

Isothermal Fatigue Testing of Particulate Metal Matrix Composites

Introduction

Some of the key applications for particulate metal matrix composites (MMCs) are for fatigue applications in the automotive and aerospace industries. Many of these applications are at elevated temperatures, typically in the range 100-250°C for aluminium-based systems. To date, a considerable amount of work has been carried out on the room temperature performance of MMCs, but relatively little published regarding the elevated temperature fatigue performance.

A review of some of the key publications and issues associated with elevated temperature fatigue life test methods for MMC is given in [Ref 1](#).

For metals one of the key methods for improving the fatigue performance is by reducing the number of second-phase inclusions in the material that can act as sites for fatigue crack initiation. In an apparent contradiction to this approach, the success of particulate reinforced MMCs has been due in some part to the improvement in fatigue strength resulting from the deliberate addition of hard ceramic reinforcement particles, such as Al_2O_3 or SiC. The incorporation of significant volume fractions of ceramic particles in the aluminium alloys has led to improved high-cycle fatigue performance in a variety of MMC systems over a range of test conditions. For MMCs, the improvement in fatigue life can be attributed to load transfer from the aluminium to the stiffer ceramic reinforcement that leads to reduced stress levels in the matrix. This improvement is not always realised, particularly with regard to some of the cast MMCs that have large angular reinforcements and in MMCs where it is difficult to control the homogeneity and uniformity of the microstructure.

Fatigue is the progressive, localised, permanent damage that occurs in materials subjected to alternating stresses and strains that may result in cracks or failure of the testpiece or component. There are three basic stages in the fatigue process: fatigue initiation - nucleation of cracks, crack growth and final fracture.

Fatigue damage normally results from cyclic stresses that are below the static yield strength of the material. The fatigue strength is determined from the S-N curve, a plot of the stress amplitude versus the number of cycles to failure, generated during high cycle fatigue (HCF). For aluminium alloys, depending on the composition and heat treatment, the room temperature fatigue strengths typically range from 0.3-0.5 of the tensile strength [\[1\]](#).

[Figure 1](#) shows the fatigue limit plotted against tensile strength for a variety of MMCs and unreinforced aluminium matrix alloys over a range of temperatures. The results include some of the materials tested in this project and those taken from the review document [\[1\]](#). All were tested at an R ratio of 0.1.

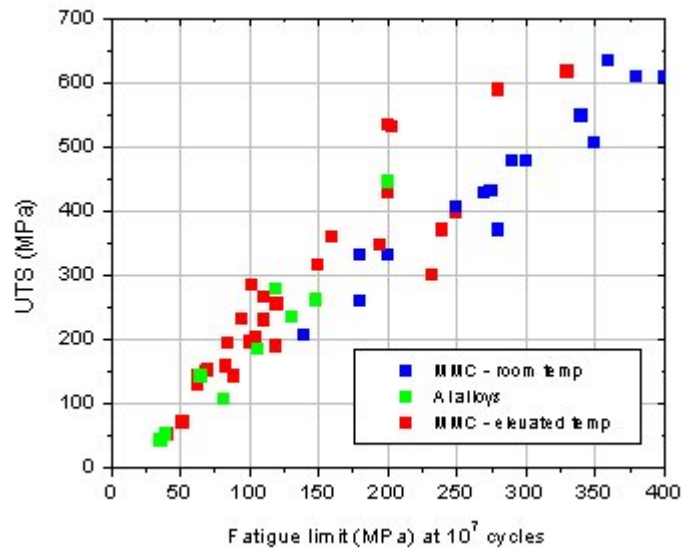


Figure 1: Relationship between tensile strength and fatigue limit for MMCs and matrix alloys

In HCF, crack initiation plays a dominant role in determining fatigue performance. For some engineering materials such as steel and titanium the S-N curve becomes horizontal at a certain limiting stress, and below this stress level - the fatigue limit - the material can endure an infinite number of cycles without failure. Most aluminium alloys however, do not reach a fatigue limit and the S-N curve continues to fall. In such cases a fatigue strength is reported at a specified number of cycles (usually between 5×10^6 and 10^8). In this work the fatigue strength is defined as 10^7 cycles.

Fatigue crack initiation sites in particulate MMCs generally occur at the surface of the specimen. Studies in particle-reinforced aluminium alloys [2,3] have shown that fatigue crack initiation and premature failure may be triggered by the presence of large angular particles. In some materials particle clustering may also lead to poor infiltration of the preform, which provides another potential site for the initiation and nucleation of cracks.

Materials Examined

The purpose of this Measurement Note is to present some of the work carried out at NPL to examine the HCF performance of particulate MMCs. Data has been generated on the room temperature and elevated temperature performance of a range of commercially available MMCs and matrix alloys detailed in [Table 1](#). Representative micrographs of some of the MMCs are shown in [Figure 2](#).

