosen. This is a typical range of operation temperatures for this alloy. A maximum stress of 186MPa with an R-ratio of 0.1 was used for both isothermal and TMF tests.

4.1 Isothermal Fatigue Tests

Isothermal test were carried out at both, 400°C and 600°C, the minimum and maximum of the temperature range of the TMF tests. A maximum bulk stress of 186MPa was applied at a loading frequency of 0.012Hz, r-ratio 0.1. Figure 2 shows the loading cycle used.
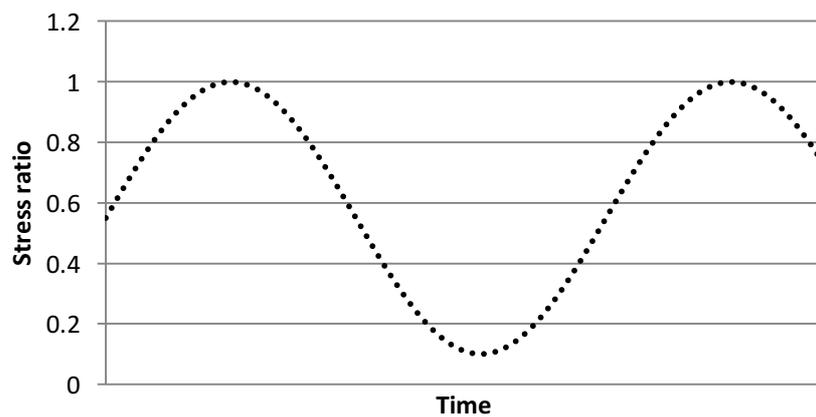
Figure 2 – Schematic Representation of Loading Cycles

4.2 TMF Tests

Both in phase (IP) and out of phase (OP) TMF tests were carried out between 400-600°C, with the same mechanical loading as the isothermal test; maximum stress of 186MPa R-ratio of 0.1. The cycling rate was chosen to be 0.012Hz so to be within the heating and cooling rates of the system. See Figures 3 and 4 for a schematic representation of IP and OP cycling.
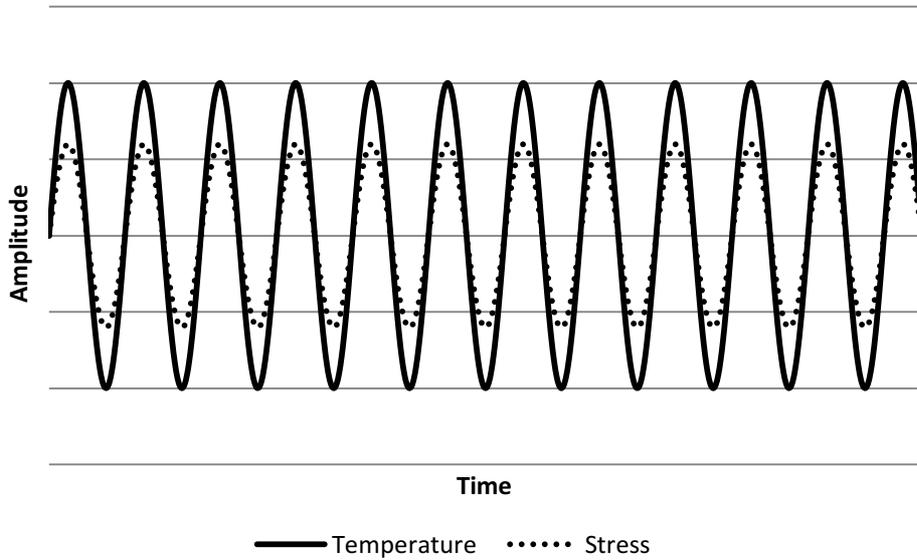
Figure 3 – IP TMF
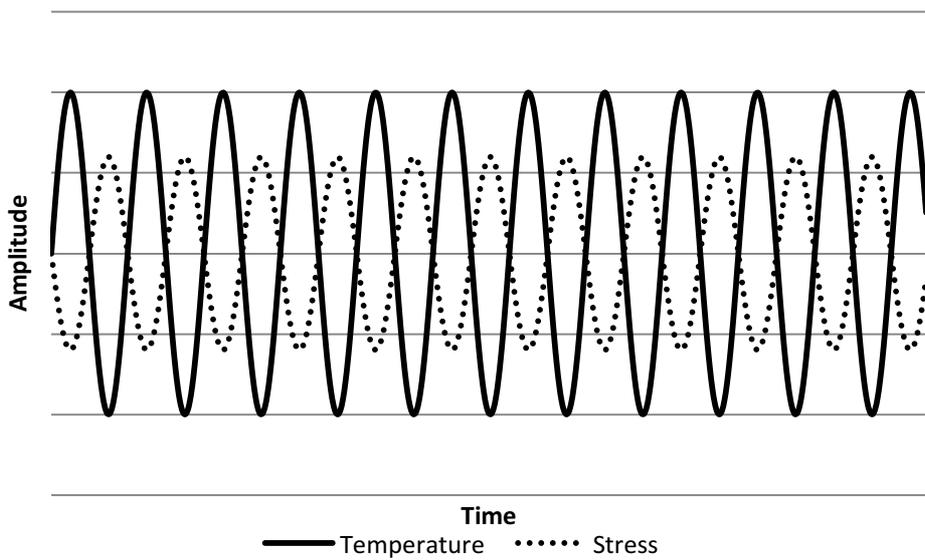
Figure 4 – OP TMF

