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Fatigue Performance of Cast and Powder Metallurgy Aluminium-Based MMCS

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Abstract

The paper explores fatigue on a powder metallurgy aluminium based MMC in two processed forms and a cast aluminium MMC. The cast alloy contained major casting defects and a larger SiC particle size. The experiments were carried out at ambient temperature and focused on plain specimens plus circumferentially notched and double edge notched specimens with K_t factors in the range 1.4 to 2.7. It is demonstrated that while the different microstructures of the alloys affect the notch fatigue response, this can be significantly modified when defects are present. The resultant behaviour is modelled using a finite element analysis and fracture mechanics calculation of residual life.

1. Introduction

Discontinuous MMCs are being considered for engineering applications particularly in the automotive industry. Important advantages are their low cost and their versatility in terms of easier production routes. Discontinuous MMCs are produced in three main ways: Powder metallurgy (P/M), Liquid metal casting and Spray forming. The product is subsequently processed or shaped using conventional metal fabrication processes such as extrusion, rolling, forging or cold working.

Many of the structural parts for which these MMCs are used experience cyclic loading. Studies of the fatigue behaviour of particle-reinforced Al-based composites demonstrate that fatigue and fracture of these materials depends on the alloy constituents and the processing method. In general, P/M processed composites contain smaller particles and display better stress-controlled fatigue properties in un-notched test-pieces compared with their cast counterparts. The present programme set out to explore how such a response relates to notch behaviour and the influence of notch geometry.

2. Experimental procedures

Fatigue tests were carried out at room temperature on plain and notched specimens under strain and load control respectively. The strain controlled fatigue tests were performed at R of 0 and -1. A trapezoidal waveform with a constant frequency of 0.25 Hz was generated via in-house software and the outputs of load and extension were monitored throughout individual strain reversals.

Three notch designs were used: Double-edge notch, DEN (K_t=1.9), Round-cylindrical notch, RCN (K_t=1.4), and V-cylindrical notch, VCN (K_t=2.7). Details of these have been reported previously (Evans et al [1]). The load controlled fatigue tests on these notches were performed at R=0.1. Microstructure and fracture surface evaluations were made using optical and scanning electron microscopes.

The study focussed on cast and powder metallurgy processed Al-based MMCs. The stir cast material, designated DURALCAN F3S2OS, is based on the A359 alloy and contains 20 vol% SiC particles. The typical SiC particle size was of the order of 10-20μm diameter. The material was supplied in the form of an as-cast ingot which was heat-treated to the T6 condition (SHT 538°C for 16 hours followed by a hot water quench to 70 - 80°C and aged at 154°C for 5 hours) prior to machining. The powder metallurgy material, designated AMC 225, is a 2124 Al alloy with 25 vol% SiC particle reinforcement. The typical particle size was of the order of 2-3μm diameter. Powder metallurgy allows finer particles to be introduced which generally improve the consistency of the measured fatigue response. There are two groups of P/M material, each manufactured by a slightly different route. The first is AMC225 XE produced by mechanical alloying while the second, designated AMC225 XH, is produced by blending and solid consolidation. Both materials were heat treated to the T4 condition (505°C for 1 hour, cold water quench and then natural aging at room temperature for more than 100 hours) prior to machining.

3. Experimental Results

The strain control response of the cast F3S2OS and AMC225 are compared in Figure 1. The fact that both R ratios which relate to the applied strains superimpose is a consequence of the fact that the resultant mean stresses in each alloy did not differ to a large extent. The associated stress R values were typically in the range 0 to -0.4 for the R=0 strain tests and -0.4 to -1 for R=-1 strain tests. In the case of the AMC 225 both processing variants have similar strain and load controlled fatigue response. This suggests that the slight differences in the processing route do not affect the fatigue performance.

