Metal Matrix Composites: In the driving seat

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ABSTRACT: Over the past thirty years Metal Matrix Composites (MMCs) have emerged as an important class of material within the engineering industry. At present, MMCs offer attractive performance or weight-saving alternatives for a wide range of applications within the sport industry, from Formula 1 racing components to golf club shafts, as they provide beneficial characteristics over existing materials (increased stiffness, strength, fatigue strength, wear resistance, density reduction, creep resistance and thermal expansion control). As with all technological advancements MMCs are expected to enter at the forefront of sporting industries, but once established and production routes become more economic, the applications for MMCs within the sporting world are numerous. This paper briefly reviews the advantages of MMCs, and presents a study of the effects of additional treatments (heat and surface) which produce beneficial characteristics in monolithic and alloy materials, but whose effects become more complex when applied to composites.

INTRODUCTION

The drive to make cars lighter, faster and stronger in the competitive environment of the motor sport industry has resulted in the development of innovative designs and exotic materials in the production of a racing engine. At present Metal Matrix Composites (MMC) are attractive alternatives for aerospace and automotive applications because of their high stiffness-to-weight characteristics. The term MMC encompasses a wide range of scales and microstructures. MMCs combine a metallic base with non-metallic reinforcement (normally a ceramic). This gives beneficial gains in specific strength and stiffness of the material. Particulate-reinforced systems have found many applications owing to their isotropic properties (making engineering design no more complex than with corresponding unreinforced alloys) and their relatively inexpensive production compared to fibre- and whisker-reinforced
materials. An improvement in elastic modulus can allow for the design of lighter and smaller components (varying from engine running gear to chassis members). In addition to engine components, MMCs have found sporting applications ranging from cycle frames to golf club shafts. These materials can be used with conventional secondary processing equipment and technologies (forging, extruding, machining and surface techniques). In some cases, small modifications are required: for example, diamond tools are the most appropriate solution for machining to achieve high productivity with acceptable tool wear.

The prime reason for using MMCs in structural applications is their improved specific strength and specific stiffness relative to unreinforced alloys. Most structural metals (e.g., steel, aluminium, titanium, magnesium) have strength/density ratios of 26–27 MN m kg\(^{-1}\). Reinforcing aluminium with 25% of particulate silicon carbide increases this to nearly 40 MN m kg\(^{-1}\); reinforcing steel with 25% titanium diboride gives an increase to around 35 MN m kg\(^{-1}\). Increases in the specific properties such as these can be exploited through weight savings and/or improved fatigue resistance.

Particulate-reinforced aluminium MMCs have significant fatigue benefits compared to aluminium alloys, particularly in terms of the stress-controlled fatigue life (Bonnen et al. 1991; Hall et al. 1994). For fine particulate-reinforced systems an increased resistance to crack initiation and growth produces improved fatigue resistance. However, advantages in terms of “safe life” design must be traded against potential reductions in fracture toughness.

Obtaining the best strength for an MMC generally requires heat treatment as for the parent alloy, although the hardening curves are likely to be significantly different: hardening generally occurs much faster in the reinforced materials, owing to the higher dislocation densities associated with the presence of the reinforcing particles (Dutta & Bourell 1989; Fitzpatrick et al. 2002). The presence of the reinforcement gives a strengthening effect as well as providing a stiffness increase, so optimization of heat treatment is less critical. In particular, it may be possible to use less aggressive quench rates from solution heat treatment temperatures; this leads to a reduction in strength, but also reduces the levels of macroscopic residual stress that can lead to distortion during subsequent machining.

Many metal components are given a surface finishing treatment, such as peening, prior to use. Peening produces a compressive residual surface stress which can enhance fatigue life. Such a treatment may not be appropriate for composite materials, and an assessment of this was carried out to inform future designs using these materials.

**MATERIAL**

The material used for this study was produced by Aerospace Metal Composites, Farnborough, UK, by a mechanical alloying, powder metallurgy route. They were based on a 2124 Al alloy matrix, reinforced with particulate silicon carbide having a mean particle size of around 3 \(\mu\)m.
RESULTS: EFFECT OF HEAT TREATMENT

Figure 1 shows the effect of quench rate on the strength obtained for an MMC reinforced with 25 wt% of SiC.

From figure 1, it can be seen that a gentler quench results in lower strengths. As the composite matrix is age-hardening, it is likely that this is caused by the formation of precipitates during the quench process. Composite matrices are known to age-harden faster than unreinforced alloy, so there is little evidence of hardening beyond the naturally-aged condition with a slower cool. The as-extruded and furnace-cooled conditions show the lowest strengths.

Fatigue life determination was carried out using a rotating bend fatigue test. Samples were cyclically-loaded to failure at different peak stresses, to generate stress-life (S-N) data for the materials. All tests were conducted using tension-compression cycling on un-notched specimens.

The strength changes seen in figure 1 are reflected in the final fatigue lives. As the yield strength falls, so does the fatigue life. Summary data for this is shown in figure 2, which shows the fatigue life obtained at stress amplitude of 346 MPa.

Further fatigue data for different heat treatments, but with differing levels of reinforcement content are shown in figure 3. The figure shows fatigue life data for materials with 25% and 35% SiC in either the T4 or T1 conditions (T4 = as-quenched and naturally-aged at room temperature; T1 = ‘as-processed’, which is generally a
very soft ‘overaged’ condition), with results from peak-aged unreinforced Al2618 for comparison. It is clear that changing the matrix strength of the composite has a dramatic effect on the fatigue life. For both composites, the fatigue life is reduced for the T1 condition relative to the T4 condition. Heat treating the 25% SiC-reinforced composite from T4 to T1 reduces the yield strength from ~480 MPa to ~300 MPa. It is clearly this drop in strength which is responsible for the reduction in the fatigue life.

