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Damage Tolerant Design for a Cast Aluminium Alloy

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Abstract

Fatigue life predictions for a notch geometry machined from an AlSi7Mg cast aluminium alloy are reported. The predictions integrate a critical strain approach based on plain specimens with propagation calculations using measured crack growth rates. Crack growth behaviour was measured by means of Four Point Bend (FPB) and Corner Crack (CC) specimens on single cast bars. The measurements emphasise two regimes of crack growth with a distinct transition between them. To support the analysis, porosity distributions were quantified using image analysis techniques. The predicted fatigue lives confirm that the fatigue performance is dominated by crack growth behaviour at high stress but is more strongly influenced by initiation at low stress.

1. Introduction

Component fatigue life prediction is traditionally based on stress-life (S-N) or strain-life (ε-N) design curves derived from plain specimens This approach, however, is not valid for cast components where the presence of defects significantly reduces the fatigue strength compared to bulk material characteristics (1-3). An alternative approach, therefore, is required. 'Damage tolerant design' methods meet this requirement (4-6). In this approach, the number of cycles for crack propagation from an initial flaw to a maximum critical size is established using laboratory growth rate data and knowledge of local stress conditions at the stress concentration feature. To support a fracture mechanics approach measurements of both small and long crack growth behaviour have been made using four point bend and compact tension specimens. However, crack initiation at the pores could be important and so strain control data on plain specimens have also been generated to support a critical strain prediction.

2. Materials and Experimental Procedures

2.1 Materials

The test specimens were machined directly from continuously cast (BT designation) and gravity die cast (ST designation) AlSiMg aluminium alloys similar in composition to 356 and LM25 materials (7.4Si, 0.38Mg, 0.11Fe, 0.11Ti, Bal Al). The ST material was modified with sodium, grain refined with 'Tibor' and rotary degassed for 5 minutes. Each specimen was given a T6 heat treatment. The BT alloy had a grain size of 0.5 mm, an average dendrite arm spacing (DAS) of 18 μm and zero pores within the detection resolution.

The ST alloy had a similar grain size, a DAS of 40 μm and a pore percentage of about 2 %. A third variant was also gravity die cast but had a high iron content and was considered to have the least satisfactory microstructure (WS designation). This latter alloy is not included in the present analysis but data are included to define the 'worst case' fatigue response. Figure 1 demonstrates the measured distribution of pore sizes in ST and WS alloys. The sizes are ideal semi-circular shapes based on measured areas. Two sizes 0.18 and 0.4 mms are highlighted for future reference.

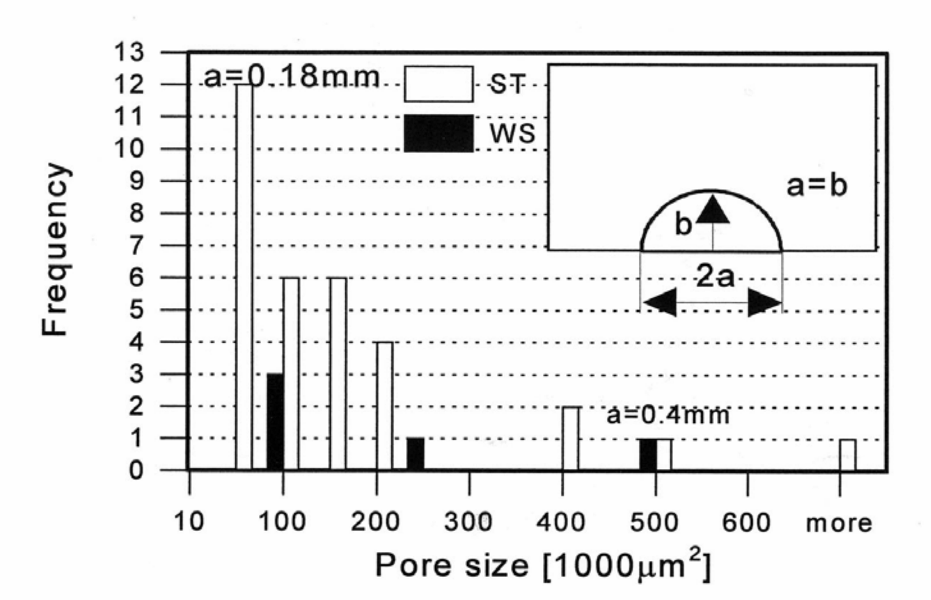

Figure 1: Measured pore size distributions.