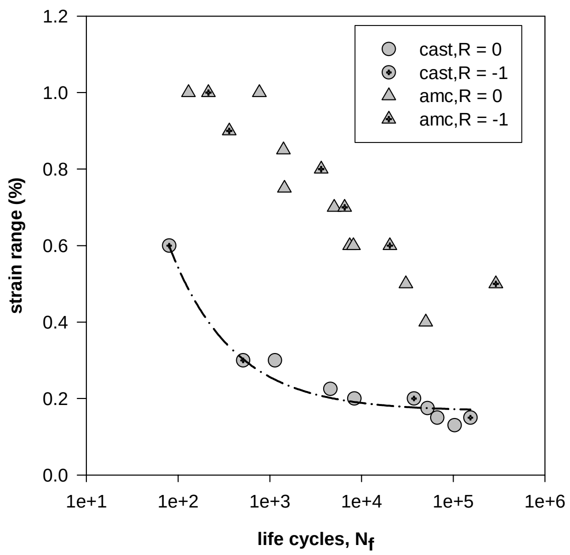

Figure 1: Strain control response of cast F3S20S and AMC225

The stabilized stress-strain range data at half life for the both materials are compared in figure 2. The significantly greater strength of the powder alloy is clearly evident.

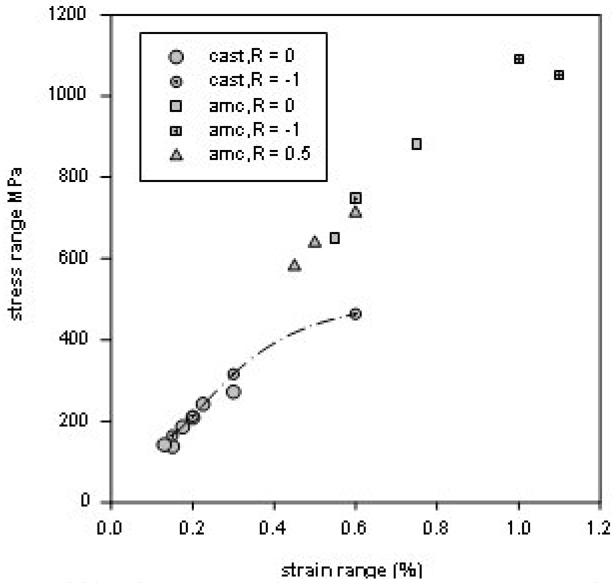

Figure 2: Stabilised stress-strain response of F3S20S and AMC225.

The notched fatigue response for the cast F3S20S is presented in figure 3 in the format: Peak elastic stress ($K_t\sigma$) against cycles to failure (N_f). The plain specimen data included on the graph were obtained from the stabilized stress range during strain control experiments reported in figure 1. The fatigue life increases in the order plain specimens, RCN, DEN and finally VCN specimens. Interestingly, the volume of critically stressed volume in the test-pieces decreases from plain specimen through RCN and DEN to VCN.

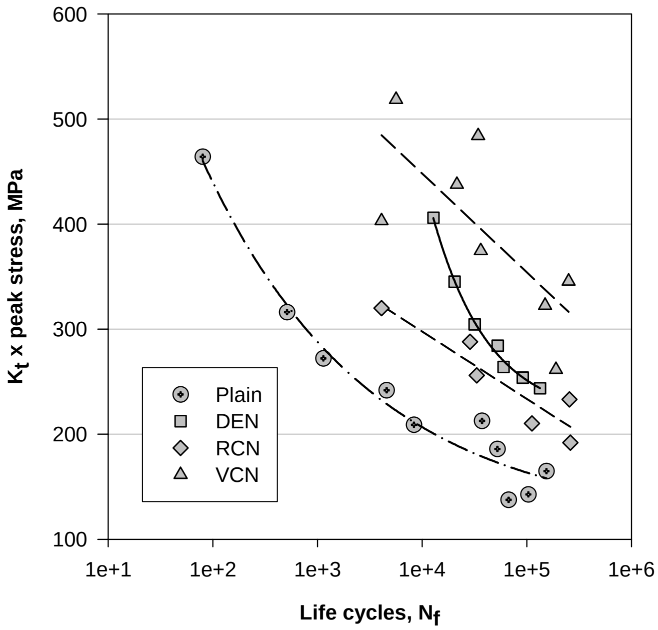

Figure 3: Notch fatigue of the cast F3S20S MMC (DEN K_t = 1.9, RCN K_t = 1.4, VCN K_t = 2.7).

