INFLUENCE OF PARTICLE SIZE AND VOLUME FRACTION ON FRACTURE AND FATIGUE OF Al 6061/SiC METAL MATRIX COMPOSITE

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The influence of particle size and volume fraction on fracture toughness and fatigue crack growth of a metal matrix composite Al 6061, heat treated at T6, reinforced with SiC particles, were studied. Three particle sizes, respectively F600, F800 and F1200 were used with two volume fractions, 10% and 20%. Results show that fracture toughness is reduced in the presence of the reinforcement phase but only a slight influence is observed on particle size dimension and volume fraction. Results are analyzed with predicted failure according to theoretical models. Fatigue crack growth rates are considerably increased in the presence of reinforced phases compared with matrix properties.

INTRODUCTION

Recently there has been a considerable scientific and industrial interest in high strength, lightweight metal matrix composites (MMCs). Light metal alloys, specially aluminum alloys, offer low density and age hardenability allied to a wide variety of possible alloys and high processing flexibility allowing to be reinforced to improve elastic modulus and strength without changing its density.

Continuos fibers whiskers and ceramic particulate are the most used reinforcements. Particulate reinforced light metal matrix composites, with their potential as low cost and easy manufacturing material become very attractive. Two generic methods for composite manufacture are used, either involving molten metal or powder metallurgy (PM). PM has several attractive features, because it allows a wide choice of alloys to be used as matrix and ceramics as reinforcement.

In the present paper, the mechanical behavior of a SiC particulate reinforced aluminum-magnesium alloy based metal matrix composite, Al 6061/ SiC_p, aged to a T6 condition, with three different particulate sizes and two different volume fractions of reinforcement, are studied. Material investigation has

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been made on this system because it shows a strong interfacial bonding between the matrix and the reinforcement phases since there is no formation of fragile reaction phases (1-2), and, therefore, no strain rupture. Completely solid state consolidation prevents the formation of aluminum carbide, Al_4C_3.

Elastic modulus, **E**, is the one mechanical property that is always improved by the addition of reinforcement. Comparing with the unreinforced materials, a 50% increase of Young's modulus can be achieved with 20%(V) SiC_p/Al MMCs. Up to a 60% increase in yield and ultimate tensile strengths have been reported on SiC particulate aluminum alloys MMCs, depending on the volume fraction of reinforcement, type of alloy, and matrix alloy heat treatment, but the increasing of strength is obtained with the reduction in ductility. The tensile elongation decreases rapidly with the addition of the reinforcement particulate, specially if the particulate is inhomogeneous distributed. Failure associated with particle clusters can be attributed to the higher stress triaxiality generated in these regions.

The lack of systematic and comparable data of fracture toughness and fatigue of MMCs restrains its application in the aerospacial industries, because the damage tolerance is a very important design parameter. The principal objectives of the current investigation were to evaluate the effects of reinforcement particulate size and volume fraction on fracture toughness and fatigue crack propagation. The mathematical models, proposed by several authors, were analyzed and the principal factors, which influence toughness and fatigue, were identified.

MATERIALS AND SPECIMENS

The matrix phase of the powder metallurgy matrix alloy, used in this work, was an aluminum-magnesium alloy, Al 6061, aged to T6 condition. The reinforcing phase was a silicon carbide particulate, SiC. The MMC was manufactured by powder metallurgy. The matrix alloy powder was blended with particles of the reinforcement to achieve a homogeneous mixture. Cold isostatic pressing (250 MPa), sintering (630° C in argon, for 1 hour) and extrusion (450 MPa, at 450° C, for 1 hour) enabled the required consolidation of the MMC. 98% of density was achieved (4) for the 20%(V) SiC_p/Al system, and near 100% of density was achieved for the 10%(V) SiC_p/Al MMC.

10%(V) SiC_p/Al and 20%(V) SiC_p/Al cylindrical extrudates were made. The 10%(V) SiC_p extrudates had three different particle sizes, F600, F800 and F1200, corresponding to a median particulate size of 13 μm, 10 μm, and 4.6 μm, respectively. The 20%(V) SiC_p extrudates had only the particle size of F600. The matrix particulate had a median size of 26,1 μm.

For the critical stress intensity factor K_{Ic} estimation, the fracture toughness tests were conducted on three point bend specimens, with the net thickness, B = 7.5 mm, following the standard procedure, ASTM E399-93 "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials". The fatigue tests were performed on compact tension specimens with the net thickness, B = 5 mm, in accordance with the standard procedure, ASTM E647-93a "Test Method for Measurement of Fatigue Crack Growth Rates".