Fatigue tests were carried out on servo hydraulic machines under strain control (plain specimens) and load control (crack growth specimens) at room temperature. The strain control tests were at R= 0 and -1. Two test-piece geometries were used in the programme. They are 10 x 10 x 100mm four point bend (FPB) and 10 x 10mm corner crack (CC) specimens. A frequency of 5Hz was used for the FPB tests and 1Hz for the CC. Crack length was monitored using a replica technique for FPB specimens and a DCPD method (direct current potential difference) for CC specimens. Tests were also carried out on the ST alloy using a double edge notch (DEN) geometry with Kt = 1.9, notch root radius of 3 mm and gross and net sections of 10x16 mm and 10x10 mm respectively. The notch was included as a vehicle for evaluating the prediction methods. Details on specimen design and measurement technique are given in reference 4. Microstructures, dendrite arm spacing (DAS) and defect distributions were measured and fracture surfaces were examined under a SEM.

3. Results and Discussion

3.1 Fatigue Tests

The strain-life responses of the BT, ST and WS variants are summarised in figure 2. These data are used below in a critical strain prediction of crack initiation at the notch root. Each variant displayed cyclic strain hardening as illustrated in figure 3 for the ST alloy. It is also clear that the BT and ST forms display similar stress-strain characteristics irrespective of defects. The notch results on ST material at R = 0 are recorded in figure 5 in terms of nominal applied stress.

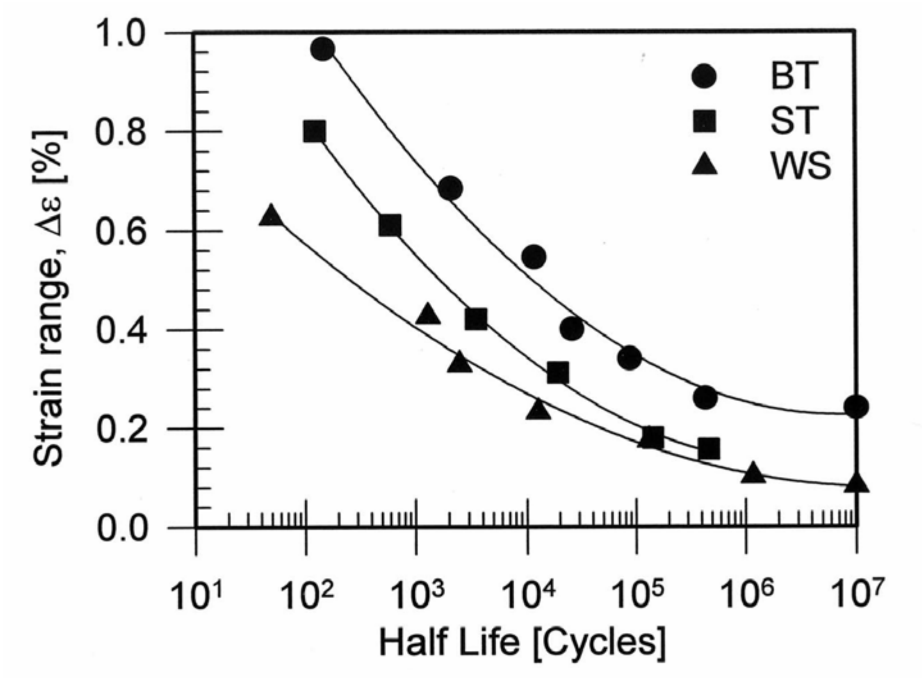

Figure 2: Comparison of strain range-half life behaviour.