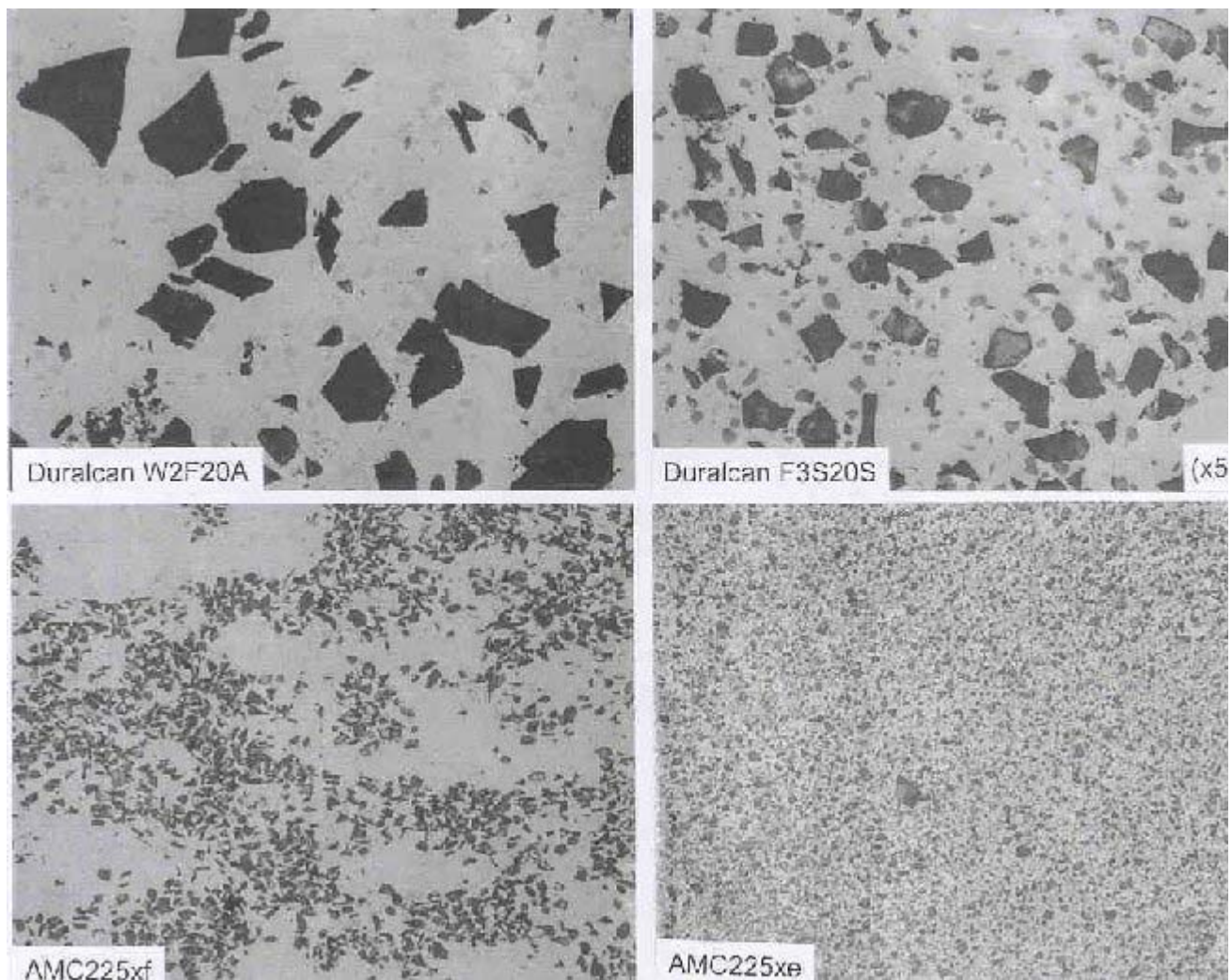


Figure 2

The microstructure of the four materials is very different and reflects the processing route used. The *Duralcan F3S20S* shows a reasonably homogeneous particulate distribution, with a mean SiC particle size between 10-30 μm . Smaller second phase silicon particles can be seen clearly. The alumina reinforcement in the *Duralcan W2F20A* material is larger, approximately 20-40 μm in size. Again, there is a reasonably uniform particulate distribution, but some orientation along the longitudinal section.

The AMC materials are produced by the powder route and use very fine (3 μm) SiC and aluminium powders. The microstructure of the AMC225xe MMC shows a homogeneous distribution of fine SiC particulate, but there are some areas where clustering does occur and this is often a feature of material produced from the powder route. The AMC225xf material is somewhat different in appearance to the 'xe' material, and this reflects the processing of the powders. The 'xe', which is mechanically alloyed, has a finer, more uniform distribution of particulate than the 'xf'. The 'xf' has a cleaner matrix but a more inhomogeneous particulate distribution, particularly in the transverse direction.