The effect of notch geometry on the AMC 225 material was also investigated on the DEN, RCN and VCN specimens. The results are presented in Figure 4 in terms of nominal applied stress. Once again on a $K_t\sigma$ basis, the lowest lives occur in DEN specimens while the best performance is associated with the VCN geometry.

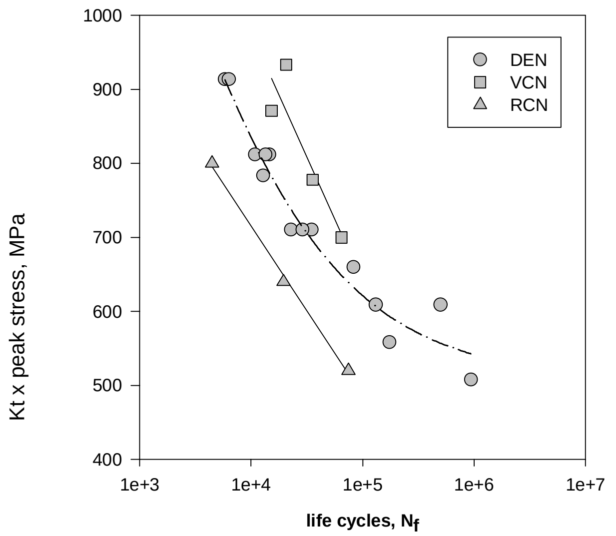

Figure 4: Notch fatigue of AMC 225 MMC (DEN K_t = 1.9, RCN K_t = 1.4, VCN K_t = 2.7).

One issue relevant in the fatigue response of the cast alloy is the presence of pores at critical ‘hot spot’ locations. The defects associated with crack initiation were, therefore, characterized in terms of their sizes and shapes. A typical distribution of pore sizes is illustrated for DEN specimens in figure 5. The unidentified pores are ones for which it was not possible to define meaningful pore dimensions. Microscopic evaluation on the AMC 225 material revealed a more uniform particle distribution than in the cast material.

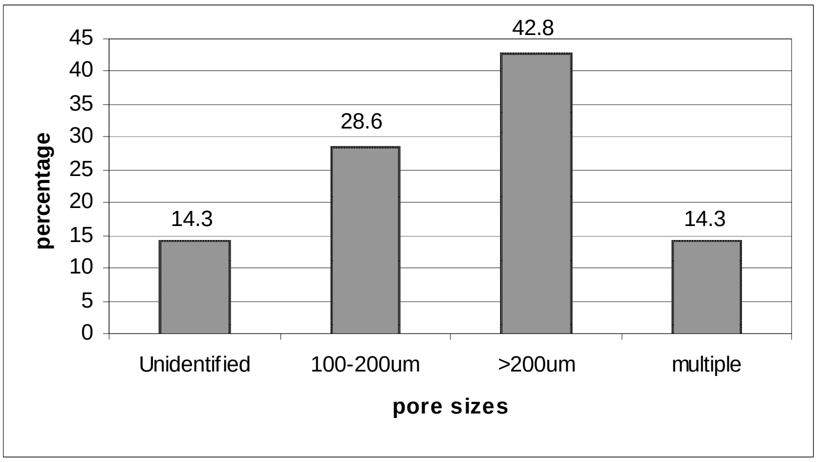

Figure 5: Pore size distribution in F3S20S DEN specimens.

4. Discussion

On comparison of the cast and P/M materials in Figure 1, it is clear that the AMC225 material has the stronger fatigue response under strain control, but that both materials react similarly to the R = -1 and 0 ratios. Figures 3 and 4 confirm that there is also a strength differential in notch behaviour between the two types of MMC. This is consistent with the stronger AMC225 matrix alloy and the finer SiC reinforcement used.

The critical strain approach is often used to predict notch behaviour from plain specimens. It is assumed that if the strain at the root of a notch and in a plain specimen is the same, then they will develop a crack in the same number of cycles. This approach was applied in the present case with the Neuber method used to determine conditions at the notch root

(Neuber [2]). The resultant predictions are compared with the experimental data in figure 6 for DEN specimens.