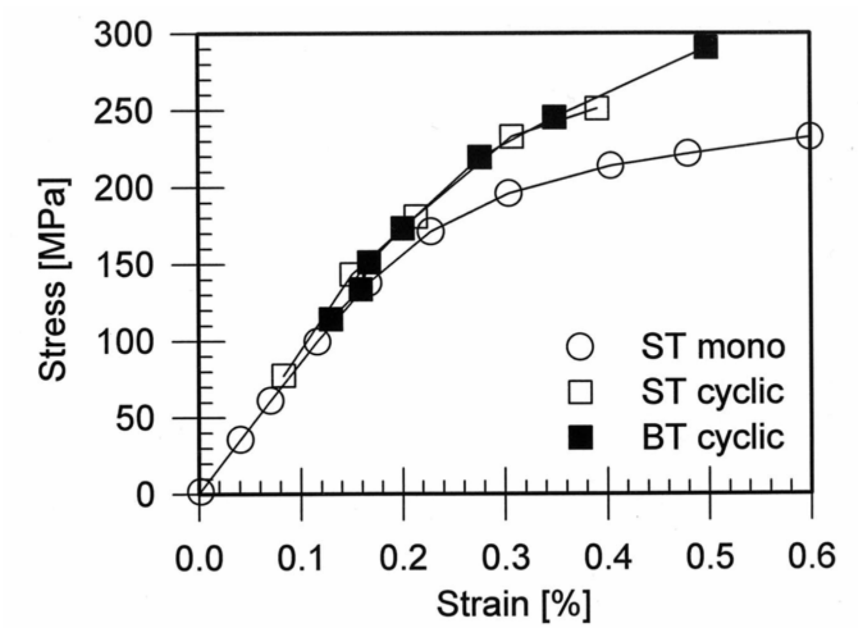

Figure 3: Mono and cyclic stress-strain response of two alloy variants.

3.2 Crack Propagation

The crack growth behaviour for FPB and CC specimens is summarised in Fig. 4. The data are for the ST alloy but the other variants behaved in a similar way. There is a transition in crack growth rate highlighted by the FPB and CC measurements. These data and the transition are used in the life prediction calculations. Linear regression lines with 95% confidence intervals are plotted in figure 4. The Paris Law applies:

$$\frac{da}{dN} = C\Delta K^m \quad (1)$$

with m = 1.46 and 4.09 and C = 2.5×10^{-10} and 5×10^{-12} respectively for each regime.

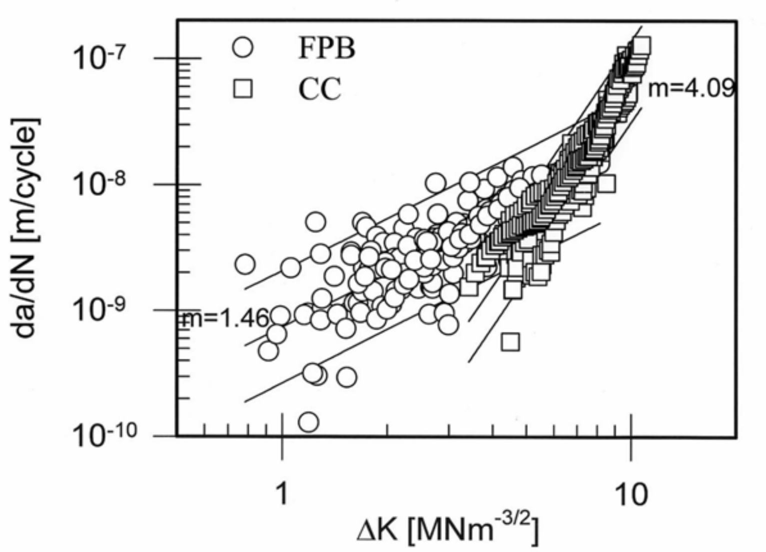

Figure 4: Fatigue crack growth in the ST alloy demonstrating transition behaviour.

3.3 Life Prediction

It is clearly evident that fatigue cracks in the ST variant initiate at pores irrespective of whether the specimen is plain or notched. What is not clear is the relative contributions from crack initiation at the pore and propagation from the pore in the overall fatigue performance. In the present programme, calculations of both phases were made.

Initiation lives were calculated by treating the pore as a notch with idealised shapes situated within the DEN geometry. A finite element analysis was carried out on pores of 0.4 mm and 0.18 mm radius hemi-spheres. The objective was to establish the cyclic strain range adjacent to the pore surface. In particular, the average axial strain range associated with a distance equal to the grain size (0.55 mm) was calculated. Typical values are summarised in Table 1.

Table 1: Average axial strain adjacent to pores

Nominal notch stress, MPa	Pore Size, mm	Average strain (for 0.55mm)
100	0.4	0.00383
80	0.4	0.00307
60	0.4	0.00230
100	0.18	0.00388
80	0.18	0.00311
60	0.18	0.00233

The assumption was made that the material between the pores was similar in character to the best or BT alloy. On this basis the initiation lives were calculated by equating the above strain ranges to the BT strain range data in figure 2. The resultant calculated initiation lives are compared with the measured notch data in figure 5. It is clear that for higher stresses, crack initiation at the pores makes only a small contribution to the overall fatigue life. However, at lower stress and longer lives, virtually the full life of the notch can be ascribed to crack initiation. Observations on failed specimens suggest that this initiation is associated with smoothing of the crack front prior to subsequent crack propagation.