The ACMC material, which has 20% SiC whisker reinforcement is not shown in [Fig. 2](#), but has been examined in separate VAMAS intercomparison exercises to investigate MMC tensile and fatigue test methods and properties [\[4-6\]](#). The whiskers are very fine - approximately 1 μm in diameter and with an aspect ratio between 10-100. Some data is also presented for wrought unreinforced 2618 aluminium - a material used for its good fatigue properties.

The mechanical properties of the relevant MMCs at room temperature and elevated temperature were also measured as part of this project and are included in [Table 2](#). The variation of tensile strength with temperature is illustrated in [Fig. 3](#).

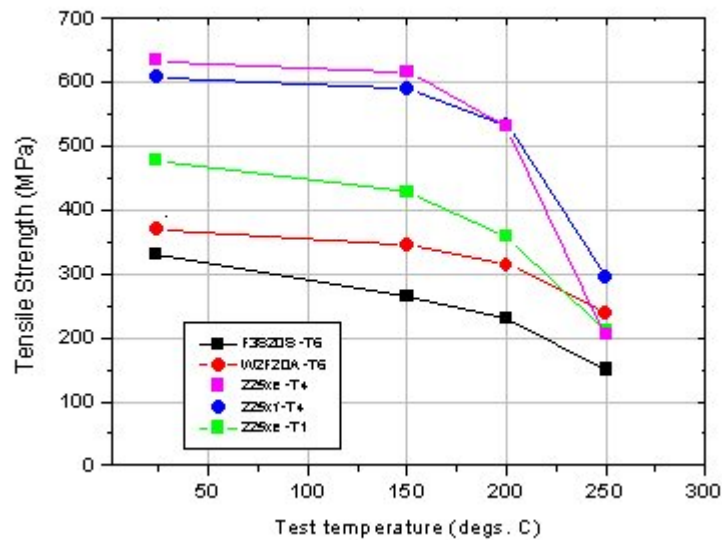


Figure 3

Supplier and Code	Composition and Form	Heat Treatment
Duralcan W2F20A - T6	2618 + 20% Al ₂ O _{3p} Extruded bar	Peak aged
Duralcan F3S20S - T6	A359 + 20% SiC _p Forged disc	Peak aged
AMC 225xe - T4	2124 + 25% SiC _p Extruded bar	ST + naturally aged
AMC 225xe - T1	2124 + 25% SiC _p Extruded bar	Naturally aged
AMC 225xf - T4	2124 + 25% SiC _p Extruded bar	ST + naturally aged
ACMC - T4	2009 + 20% SiC _w Extruded bar	ST + naturally aged
Alcan - T651	2618 Al alloy - Extruded bar	Stretch + peak aged

Table 1: Details of the materials examined

	Test Temp (°C)	0.2% Yield Stress (MPa)	Tensile Strength (MPa)	E (GPa)	Fatigue Limit (MPa)
W2F20A-T6	24	286	369	97.3	280
	150	267	345	92.1	195
	200	236	314	89.9	150
	250	213	228	87.3	110
F3S20S - T6	24	282	331	104.9	180
	150	225	264	99.8	110
	200	201	230	97.2	95
	250	122	150	94.6	70
225xe - T4	24	486	633	116.2	410
	150	474	616	110.9	330

	200	448	530	108.3	203
	250	128	194	106.6	100
225xf - T4	24	453	608	121.8	380
	150	427	588	115.2	280
	200	402	533	114.6	200
	250	205	283	110.5	102
225xe - T1	24	328	477	115.2	290
	150	321	428	111.1	200
	200	276	358	109.2	160
	250	102	200	107.3	105

Table 2: Tensile properties of MMCs examined

Most of the parameter investigation tests presented in this study have been carried out on the AMC225xe MMC (2124 + 25% SiC). Where appropriate other materials are included for comparison.

In the following sections results will be presented on the:

- effect of specimen geometry
- effect of surface finish
- elevated temperature performance
- comparative data for rotating bend tests
- VAMAS intercomparison exercise on a SiCw/Al MMC

Unless stated, all the tests carried out in this study were axial fatigue tests, performed in load control with an R ratio of 0.1 and at a frequency of 10 Hz. Throughout this document all the S-N curves are plotted on the same horizontal and vertical scales to facilitate comparison.