The specimens were manufactured from the as-extruded material, by machining (3PB specimens) and by electric discharge machining (3PB and CT specimens). The material should exhibit isotropic properties, but, to prevent some anisotropy got on the extrusion phase, the specimen notches were machined in a direction parallel to the nominal direction of pressing, corresponding to the C-L orientation, prescribed on ASTM E399. After machining, the specimens were subjected to a heat treatment consisting of solutionising at 530° C for 2 h, followed by a cold water quench and artificial age at 175° C for 8 h, to provide the T6 condition. The MMCs properties are given in Table 1.

RESULTS AND DISCUSSION

Fracture Toughness

A fatigue precracking was started from the notch, keeping K_{max} below 60% of the estimated K_{Ic}. The tests were performed at an increasing load rate of 1 $MPa\sqrt{m}$. The crack length was monitored by the COD gage, and followed using automatic data acquisition.

On the fractured specimen, the crack length was measured at three positions: at the center of the crack front, and midway between the center and the end of the crack front each side. The average of these three measurements was used. The test was valid only if each these three measurements did not exceed 10% of the average and if the greatest angle between the crack surface and the plane of symmetry of the notch did not exceed 10°. The tests were invalid, as well, when the ratio P_{max}/P_Q exceeded 10%. P_Q was the intersection of the load-displacement curve with a line which slope is 95% of the slope of the tangent to the initial linear part of the curve. All these conditions restricted the valid tests in order to establish a valid K_{Ic}.

To evaluate the fracture toughness, 3PB tests on 10%(V) SiC_p/Al MMC specimens with three different particle sizes, F600, F800 and F1200, and 20%(V) SiC_p/Al MMC with particle size of F600, were made. As it has been noted in other work on the toughness of particulate reinforced MMC, the most frequent source of invalidity was the length of the fatigue precracking. Following the standard validity criteria, the length of the fatigue precracking has to be 50% of the width of the specimen, and it was very difficult to produce it without fragile fracture of the specimen. The evaluation of K_{Ic} was impossible with some of the valid tests, because it was not possible to satisfy the standard criteria of maintaining the load rate within the range 0.55-2.75 $MPa\sqrt{m}/s$. Instead, K_Q was evaluated.

Figure 1 illustrates the obtained results where a slight effect of particulate size dimension and volume fraction on fracture toughness is shown. Comparatively to the unreinforced Al 6061 fracture toughness, reduction of K_{Ic} is observed.

The experimental results of this investigation can be related with theoretical approaches. Hahn and Rosenfield (5) assumed that crack extension occurs when the extent of the heavily deformed region ahead of the crack tip is comparable with the width of the unbroken ligaments separating cracked particles. They related the critical stress intensity factor, K_{Ic}, to f_p the volume fraction of reinforcement by:

$$K_{Ic} = \left[2\sigma_y E(\pi/6)^{1/3} d\right]^{1/2} f_p^{-1/6} \tag{1}$$

where σ_y is the yield stress and d the particle diameter of the particulate. A problem with this model is that it predicts an increase in toughness with increasing strength; which is not always valid.

Thomason (6-7) proposed that fracture was controlled by microvoid nucleation. This model gives the expression

$$K_{Ic} = 2.58\left(\rho\sigma_y E\varepsilon_c\right)^{1/2} \tag{2}$$

where r is the crack tip radius (Thomason proposes ~50 mm) and ε_c the microvoid nucleation strain. This equation relates a decreasing of ductility with the decreasing of toughness. However, this model needs to be further developed, because it does not relate K_{Ic} with the particulate size and distribution, and stress state before fracture. There are no sufficient data available for this to be done at present.

Table 1 compares the fracture toughness predictions of equations (1) and (2) with experimental results. It shows a much better agreement of experimental results with Thomason model than with the Hanh-Rosenfield model. This one overestimates the fracture toughness of the tested MMCs. Regarding the experimental data, the fracture toughness does not show a strong dependence on reinforcement particulate size and volume fraction, which is contrary with the predictions of both theoretic approaches. Similar conclusions have been made by Arsenault (8), who studied the effect of particulate size on SiC/Al MMCs toughness, and Mortensen (9), when he studied the influence of the volume fraction, on his work about the fracture toughness of particle reinforced aluminum alloys. Notice that clusters of particulate reinforcement have been found on the MMCs with SiC particulate size F600 (3). This inhomogeneity in particulate distribution influenced the MMCs behavior, decreasing its fracture toughness to unexpected values.