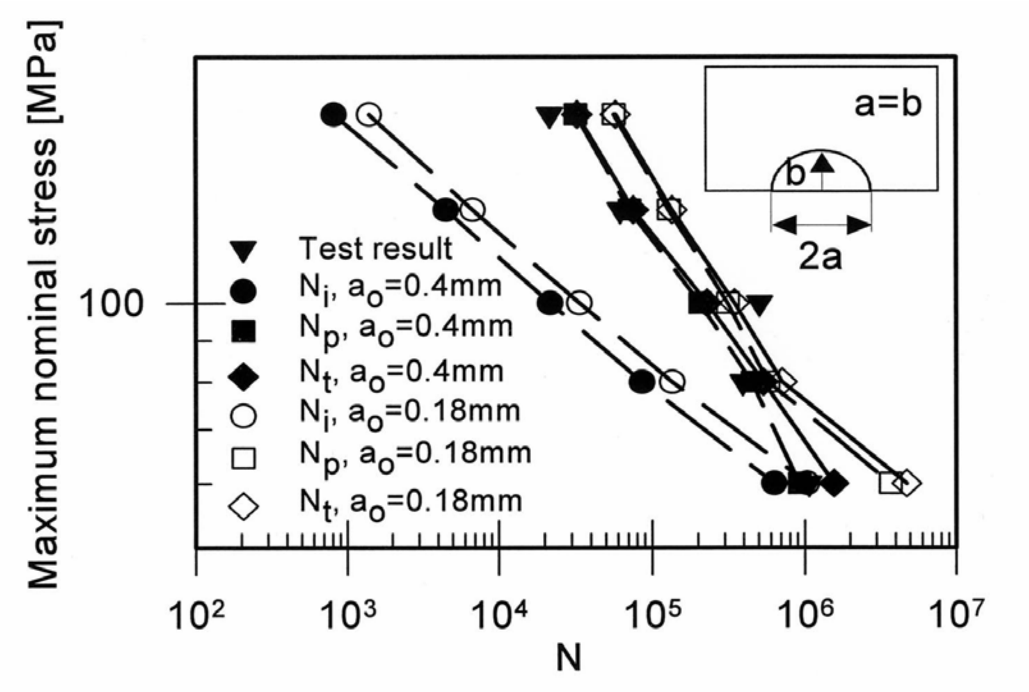

Figure 5: Measured and predicted notch behaviour.

The crack propagation prediction was based on the Paris Law and a method due to Pickard (5). The number of cycles for growth over the increment $\Delta a=(a_2-a_1)$ is given by

$$\Delta N = \frac{1}{CY^m F(\Delta\sigma)^m \pi^{m/2}} \left\{ \frac{a_2^{(1-2/m)} - a_1^{(1-m/2)}}{1-m/2} \right\} \tag{2}$$

with the stress intensity factor given by

$$K=M_G M_S M_B F(\Delta\sigma)\phi(\pi a)^{1/2}, \tag{3}$$

where M_G, M_S, and M_B are general, side-face, and back-face correction factors respectively and ϕ accounts for crack shape ellipticity. The Y factor in Eq. 2 is $(M_G M_S M_B \phi)$. The stress function, $F(\Delta\sigma)$, describes how the stress field changes with distance x from the edge of the arm. In the present work, $F(\Delta\sigma)$ is a polynomial function obtained by a finite element analysis of the form

$$\sigma(r)=\sigma_0+\sigma_1 x+\sigma_2 x^2+\sigma_3+\sigma_4 x^4+\sigma_5 x^5+\sigma_6 x^6+\sigma_7 x^7,$$

where x is the distance from the edge of the pore.

For simplicity, it was assumed that initial crack size in the calculation could be equated with pores of semi circular shape situated at the notch root. The calculated lives for the 0.4 and 0.18 mm pores are compared in Fig. 5. It is clear that propagation response dominates the lower lives. At lower stress the propagation phase contributes less than one half to the overall life. The analysis confirms that a damage tolerance analysis based solely on fracture mechanics could be significantly flawed. Crack initiation at defect boundaries makes a significant contribution for lives in excess of 10^5 cycles. It is also clear in figure 5, that scatter in observed notch behaviour can be related back to the initiation process. On this basis, it is vital that work should continue to develop a total life design approach for defect sensitive structural integrity.

4. Conclusions

- A total life calculation approach amalgamating a crack initiation model and a fracture mechanics based calculation method for crack propagation has successfully been applied to predict fatigue life for a notch geometry from laboratory test data.

- The fatigue life is well described by crack propagation behaviour at lower lives, but the crack initiation from defects needs to be taken into consideration in the longer life regime.

References

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