Effect Of Specimen Geometry

Three different specimen geometries have been examined in this study, based on those proposed in ASTM E466 [9]. The machining of MMCs is expensive and should be kept to a minimum, but the issue of whether to use flat or round specimens is often determined by the form of material stock. Material supplied in sheet or plate form would normally be machined into flat specimens, material in the form of round bar and rod could be turned into round specimens. For large billets or forgings it is often economical to machine flat specimens. Most of the materials examined in this study were supplied in thin sheet/plate form and were machined into flat specimens.

In the present study a modification of the ASTM E466 geometry was used, by increasing the length of the ends of the specimen to enable a short furnace to fit around the specimen gauge length. Two different profiles were examined - one with a continuous radius between the ends of the gauge length (Spec A) and the other using a parallel gauge length and tangentially blended radii between the gauge length and the grip section (Spec B). Both specimen geometries were 200 mm long and had a minimum gauge length cross-section of 6 x 3mm. In the case of Spec. B, the gauge length had a parallel section of 10 mm. Where possible a limited number of comparative measurements were made on an ASTM round specimen geometry with threaded grips (Spec C).

Flat geometries may be more susceptible than round specimens to misalignment and out of plane bending. Materials with high volume fractions of reinforcement and with large size particulate reinforcement are vulnerable to damage and premature failure. Failure of round specimens in the threaded grip area has been reported as a problem, in some MMCs which are difficult to machine.

Flat specimens are generally more difficult to polish particularly over the profiled sides of the specimen and the edges. Often this must be carried out by hand and can be expensive and time consuming. Round specimens can be polished automatically in standard fatigue polishing machines providing the correct abrasives and cloths are chosen. This method also gives a more repeatable surface finish.

Results are presented in [Figure 4](#) for the AMC 225xe-T1 material at room temperature.

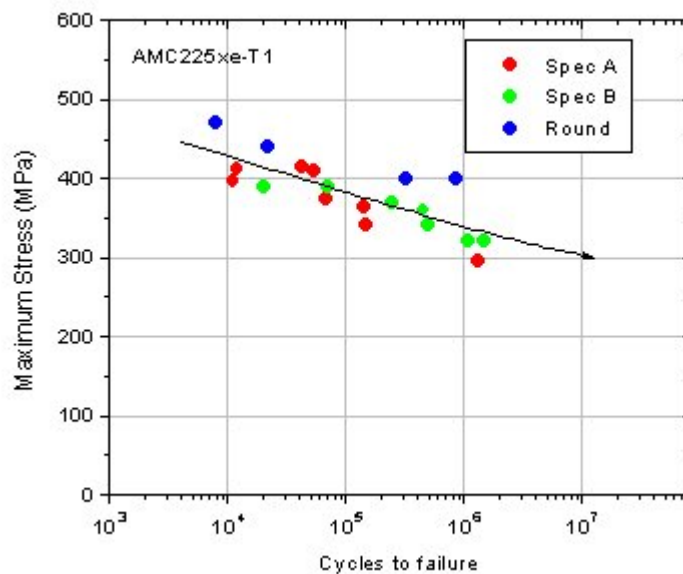


Figure 4: Effect of specimen geometry for AMC225xe-T1

The results show a small effect of specimen geometry with the round specimens giving slightly superior fatigue performance. The gauge length dimensions are important as a smaller cross-sectional area reduces the probability of a defect being present in the gauge length, but the condition of the surface, which is vital to fatigue performance, will have a greater effect in this case. It is not clear whether the differences in [Fig. 4](#) are due to the size effect or an inherently more uniform surface finish of the round specimen.

Effect Of Surface Finish

[Figure 5](#) shows the effect of different surface finishes on the room temperature fatigue performance of the AMC225xe-T1 MMC. Details of the surface preparation are given in [Table 3](#) along with the average surface roughness values that were measured prior to testing.

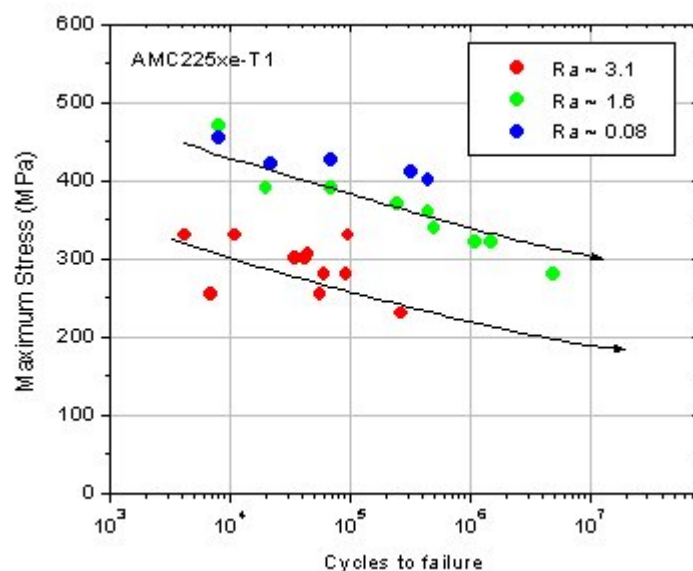


Figure 5: Effect of surface finish

	Details of Preparation	Ra (μm)
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Case A	Ground surface. No additional preparation	3.1
Case B	Ground surface + 800 & 1200 grade SiC, with 3 μ m diamond polish	1.6
Case C	As Case B, but with additional 1 μ m diamond polish, + OPS	0.08