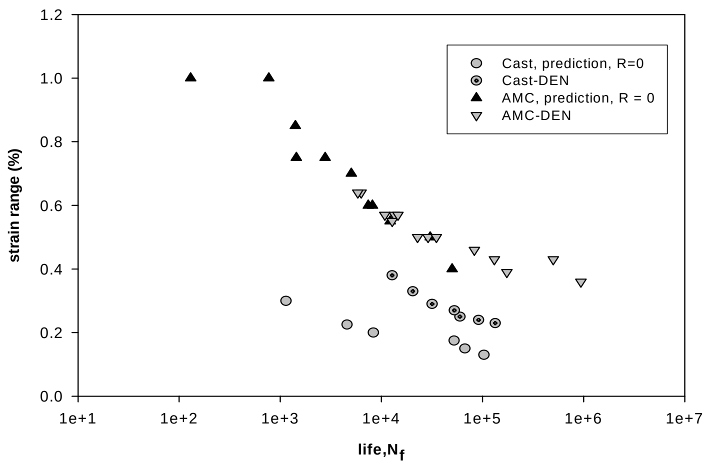

Figure 6: Critical strain predictions of DEN fatigue in cast and powder MMCs.

Clearly, the prediction works for the AMC225 which is consistent with previous work on this alloy (Bache et al [3]). It is also consistent with work on conventional alloys. However, it under predicts the notch response in the cast alloy. This discrepancy can be attributed to porosity. Clearly, the volume of critically stressed material is greater for plain specimens. A bigger volume is likely to contain the larger defects and hence the lowest fatigue lives. Consequently, predictions based on plain specimens will under estimate notch fatigue lives.

To explore the role of porosity, a finite element model was constructed in which idealized pore shapes, based on actual measurements from failed specimens, were located at the notch root. Using published information (Evans et al [4]) on the rates of crack propagation, the residual life, ΔN, can be calculated from expressions based on standard fracture mechanics techniques (Evans et al [5]). A range of predictions for the RCN (Kt = 1.4) test-piece is presented in figure 7 where typical initial flaw sizes from the measured distributions are used. It is clear that the notch response is predicted by the fracture mechanics calculation without invoking a crack initiation period. The calculation also illustrates how the observed variability in the life data can be related to variations in initial flaw size. The calculations clearly confirm the impact of porosity on the notch fatigue response of the cast aluminium MMC.

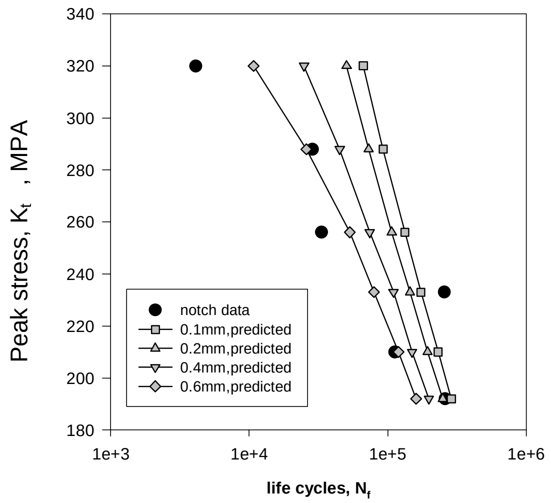

Figure 7 Fracture mechanics prediction of fatigue for RCN (K_t = 1.4) specimens in the cast MMC

5. Conclusions

The analysis confirms that porosity in the cast aluminium MMC has a dominant influence on the fatigue performance not only of large volume plain specimens but also of notches even when the K_t factor is high and the critically stressed volume low. The failure behaviour of the notches can be predicted from a fracture mechanics approach. In contrast, the powder metallurgy aluminium MMC, with a much finer reinforcement size, behaves in a similar way to conventional alloys in that the notch fatigue behaviour can be predicted by a critical strain approach based on plain specimen fatigue data.

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