VARIABLE AMPLITUDE LOADING FATIGUE LIFE PREDICTIONS OF A PARTICLE REINFORCED ALUMINUM MATRIX COMPOSITE

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Compact keyhole specimens made of A356 cast aluminum alloy reinforced with 20 volume % SiC particles were tested under variable amplitude loading at room temperature and 150°C. Test results were compared to calculated fatigue lives obtained using strain based fatigue crack "initiation" (defined as 1.5 mm crack extension) and linear elastic fracture mechanics based fatigue crack propagation. Calculated initiation lives were closer to experimental lives if an empirical notch factor was used instead of theoretical stress concentration factor. Calculated fatigue crack growth lives were largely non-conservative. It was shown that common fatigue life prediction techniques can be used for this composite, but with care.

## INTRODUCTION

Room temperature and 150°C variable amplitude loading tests were perfoṛmed on compact keyhole specimens made of a metal matrix composite (MMC), based on cast aluminum A356 alloy reinforced with 20 volume % SiC particles. Common low cycle fatigue and fatigue crack growth based concepts were used for variable amplitude fatigue life calculations. The calculations were based on the composite constant strain amplitude (low cycle fatigue) and constant load amplitude (fatigue crack growth) data, obtained from independent experiments. The test procedures and calculations were similar to those performed on the unreinforced matrix material A 356-T6 (1), which made a good starting point for comparison. This research was a part of a larger scale investigation of the metal matrix composite behavior under fatigue lading.

## TEST SPECIMEN AND PROCEDURES

The metal matrix composite used in this research is based on cast aluminum alloy A 356 reinforced with 20 volume % SiC particles. The material was obtained by adding SiC particles into the melted matrix material, kept at constant temperature (proprietary information). The composite was initially cast in ingot form. The ingots were later sand cast into blocks, from which the keyhole specimens were made. Some stirring of the mixture was applied during sand casting until the liqiudus temperature was reached, to avoid particle clustering. The sand cast blocks were solutionized at 510°C for twelve hours, hot water quenched and artificially aged at 154°C for five hours (T61 thermal treatment) (2). SiC particles

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were elongated, with aspect ratios between 2:1 and 5:1. The particle size distribution had a median of 13±1 μm, with 3% of the particles larger than 25 μm and 94% larger than 5 μm (2).

Test Specimen. The specimen used for variable amplitude fatigue testing is a compact keyhole specimen with an H/W ratio of 0.49 (W=56.9 mm) and a thickness of 8.9 mm. The keyhole was drilled and reamed to a diameter of 6.4 mm. The specimen was slightly smaller compared to the one used in (1), due to different casting requirements. It allowed for both crack "initiation" and crack propagation analysis. It had a theoretical stress concentration factor of $K_t$=3.4, and the fatigue notch sensitivity factor q=0.625 was obtained. If applied to the MMC specimen at hand, the q factor would give a fatigue notch factor of $K_f$=2.3.

Test Procedures. The variable amplitude loading fatigue tests in this research were performed using an 89 kN computer controlled closed loop servo-hydraulic fatigue test machine under load control conditions. 150°C testing was done in an electric-heated environmental chamber with automatic temperature control and with accuracy of ±1.5°C.

Fatigue crack lengths were measured by a 33x traveling telescope. They were recorded from the first detectable surface crack to final fracture. A surface crack of 1.5 mm was defined as crack "initiation", since it can be easily measured and is consistent with final crack sizes in independently performed low cycle fatigue tests. All tested specimens exhibited flat and horizontal fracture surfaces and thus fatigue life results were considered valid for comparisons with analytical fatigue crack growth analysis.

Variable Loading Test History. The variable amplitude loading history was constructed by Lease (1) from four log skidder strain histories. Those histories were manipulated in an attempt to create an efficient test spectrum that was not dominated by very large or very small range magnitudes. The history contained 41912 reversals with various mean values. It was normalized such that maximum amplitude had a value of 1000 and the rest of reversals were scaled accordingly. When applied, the history was assigned three different levels of loading, corresponding to short (about $10^4$ reversals), intermediate, and long (about $10^7$ reversals) fatigue lives. Loading frequency varied from 3 to 10 Hz, with lower rates used for the "high load" histories and higher rates for the "low load" histories. The three load scaling factors correspond to maximum peak loads of 6.2 kN, 5.3 kN, and 4.4 kN, which resulted in nominal net stresses at the notch root of the keyhole specimens of 123 MPa, 105 MPa, and 87 MPa, respectively. The theoretical elastic stress at the notch root would be $K_t$=3.1 times the nominal values, or 381 MPa, 326 MPa and 270 MPa, respectively. These values are expected to cause local plastic cyclic yielding at the notch root. For the purposes of fatigue life predictions, the history was rainflow counted using LifEst software algorithm (3).

