High Strain Cyclic Fatigue and Fracture Behavior of a SiC Reinforced Cast Aluminum Alloy Composite

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The high strain cyclic fatigue characteristics of a cast aluminum alloy A356 discontinuously reinforced with 20 vol% silicon carbide particulates strained to failure over a range of strain amplitudes giving lives of less than 10^4 cycles to failure were studied. The specimens were cycled using tension-compression loading under total strain control. The as-cast material displayed cyclic hardening and eventual softening to failure at the higher cyclic strain amplitudes, and progressive cyclic softening at low strain amplitudes. The observed cyclic hardening and softening behavior are a mechanical effect and attributed to concurrent and competing effects of an increase in dislocation-dislocation interaction, dislocation multiplication and dislocation-particle (SiC) interactions. The cyclic fracture behavior of the alloy is discussed in light of composite microstructural effects, plastic strain amplitude and concomitant response stress.

(Received February 25, 1991)

Keywords: metal-matrix composite, microstructural effects, stress response fatigue life, fracture

I. Introduction

In recent years, the critical need for structural materials to be cost effective and also provide an optimum level of performance coupled with an increased emphasis on efficiency and reliability over a spectrum of temperatures has engendered considerable scientific and technological interest in the development and use of metal-matrix composites [MMC's]. When high specific strength and stiffness above that for a corresponding monolithic alloy are required, especially at elevated temperatures, the use of aligned continuous fibers was chosen. However, for more general applications metallic matrices reinforced with a discontinuous phase in the form of whiskers, chopped fibers, platelets or particulates are preferred⁽¹⁾⁽²⁾. While the continuous fiber reinforced metallic matrices offer highly directional properties such as high specific stiffness in the reinforcement direction, the discontinuously reinforced metal-matrix composites based on particulate reinforcement are preferred since they offer a number of advantages. In particular, the particulate reinforced MMC's are attractive and preferred since they exhibit near isotropic properties compared to the continuously reinforced counterparts and with substantial improvements in strength and stiffness relative to those available for unreinforced alloys⁽³⁾⁻⁽⁶⁾. Furthermore, they are easier to produce using standard metallurgical processing such as powder metallurgy, direct casting, rolling, forging and extrusion, and can be shaped, machined and drilled using conventional metal fabrication facilities⁽⁷⁾ and made available for a spectrum of structural applications. While the

whisker-reinforced and particulate reinforced MMC in general exhibit higher strength and stiffness than the matrix alloy they frequently suffer from low tensile ductility and inadequate fracture toughness compared to that of the constituent matrix material⁽⁸⁾⁻⁽¹²⁾.

Despite extensive documentation of the recognized and established advantages of discontinuously reinforced metal-matrix composites for use in the aerospace, space-related and defense industries, and comprehensive studies into an understanding of the role of nature and volume fraction of reinforcement on macroscopic mechanical properties⁽¹³⁾⁻⁽²²⁾, there have been few studies to systematically characterize the effects of matrix microstructure on the low cycle fatigue and cyclic fracture behavior of these newer generation structural materials. Information on cyclic fatigue properties is both essential and critical for the selection and use of the material in several high performance engineering applications.

It is the objective of this study to investigate the cyclic stress response characteristics and fracture behavior of silicon carbide particulate (SiC_p) reinforced cast aluminum alloy based metal-matrix composite. The stress response characteristics were evaluated over a spectrum of strain amplitudes with a view to gaining information on cyclic deformation characteristics and relating mechanistically the role of composite microstructural effects in governing cyclic fatigue and cyclic fracture. An examination of the cyclic fracture behavior of the metal-ceramic composite would provide an insight into the flaw tolerance capability of this material. The cyclic stress response behavior is discussed in terms of concurrent and mutually competitive factors involving plastic strain amplitude, response stress, composite microstructural effects and macroscopic aspects of fracture.

II. Material and Experimental Procedure

The metal matrix composite used in this investigation

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Table 1 Chemical composition of the matrix (A356 aluminium alloy).

Element	Al	Si	Cu	Mg	Mn	Fe	Zn
Amount (mass%)	Bal.	7.00	0.20	0.35	0.10	0.20	0.10

was a cast aluminum alloy [A356] reinforced with 20 percent by volume of silicon carbide (SiC) particulates. The chemical composition of the matrix alloy is shown in Table 1. The material was produced and provided by DURAL Aluminum Company, California. The material was received in the as-cast condition as an ingot.