Table 3: Details of specimen preparation

Repeat tests at specific stress values showed generally increased scatter in the fatigue strength values for the specimens with the minimum surface preparation and higher surface roughness. Increasing the quality of the surface finish also led to a positive shift in the S-N curve and higher fatigue lives - as might be expected.

The difference between the fatigue performance of specimens with surface roughness of 0.08-1.6 is small and this is in general agreement with the results presented in more detailed work on other MMCs [7,8]. **Except where stated, all the tests in this study were carried out on specimens prepared according to Case B.**

Examination of the fracture surfaces of the broken specimens revealed that, irrespective of the surface preparation and polishing, a number of specimens still failed outside the gauge length, with the fatigue crack often initiated at a corner of the flat specimen.

Tests At Temperature

Tests have been carried out to compare the fatigue performance of MMCs over a range of temperatures. Results are presented in Figs 6-10 for selected MMCs and a 2618 matrix alloy at room temperature, 100, 150, 200 and 250°C. For some of the materials only a few tests were carried out due to the limited number of specimens available. Some rotating bend test data (with R = -1) are included for the *AMC225xe-T1* MMC in Fig. 11 for comparison [10], together with commercial data from an MMC supplier for comparison in Fig. 12 [11].

The room temperature fatigue results can be grouped into three sets. The *AMC225xe* and *xf* materials in the T4 (solution treated + naturally aged) showed the best fatigue performance, followed by the *225xe-T1* (naturally aged) and Duralcan *W2F20A-T6*. The unreinforced 2618 aluminium matrix was of comparable performance to the Duralcan *F3S20S-T6* composite.

On heating to 100 and 150°C similar behaviour is observed, but the fatigue strength values fall with increasing temperature in all cases. At 200°C, the effect of the initial heat treatment is of little consequence and all but the *F3S20S-T6* MMC show a similar fatigue performance. Under these conditions the fatigue performance of the 2618 aluminium matrix is superior to the *F3S20S-T6* MMC and approaching that of the other MMCs tested.

At 250°C the fatigue strength of all the materials is significantly reduced and the S-N curves have become very flat. The unreinforced 2618 matrix alloy now has comparable fatigue performance, and may even be slightly superior, to the powder based MMCs.

For MMCs and heat treatable aluminum alloys the initial heat treatment has an important effect on properties including the tensile strength and fatigue performance, but the influence of initial heat treatment is important only up to a point. For the materials examined the T4 condition gives higher fatigue strengths than the T1 condition up to ~ 200°C, above which there appears little difference as the MMCs overage. The 'xe' composition, which has a uniform distribution of fine particulate is superior to the 'xf' composition for the same initial heat treatment. At high temperatures the presence of the particulate reinforcement has little effect and the fatigue behaviour is dominated by the fatigue strength of the matrix alloy.