## VARIABLE LOADING FATIGUE TEST RESULTS

The number of loading history repetitions until specimen fracture ranged from 7 to 160 at room temperature and from 3 to 80 at 150°C. Scatter of the fatigue initiation life results (life to grow a 1.5 mm crack) ranged from factor of 1.2 at room temperature to 2.3 at 150°C. The fatigue initiation lives accounted for more than 80% of the total fatigue life at room temperature and more than 65% at 150°C, indicating that crack initiation life calculations for this metal matrix composite, loading history and keyhole specimen are more important in comparison with crack growth life calculations. For comparison, the room temperature fatigue initiation life of the unreinforced matrix material accounted for 25% to 70% of the total fatigue life (1).

## VARIABLE LOADING FATIGUE LIFE CALCULATIONS

All fatigue life calculations were performed using a commercially available SoMat LifEst software package. Fatigue crack initiation life was calculated using the local strain approach, utilizing either the Morrow or the Smith Watson Topper (SWT) mean stress models (4). The notch root strains were approximated using either the Neuber (3) or the Glinka rule (5). The linear damage rule (4) was used throughout the calculations, which neglects load interaction effects. The difference in calculated fatigue initiation lives using the four combinations of mean stress models and notch root strain approximation rules was negligible. Figure 1 presents calculated vs. experimental fatigue crack initiation life results for the Morrow mean stress model and the Neuber rule with $K_t$=3.1 at both temperatures. The calculated lives were conservative by an order of magnitude at room temperature and even more conservative at 150°C. If the assumed fatigue notch factor $K_f$=2.3 was used, the fatigue initiation life calculations were substantially improved at both temperatures, Figure 2, although at room temperature they now tend to be slightly non-conservative. One should keep in mind that the real value of the composite fatigue notch sensitivity factor q was not known, i.e. it was assumed to be the same for the composite as for the unreinforced matrix, so the $K_f$ value used was not reliable.

Fatigue crack propagation life (i.e. fatigue life from 1.5 mm crack initiation to final structure) was calculated using linear elastic fracture mechanics based concepts. The stress intensity factor $K_I$ calibration for the keyhole specimen is given in (1). It was derived for a C(T) specimen, and the under lying assumption for its use with the keyhole specimen is that, after 1.5 mm crack extension, the crack tip was beyond the influence of the keyhole stress concentration. The crack propagation analysis was performed using the independently determined Paris equation composite parameters and composite threshold stress intensity factors for R=0.05 at room temperature and 150°C, respectively. A non-interaction crack propagation model was used in the calculations. Figure 3 presents calculated vs. experimental fatigue crack growth lives without closure effects at both temperatures. Calculated lives were non-conservative by about a factor of 5. If simplified closure analysis (3) was utilized in the calculations, even more non-conservative results were obtained.

Total fatigue lives were calculated as a sum of fatigue initiation and propagation lives. Figure 4 presents calculated vs. experimental total fatigue lives at both temperatures with $K_t$=3.1 and without closure effects. Reasonably good agreement can be seen, with maximum scatter of about a factor of 3. It should be noted, however, that if the $K_f$=2.3 value was utilized, the total fatigue lives were non-conservative by about a factor of five, due to non-conservative fatigue crack growth results.

## SUMMARY AND CONCLUSIONS

The fatigue crack initiation lives calculated using the theoretical stress concentration factor $K_t$=3.1 were overly conservative at both temperatures. Better results were obtained using assumed fatigue notch factor $K_f$=2.3, determined by employing the unreinforced matrix fatigue notch sensitivity factor q=0.625. The predictions then tend to be slightly non-conservative at room temperature. The fatigue crack growth calculations were non-conservative by about a factor of 5 at both temperatures.

