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Evaluation of High Temperature Fatigue Behaviour of P22 by Miniature Specimen Testing

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Abstract. Miniature specimen testing to evaluate mechanical properties, presents a novel opportunity to undertake structural integrity assessments of in-service power generation components, by removing only a very small volume of material. In this study, high temperature fatigue testing of P22 steel was undertaken and a number of fatigue properties determined using a miniature specimen testing methodology. Good comparisons were observed between fatigue properties determined by miniature specimens and the more established standard-sized specimen testing reported in literature.

Introduction

P22 (2.25Cr-1Mo) steel is used for components operating in fossil-fuelled and nuclear power generation plant, owing to its good creep and fatigue properties and weldability. During operation, these components may experience thermal and mechanical cycling and as a consequence service-life may be reduced. Therefore, structural integrity assessments for both creep and low cycle fatigue (LCF) are imperative.

There are a number of small specimen testing methodologies used in both the nuclear power generation industries [1], as well as fossil-fuelled power generation [2,3]. Small specimen testing presents much difficulty due to the reduced geometry of specimens and associated test equipment. The development of miniature fatigue specimens has been restricted to the nuclear industry and used to assess materials property changes involved with irradiation and cyclic thermal transients. No data or fatigue property characterisation has been obtained by miniature fatigue specimens, or to determine a comparison of miniature and standard-sized specimens for P22 steel at elevated temperatures.

This paper describes the use of miniature specimens to evaluate the fatigue behaviour of P22 at 540°C, under a strain-controlled testing methodology. Comparisons in the fatigue properties with data generated by standard-sized specimens in previous literature are examined. Various analytical techniques were used to investigate the response of miniature specimens.

Experimental

Test Material. The material investigated was P22 (2.25Cr-1Mo) alloy steel in the form of a hot-rolled, normalised and tempered plate. Miniature fatigue specimens were axially oriented parallel to the rolling direction of the plate. The elemental composition of the test material is presented in Table 1.

Table 1. Minor elemental composition of P22 steel.

Element	C	P	Mn	Si	S	Ni	Cr	Mo	Cu	Al	Sn	V
Wt. %	0.11	0.008	0.41	0.161	0.021	0.22	2.18	0.91	0.11	0.017	0.007	0.017

Equipment and specimen geometry. Fatigue experiments were conducted on an Instron servo-hydraulic test machine. A 3-zone furnace was employed to provide precise heating to specimens throughout testing. Two thermocouples were attached to specimens, close to the gauge length in order to monitor temperature. Extensometry for strain measurement consisted of capacitance non-contact probes attached to the shoulders of specimens. These probes provided very accurate strain measurement, without introducing contact effects on the gauge-length of the miniature specimens, which often result in premature failure.

The geometry of specimens contained a uniform gauge length section, presented schematically in Fig. 1. Specimens were polished in the axial direction before testing, to obtain a fine surface finish in order to reduce the possibility of crack initiators, that may have been produced by the machining process.

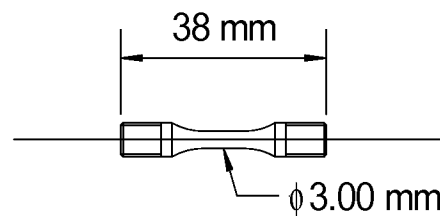


Fig. 1. A schematic of a miniature fatigue specimen.

Fatigue testing and fracture surface analysis. High temperature fatigue testing was conducted in air at 540°C, under a fully-reversed axial strain controlled regime. A continuous triangular waveform was imposed at a frequency of 1 Hz for each test. Testing was conducted using total strain ranges of between 0.61% and 1.52% strain.

After testing the fracture surfaces of specimens were examined by scanning electron microscopy (SEM). A JOEL 6300 scanning electron microscope was used to investigate the fracture surface morphology and failure mechanisms.

Results and discussion

Hysteresis loops. The hysteresis loop behaviour observed during fatigue testing at 540°C is shown in Fig. 2, for total strain ranges between 0.74% and 1.52%. The hysteresis behaviour was determined at 50% of fatigue life. It was found that an increase in total strain range was accurately reflected with an increase in maximum and minimum stresses reached. The Bauschinger effect was observed, where the peak stress reached in the compressive cycle was larger than the peak stress in the tensile cycle. This was in agreement with research by Skelton [4] on normalised and tempered P22 fatigue tested at 550°C.