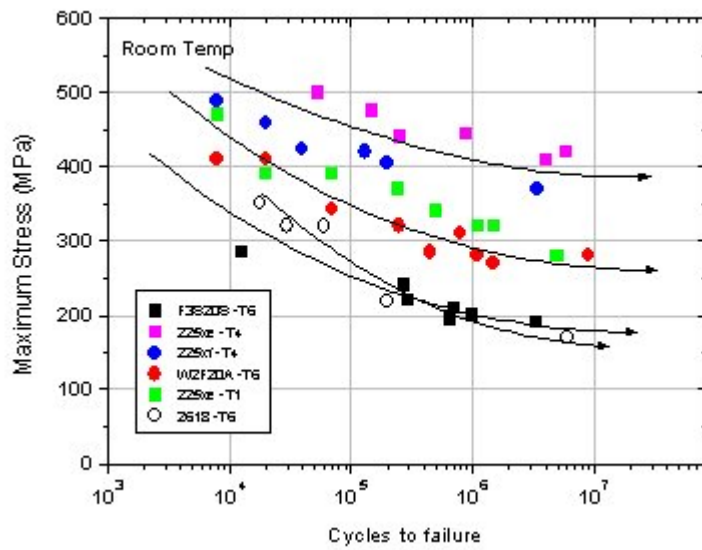


Figure 6

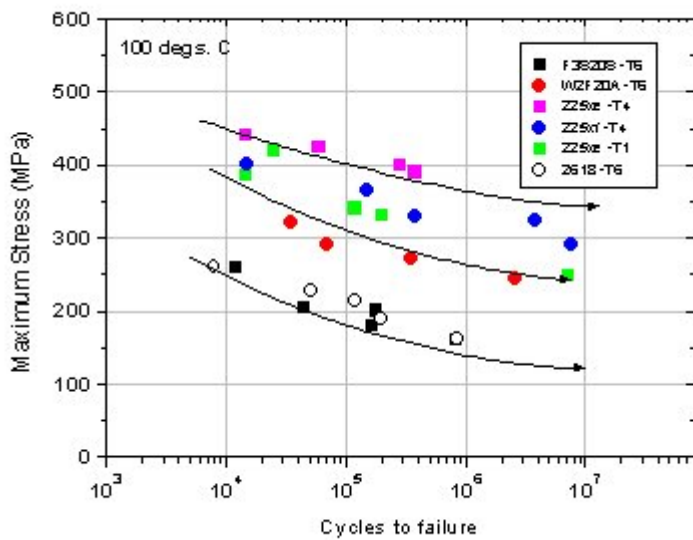


Figure 7

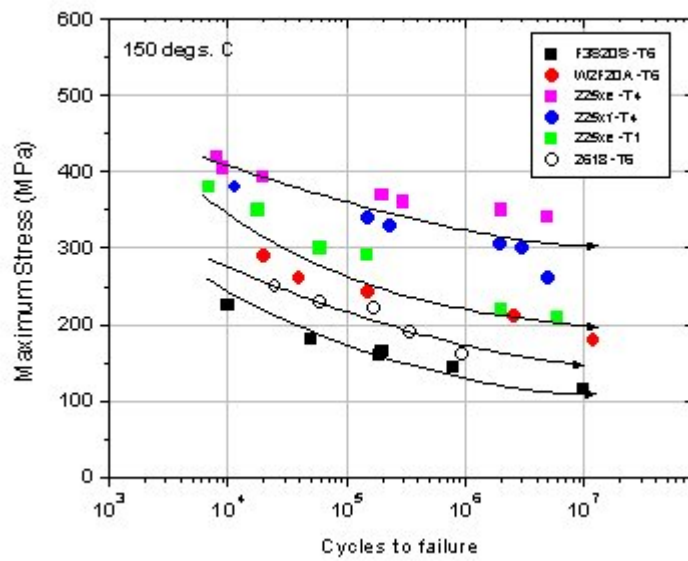


Figure 8

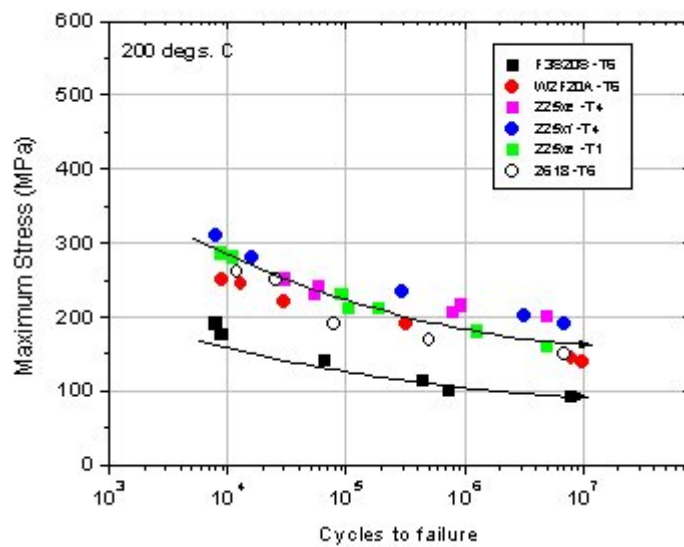


Figure 9

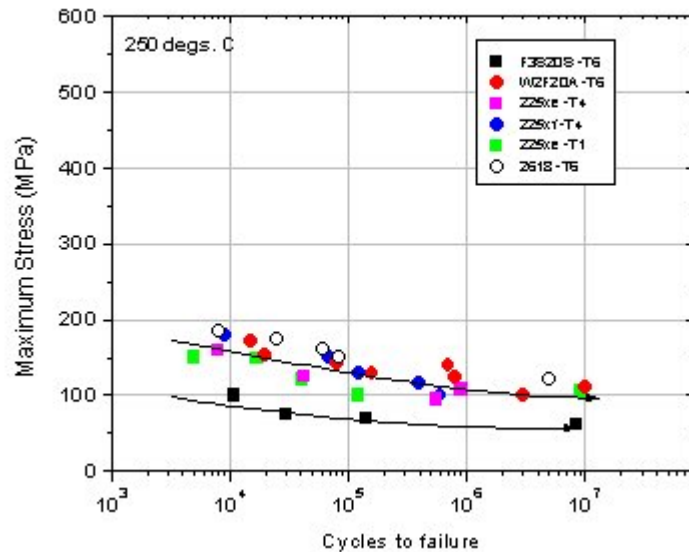


Figure 10

Rotating Bend And Commercial Test Data

Figure 11 shows comparative data on the *AMC225xe-T1* and *2618-T6* alloy generated in rotating bend tests at room temperature, 150 and 200°C [10]. These tests are carried out with an R ratio of -1. For all the tests carried out by NPL an R ratio of 0.1 was used, but it was not possible to perform fully reversed loading with the specimen geometries employed because of the potential problems of buckling of the long, thin, flat specimens when loaded in compression.

Care should be taken in comparing data from the axial and rotating bend test configurations because the rotating bend test does not produce a uniform stress in the specimen cross-section and is more susceptible to surface effects.

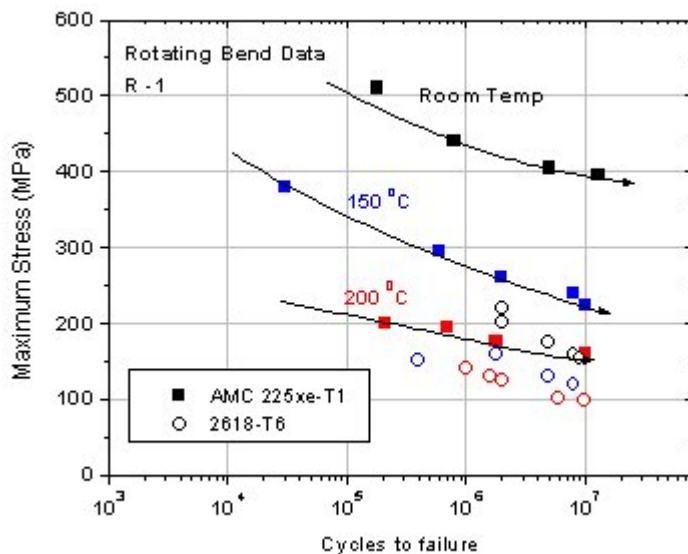
Figure 11: Rotating Bend Test Data for the *AMC225xe* and *2618* materials [10]