It can be concluded that reasonably good fatigue life predictions for this metal matrix composite can be obtained using common low cycle fatigue and fatigue crack growth approach, but with care. The value of the material fatigue notch factor $K_f$ plays an important role in fatigue crack initiation life calculations and further experimental and theoretical research in that direction is recommended. Although the fatigue crack growth lives accounted for only a small portion of the total fatigue lives, additional work on improving the accuracy of these fatigue crack growth life calculations is needed.

## REFERENCES


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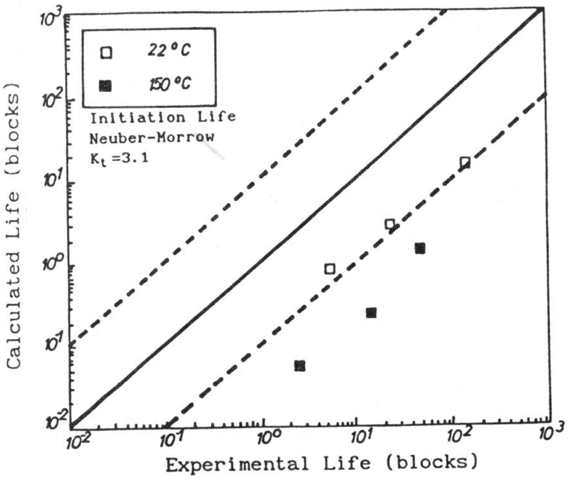


Figure 1 Calculated versus experimental fatigue crack initiation life, $K_t$=3.1.

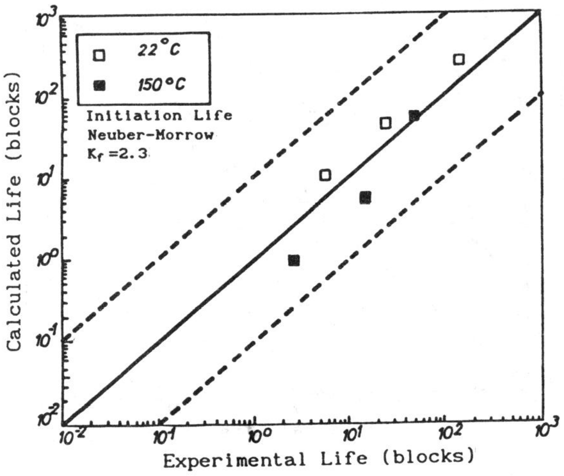


Figure 2 Calculated versus experimental fatigue crack initiation life, $K_f$=2.3.

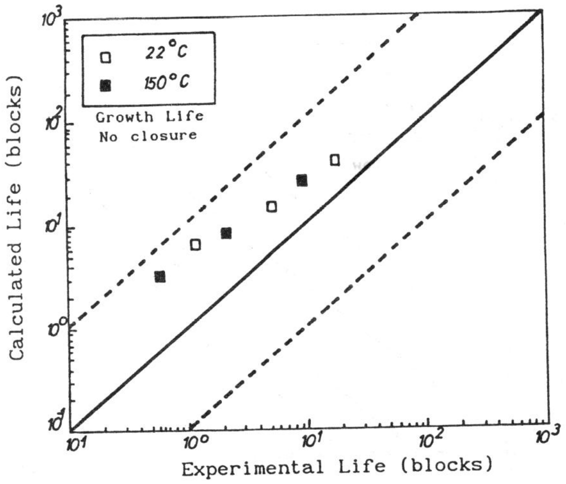


Figure 3 Calculated versus experimental fatigue crack growth life.

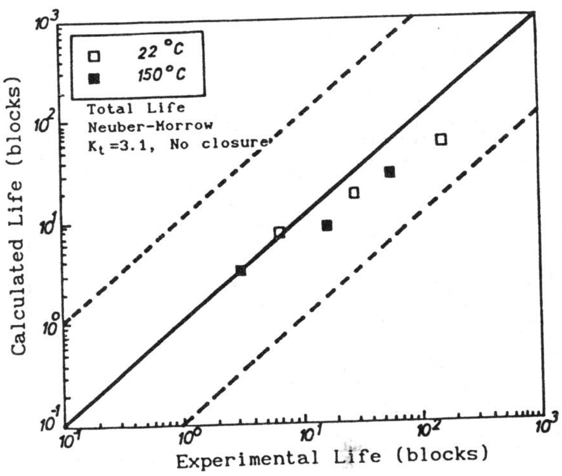


Figure 4 Calculated versus experimental total fatigue life, $K_t$=3.1.