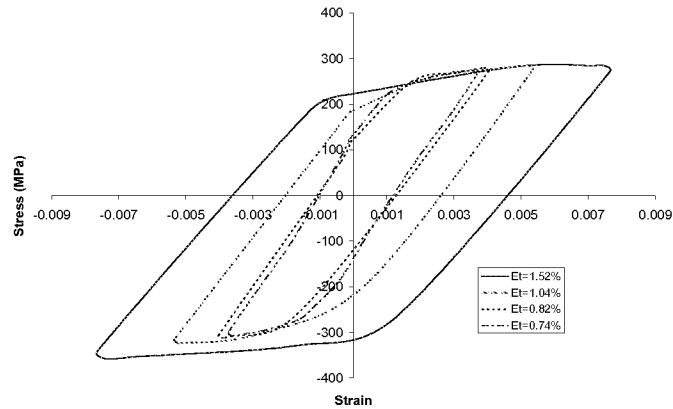


Fig. 2. The hysteresis loop behaviour of P22 determined through miniature specimen testing.

Cyclic stress response. The cyclic stress response of the test material is shown as a function of life-fraction in Fig. 3, for total strain ranges between 0.61% and 1.52% strain. Cyclic softening was observed for tests, evidenced by a decrease in total stress range during the early stages of each test, up to approximately 0.10 life-fraction (10% of life consumed). After this point cyclic stabilisation was observed, signified by a stable stress range. Depending on the test, cyclic stabilisation ended between 0.65 and 0.95 life-fraction and was indicated by an exponential reduction in stress until failure which signified macro-crack propagation. This behaviour has been observed previously in standard-sized specimen testing of P22 [5]. The cyclic stabilisation period was observed to reduce with an increase in total strain range of testing.

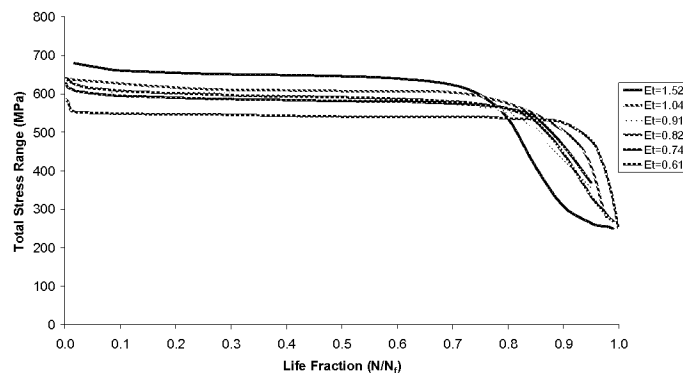


Fig. 3. The cyclic stress response of the test material observed in specimens.

Cyclic stress-strain. The results of cyclic stress-strain behaviour obtained through miniature specimen testing is shown as a function of true stress amplitude and plastic strain amplitude in Fig. 4. From this graph and using the Ramberg-Osgood relationship, the cyclic strain hardening exponent (n') and the cyclic strength coefficient (K') were determined and are presented in Table 2. Values of n' and K' reported by previous research testing standard-sized P22 specimens 550°C [5] are also shown and compare well with the results of this study.

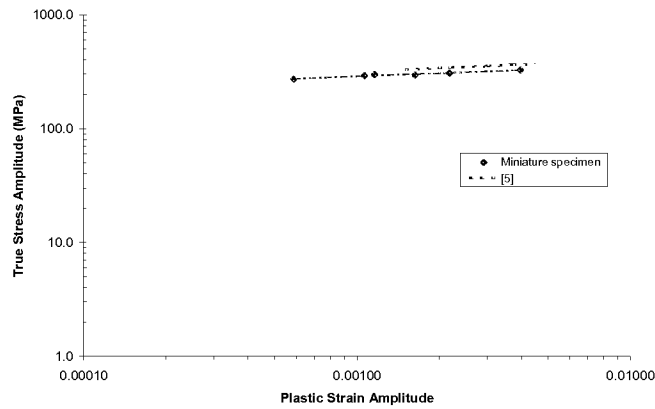


Fig. 4. The cyclic stress-strain behaviour as a function of true stress amplitude versus plastic strain amplitude.

Table 2. The cyclic strain hardening exponents (n') and the cyclic strength coefficients (K') for miniature and standard-sized specimens.

Specimen type	n'	K' (MPa)
Miniature	0.0904	538.57
Standard-sized [5]	0.105	652.00

Strain-life analysis. LCF is dominated by plastic strain. Hence, the strain-life analysis was investigated in terms of plastic strain as a function of cycles to failure (Fig. 5). Previous research testing standard-sized specimens at 500°C [5] is also presented in Fig. 5 to compare with the current study. The Coffin-Manson power-law relationship [6,7] was employed to determine the fatigue ductility properties, including the fatigue ductility coefficient (ϵ_f') and the fatigue ductility exponent (c) and is shown in Table 3. It was observed that the properties calculated in this study compared very well to previous P22 fatigue research using standard-sized specimen tested at 500°C [5].