Fig. 12 below shows some data from room temperature axial fatigue tests on the *W2F20A-T6* and *F3S20S-T6* MMCs. The results show the relatively poor performance of the *F3S20S-T6* MMC compared to the 2014 matrix and wrought *W2F20A-T6* MMC. The tests are presented for an R ratio of -1 so the results cannot be compared directly with the results presented elsewhere in this report. This does however illustrate the importance of generating data that is appropriate to the application, as significant differences in relative performance can be

achieved with different test conditions.

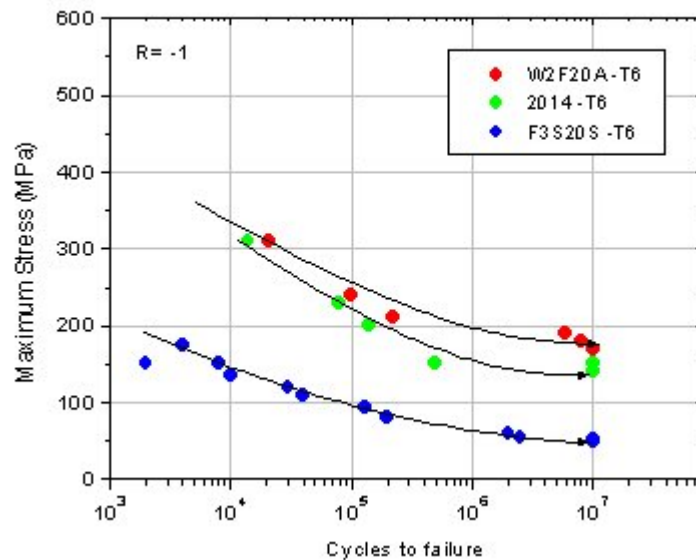


Figure 12: Duralcan data for selected MMCs [11]

VAMAS Intercomparison Exercise On SiCw/Al MMC

Fig 13 shows results from a VAMAS activity organised as part of the current project to measure the fatigue performance of a SiC whisker reinforced aluminium MMC. The results show fatigue data from 4 laboratories at room temperature and 200°C from tests on flat specimens with a rectangular cross-section. Maximum stress levels of 500 MPa and 425 MPa were chosen for the room temperature and elevated temperature tests respectively. Additional tests have been carried out at other stress levels to give a more complete S-N curve. Tests were carried out at a frequency of 10Hz and an R ratio of 0.1. All the specimens were prepared and polished to the same finish by one of the participating laboratories and for each condition and laboratory 3 repeat tests were performed.