Fig. 2: Variation of fatigue life (at a stress amplitude of 346 MPa) as a function of the 0.2% proof stress of the material (the low fatigue lives are obtained from the low-strength T1 condition composites, as-extruded or furnace cooled in figure 1).

Fig. 3: Fatigue lives for MMCs reinforced with 25 or 35% SiC, in either the T1 or T4 condition, compared with peak-aged Al2618 alloy.
The poorer fatigue strength of the material in the T1 condition highlights one of the dilemmas that faces designers in using MMCs: the T1 condition offers low levels of macroscopic residual stress and improved toughness; but its lower strength, although not a problem per se, does have the effect of lowering the fatigue resistance.

An alternative to using a full T1 condition to alleviate residual stress effects is therefore to use a quench medium other than cold water to reduce the quench severity. Quenching into hot water or into a polymer glycol solution reduces the cooling rate during the quench, as was shown in figure 1.

Careful thought needs to be given, when selecting MMCs, into the heat treatment route needed to give acceptable strength. The heat treatment is likely to be quite different from that applied to an existing material, even if based on 2xxx-series aluminium.

RESULTS: SURFACE TREATMENTS

Many treatments exist to try and improve the strength of materials or components, and may be applied before or after final machining. An example of such a process is shot peening (SP). SP involves bombarding the surface with small spherical media (shot), which should be as hard as or harder than the parts being processed. The surface modifications caused by SP include: (a) roughening of the surface; (b) increased near-surface dislocation density from work hardening; (c) development of a residual compressively-stressed zone. In terms of fatigue life, the surface roughening can accelerate the initiation and propagation of cracks, work hardening will retard the initiation of cracks by increasing the resistance to plastic deformation, and the compressive residual stress zone will reduce the driving force for crack initiation and propagation. The performance of SP therefore will depend on the balance between its beneficial and detrimental effects (Hertzberg 1983). SP has been seen to be highly advantageous in monolithic materials and alloys (Taylor & Clancy 1991). This is especially so in high-strength materials which can store large compressive residual stresses, producing beneficial fatigue characteristics.

This process is often used to enhance fatigue resistance of components, but its effects are not easily predictable for two-phase materials, due to the pre-existing complex stress fields (thermal and mechanical) in such materials induced by manufacturing processes (Baragetti & Guagliano 1998). Little is understood about the effects, if any, of SP on a metal matrix composite, regarding actual fatigue improvements using a Wohler (S-N) curve (Natkaniee-Kocanda et al. 1996; Jesus Filho et al. 2001).

Plate samples of the Al MMC reinforced with 25% SiC were prepared with a cold-water quench and a polymer glycol quench. Bars were machined from the plates for fatigue testing in bending. A number of the bars were shot peened by Metal Improvement Company, in a two-stage peening process.

Figure 4 shows the fatigue lives obtained from the two differently-treated materials, in the peened and un-peened conditions.
Fig 4: Bending fatigue of an Al/SiC MMC subjected to two different quench rates, in peened and unpeened conditions. Results at $1.6 \times 10^6$ and $2 \times 10^6$ cycles are from samples that did not fail and are considered to be ‘run-out’.

As shown in figure 1, polymer glycol quenching produces a material with a lower strength than the faster quenching rate produced using cold water, resulting in a lower fatigue life (figure 2). This is reflected in the results for the unpeened samples in figure 4, where the PGQ samples show a lower fatigue limit than the CWQ.

Shot peening of the CWQ material does not greatly influence the fatigue life. This may be because of the high strength already present in this material, which limits the amount of hardening available to deformation processes such as peening. The PGQ material shows a better response, with a clear increase in the fatigue limit for the peened material.

SP increases the fatigue life through the compressive stress layer produced by plastic deformation. This compressive layer prevents cracks from initiating and propagating from the surface, thus increasing the fatigue life. However, there can be detrimental side effects to SP (such as increasing surface roughness and matrix cracking) which reduce its effectiveness, resulting in no or little change to the fatigue life. These detrimental effects are likely to be less prevalent in the softer material produced by the polymer glycol quench, as there is more scope for deformation and hardening before cracking of the matrix occurs.

Overall, the results show that surface treatment of MMCs needs to be approached with caution. The high strength of the materials studied means that there is not always scope for additional deformation hardening by methods such as shot peening. If near-surface compressive stresses are needed for fatigue performance, then the
material must be prepared in an initial lower-strength condition, by using a gentler quench medium.

CONCLUSIONS

1. Al alloy-based MMCs offer improved stress-controlled fatigue resistance relative to unreinforced Al-alloys. This improvement can be attributed both to the higher elastic moduli of the composites, plus benefits from the thermal misfit stresses which exist between the two phases of the composite.

2. The cooling rate during quenching of the composite can be altered to reduce the levels of quench stress in the materials. However, lowering the quench rate gives a lower material strength, which in turn gives slightly lower fatigue endurance limits.

3. Shot peening is more effective at improving fatigue resistance in softer materials. For high-strength MMCs, little improvement in fatigue resistance is seen following shot peening.

4. MMCs offer attractive weight saving potential for automotive applications, with the possibility of altering the available strength through careful heat treatment and quenching. Use of surface treatments such as shot peening should be used with care, as higher-strength materials may not benefit from a peening treatment.

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