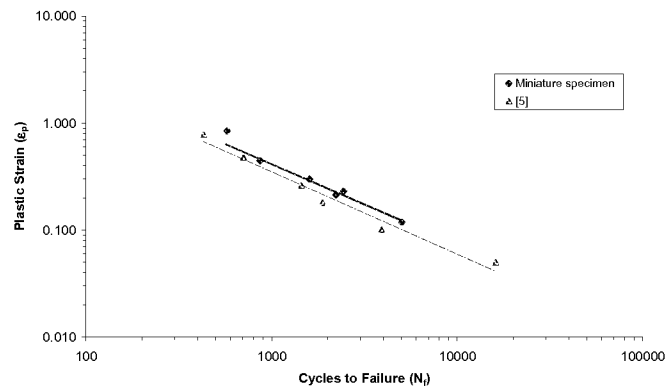


Fig. 5. Plastic strain-life as a function of cycles to failure for miniature fatigue tests.

Table 3. The ϵ'_f and c values, calculated for miniature and standard-sized specimens.

Specimen type	ϵ'_f	c
Miniature	74.57	-0.7524
Standard-sized [5]	71.54	-0.7701

Fracture surface analysis. Scanning electron microscopy (SEM) conducted on the fracture surfaces revealed the presence of striations (Fig. 6A), indicative of the fatigue process. The striation distance measured was found to be different for different total strain range tests. However, for each individual test the striation distance appeared to be uniform over the fracture surface.

Secondary cracking was evident in all fracture surfaces and was generally oriented in a particular direction, which coincided with the direction of inclusions present in the material. Secondary cracking was found to occur between the MnS or Al₂O₃ inclusions and the material's matrix, as shown in Fig. 6B.

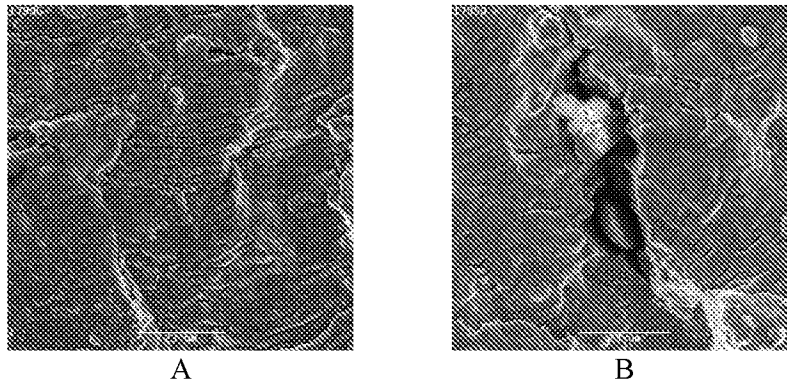


Fig. 6. A) Fatigue striations on the fracture surface at x500 magnification. B) Aluminium Oxide inclusion (upper) and a Magnesium Sulphide inclusion (lower) are observed on the secondary crack at x500 magnification.

Conclusions

The low cycle fatigue properties of P22 steel were characterised through the use of miniature specimen testing under strain-control at 540°C. The methodology facilitated in consistent and comparable fatigue data that was observed in standard-sized specimens in previous literature.

Hysteresis loop behaviour was found to be accurately represented and the Bauschinger effect was observed for each test. The cyclic response of the material was determined, with cyclic softening occurring in each test up to approximately 10% of consumed fatigue life, after which stabilisation was reached until macro-crack propagation occurred, which resulted in an exponential decrease in stress until fatigue failure. The cyclic stress-strain performance was evaluated through the cyclic strain hardening exponent (n') and the cyclic strength coefficient (K'), both of which compared well with previous P22 literature for standard-sized specimen. By employing the Coffin-Manson power law relationship, a measure of plastic strain versus cycles to failure was obtained and shown to compare very well with previous literature determined through standard-specimen testing. SEM analysis on fracture surfaces revealed striations that were uniform in distance, however the uniform distance was different from test to test. Secondary cracking was observed and coincided with the presence of inclusions within the material.

Therefore, it has been shown in this study that through the developed methodology, miniature fatigue specimens can accurately evaluate the fatigue properties of P22 steel, under the low cycle fatigue regime at elevated temperature.

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