Fatigue Behaviour

Three specimens of each kind of MMC were tested at a constant ΔP and at a constant stress ratio, $R = 0.1$. In order to evaluate the crack growth rate, da/dN, the crack length was monitored using the compliance method above described. The records were made so that the da/dN values were equally distributed relatively to ΔK. Whenever the crack path exceeded $\pm 5°$ the ideal path growth, the test was invalid.

The fatigue tests were performed on 10%(V) SiC_p/AL MMC specimens with SiC particulate size of F600, F800 and F1200. There were no difficulties to meet the ASTM E647 validity criteria with a relatively few tests. Only the tests with F600 MMCs failed the standard validity criteria. All these specimens fractured in a perpendicular path to the initial direction of the notch.

The constants C =1.6E-16 and 1.1E-18 and n =11.6 and 14.3 (respectively for F800 and F1200) of Paris law were evaluated. The plots are shown on Figure 2. The obtained values of ***n*** are significantly lower than that of the unreinforced alloy, and it is apparent a slight effect of the particulate size on crack growth rate. Smaller particulate reinforcement MMCs seems to show better fatigue behavior.

The anomalous behavior of F600 MMCs is probably caused by the inhomogeneity of reinforcement particulate distribution (3). The clusters of particles formed a barrier on the crack propagation path resulting an excessive curvature in the initial fatigue crack which invalidated the test.

TABLE 1 - Mechanical properties of Al6061/SiC$_p$/T6 MMCs

Material	Density	E GNm^{-2}	$\sigma_{0,2}$ MN m^{-}	σ_{max} MN m^{-2}	ε_f (%)	K_{Ic}exp. MPa $\sqrt{m}$	$K_{Ic}^{(*)}$ MPa $\sqrt{m}$	$K_{Ic}^{(**)}$ MPa$\sqrt{m}$
Al 6061 SiC/10 F600	2.75	92	351-361	375-391	2-5	10.6 (>14)	36	15
Al 6061 SiC/10 F800	2.75	78-87	361-370	389-401	2-6	13.8	31.6	18.6
Al 6061 SiC/10 F1200	2.71	88	350-370	405-406	2-4	12.9	21.6	17.4
Al 6061 SiC/20 F600	2.69	102-109	369-376	384-392	0.3-0.4	12.3	33.75	10.8

(*) -Hahn and Rosenfield (5) model
(**) -Thomason (6-7) model

CONCLUSIONS

From the data generated in this research we arrived at these general conclusions.

- The addition of reinforcement, in the aluminum alloy matrices, increases significantly the elastic modulus, and the yield and the ultimate tensile strengths.

- The fracture toughness decreases about 50% with the addition of the reinforcing particulate. The reinforcement particulate size and volume fraction slightly affect the fracture behavior of MMCs.

- The presence of the reinforcement phase produces an evident decreasing of damage tolerance of the matrix alloy. However, the reinforcement particulate size slightly affects the crack propagation rate.

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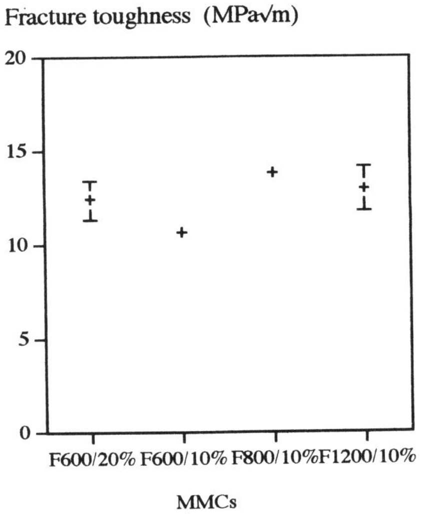

Figure 1 Fracture toughness of MMCs

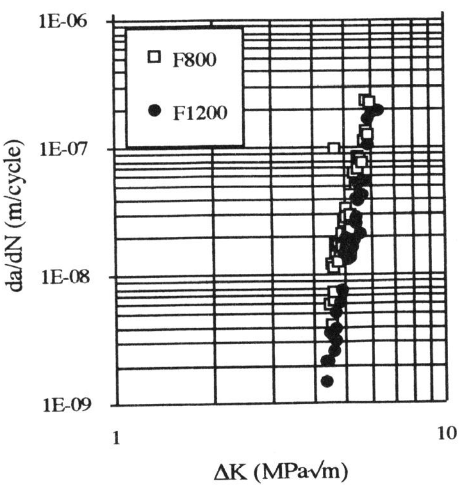

Figure 2 Crack growth rates of MMCs