Table 4 gives the range of values measured and the standard deviation associated with the respective set of room temperature and elevated temperature measurements.

Test Conditions, No. of cycles to failure				
	Room Temp, 500 MPa		At 200°C, 430 MPa	
	Mean	Range	Mean	Range
Lab A	115	88 - 156k	24	19 - 33k
Lab B	98	64 - 124k	35	22 - 47k
Lab C	181 *	180 - 10 ⁷ k	35	25 - 41k
Lab D	197	53 - 280k	32	24 - 41k
Mean	148 ± 48k		32 ± 5k	

Table 4: Fatigue strength data from the VAMAS exercise on a SiCw/Al MMC. [b].

The scatter in the room temperature fatigue strength data is significantly higher than that at 200°C but it is not immediately clear why this is the case. Based solely on the practical issues of carrying out tests at 200°C, it might be expected that the reverse be true.

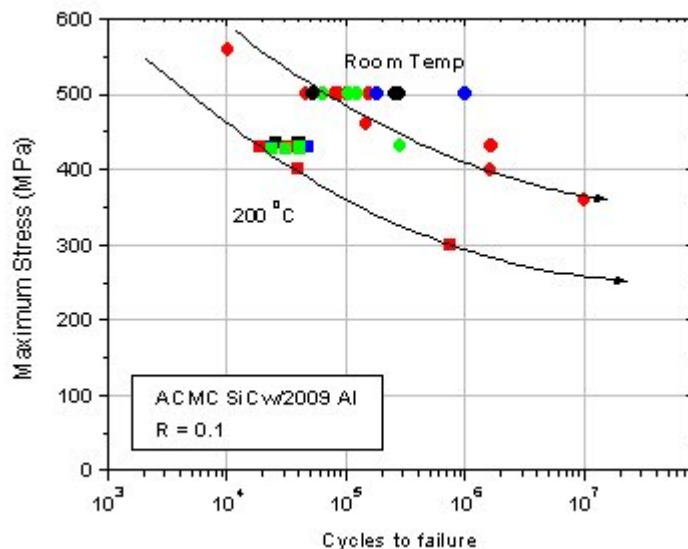


Figure 13: VAMAS fatigue results at room temperature and 200°C on the ACMC SiCw reinforced MMC.

Examination of the respective specimens however showed that a greater percentage of those tested at 200°C failed in the gauge length. The majority of the room temperature specimens failed outside the gauge length, at the transition from gauge length to the grip area, with failure originating from a corner of the specimen. All four organisations involved in the exercise used a small furnace to heat the gauge length with the ends of the specimen held in cold grips. At the stress levels encountered during the fatigue cycle the effective strength of the central part of the hot specimen is considerably lower than the cooler ends and as such will be the preferred site for failure.

Summary

The fatigue properties of a range of MMCs and test conditions have been presented. Some general observations can be made:

- For aluminium-based MMCs the initial heat treatment has an important effect on the fatigue performance - but only up to a point. For the materials examined in this study the T4 heat treatment condition gave higher fatigue strengths than the T1 condition up to ~200°C, above which there was little difference as the MMCs overaged. The influence of particulate size and distribution is also important. The 'xe' composition, which had a uniform distribution of fine particulate was superior to the 'xf' composition with the same volume fraction and same initial heat treatment. However, at high temperatures the presence of the particulate reinforcement has little effect and the fatigue behaviour is dominated by the fatigue strength of the matrix alloy.
- Generally there is a reasonable link between the tensile strength and fatigue limit. As the test temperature increases the S-N curve becomes very flat.
- Care should be taken in comparing data from the axial and rotating bend test configurations because the rotating bend test does not produce a uniform stress in the specimen cross-section and is more susceptible to surface effects.
- Detailed examination of the fatigue initiation sites and fracture surfaces was not carried out in this work, but the results seem to confirm other studies of particle-reinforced MMCs, which have shown that fatigue crack initiation and premature failure usually originates at the surface and may be triggered by the presence of large angular particles.
- Surface finish is an important parameter in fatigue testing and results carried out in this work were in reasonable agreement with more detailed work on other MMCs. It is recommended that fatigue tests on MMC should be carried out with a surface finish better than ~1.5 μm .
- The choice of particular specimen type is often determined by the nature of the product form. In practical terms round specimens are preferred to flat specimens because of the relative ease of polishing. But for round specimens, care should be taken with the machining of the threaded ends as these are often the

source of premature failure.

Some of the above points and other practical issues raised in this work are covered in the "*Good Practice Guide for Isothermal Fatigue Testing of Particulate MMCs*" [12], which has also been developed as part of this project.

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