5 Discussion and Results

Fracture Mechanics methods have been used to determine crack growth rates in the mid-ΔK (Paris) region[3]. The cracks were considered to be uniform quarter circle in geometry growing from the starter notch. Equations for stress intensity factor (K)[4-5] were used to calculate values of

K throughout the test based on the crack length and the knowledge of the geometry of the sample. The crack growth rate (da/dN) to be calculated taking logs of both K and da/dN the plots in Figure 5 were generated. The mid-ΔK portion (Paris Region[3]) of these plots was considered and the crack growth rate parameters were calculated and can be found in Table 1.

$$\log\left(\frac{da}{dN}\right) = m log(K) + C$$

	C	m
Isothermal 400°C	-12.02	2.91
Isothermal 600°C	-10.48	2.52
TMF 400-600°C IP	-12.57	3.26
TMF 400-600°C OP	-11.26	2.68

Table 1 – Crack Growth Rate Parameters
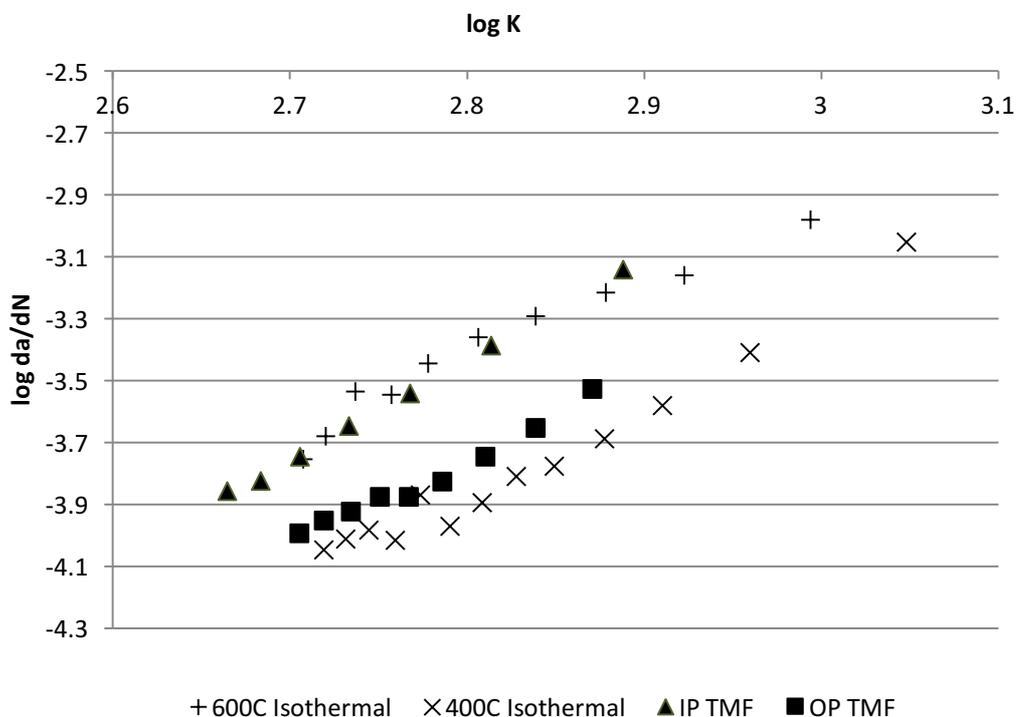
Figure 5 – Crack Growth Rates

There looks to be a significant difference in the response which is dependent mainly on the temperature at which the maximum stress is applied. It can be seen that the IP TMF, which has the maximum stress at 600°C has a similar crack growth rate to the 600°C isothermal tests. Similarly the OP TMF test, with maximum stress at 400°C, has a crack growth rate in line with 400°C isothermal test. It is likely that this is due to the significant role of creep at these temperatures[6]. It can been seen that when there is a large stress applied at 600°C there is a higher crack growth rate, this can be attributed to higher creep rates at higher temperatures.

However, this is not to say that the isothermal condition is the same as the TMF condition with the same temperature at maximum stress. It can be seem from Figure 5 that the m values for the TMF tests are higher than the corresponding isothermal test, suggesting a greater susceptibility of the material to the increased stress concentration factor.

Other work has shown that the relationship of TMF and isothermal fatigue life is not straightforward[6-9]. Factors such as creep, oxidation and dynamic strain aging have a complex interplay with cycling temperatures.

6   Conclusion

- Powerful induction heating and forced air cooling allows TMF testing to be carried out in a reasonable time scale and at a wide range of loading and heating/cooling rates.
- High rate heating and cooling, and interference from such systems can make ACPD measurements difficult.
- IP TMF and isothermal testing at 600°C give the highest crack growth rates.
- It is likely that creep plays a significant role in crack growth at high temperatures.
- As creep is significant, the temperature at the maximum load is the main factor determining crack growth rate.

7   References

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