All mechanical tests were conducted on a closed-loop servohydraulic test machine. Specimen blanks for the fatigue test specimens were cut from the as-received ingot, with the major stress axis parallel to the longitudinal and transverse directions of the ingot. The length-to-diameter ratio of the fatigue test specimen was chosen so as to ensure that the specimen would not buckle under large compressive strains. The blanks were machined using a diamond tip tool. The fatigue specimens were smooth and cylindrical in the gage section which measured 6.35 mm in diameter and 24 mm in length. The machined surfaces of the test specimens were ground with 600 grit silicon carbide paper and then mechanically polished to remove all circumferential scratches and machine marks. Fully reversed, total strain controlled, tension-compression ($R = -1$) low cycle fatigue tests were performed at a constant strain rate of 0.1% per second. The strain function exhibited a triangular waveform and the mean strain was zero. The tests were conducted in controlled laboratory air environment (relative humidity of 55%, temperature = 300 K). An axial 12.5 mm clip-on extensometer was attached to the gage section of the test specimen to control the total strain range. The stress-

strain hysteresis loops were recorded on an X-Y recorder. The stress range ($\Delta\sigma$) and plastic strain range ($\Delta\epsilon_p$) were determined from the height and width of the monitored hysteresis loop.

Optical microstructure was characterized using standard metallography and polishing techniques. Fracture surfaces of the deformed fatigue test specimens were examined in a scanning electron microscope so as to determine the predominant fracture mode and to characterize the fine scale topography of the fatigue fracture surface. Samples for SEM observation were obtained from the deformed fatigue specimens by sectioning normal to the fracture surface.

III. Results and Discussion

1. Microstructure

The optical micrographs of the as-cast ingot are shown in Figs. 1 and 2. The SiC particulates were dispersed randomly through the matrix of the A356 alloy. At frequent intervals an agglomeration of SiC particles was found. The number and size of agglomeration sites was found to be more in the longitudinal direction of the as-cast ingot than in the transverse direction. An agglomerated mass consisted of SiC particles of sizes varying from coarse to fine.

2. Cyclic stress response

The manner in which stress response varies with cycles and plastic strain amplitude is an important feature of the low cycle fatigue process. The cyclic stress response curves, which were determined by monitoring of stress response during total strain controlled fatigue, provide useful information pertaining to the mechanical stability of the material. Mechanical stability of the intrinsic

Fig. 1 Optical micrograph showing distribution of particles and general matrix microstructure of the A356-SiC_p composite in the longitudinal direction.

Fig. 2 Optical micrograph showing general matrix microstructure and shape and distribution of the A356-SiC_p composite in the transverse direction.

microstructural features during reverse plastic straining coupled with an ability of the material to distribute the plastic strain over the entire volume are the two key factors governing the cyclic response of a material⁽²³⁾⁽²⁴⁾.

The cyclic stress response curves or cumulative glide plots of stress amplitude during a low cycle fatigue test versus number of cycles, at a fixed plastic strain amplitude, illustrates the path by which the material arrives at its final flow stress level. The stress response curves for the A356-20%SiC_p composite are shown in Fig. 3. At high cyclic strain amplitudes {discussion based on total strain amplitude}, the material progressively hardened and eventually softened prior to failure. The hardening behavior dominated for most of fatigue life (75%) and the softening or drop in load carrying capability occurred following the onset of crack initiation and macroscopic crack growth. At lower cyclic strain amplitudes ($\Delta\epsilon_T/2=0.2\%$) and resultant enhanced fatigue life, the material exhibited progressive softening to failure. Variation of normalized stress with fatigue cycles at high and low cyclic strain amplitudes confirms

the observation of an increased hardening at higher cyclic strain amplitudes and softening, of random nature, at the lower cyclic strain amplitude (Fig. 4).

Since fatigue life is strongly dependent on cyclic strain amplitude, a comparison of the cyclic stress response behavior of the material at fixed high strain amplitude and low strain amplitude is provided in Fig. 5. This figure shows the variation of stress amplitude, during a low cycle fatigue (LCF) test, as a function of fraction of life in order to make comparison easier. The occurrence of hardening is more evident at the higher strain amplitudes for the cast aluminum alloy metal-matrix composite [A356-SiC_p]. The hardening behavior at higher strain amplitude was observed to occur for most of fatigue life and the decrease in load carrying capability occurred between 80–95% of life (Fig. 5). At the lower cyclic strain amplitude [$\Delta\epsilon_p/2=0.02\%$] a period of cyclic stability is followed by progressive softening to failure.

For the transverse specimens a higher cyclic strain amplitude resulted in an initial hardening followed by eventual softening to failure. Since fatigue life is strongly

Fig. 3 Cyclic stress response curves for the A356+20 vol% SiC_p composite.

Fig. 4 Variation of normalized stress [σ_N/σ_1] with cycles for the A356+20 vol% SiC_p composite.

Fig. 5 Comparison of the effect of strain amplitude on cyclic stress response of the A356+20 vol% SiC_p composite. N/N_f denotes percentage of life.

Fig. 6 Comparison of the effect of specimen orientation on cyclic stress response of the A356+20 vol% SiC_p composite.

dependent on cyclic strain amplitude and orientation of the test specimen, a comparison of the cyclic behavior in the two orientations (longitudinal and transverse), at near equivalent total strain amplitude, is provided in Fig. 6. This figure shows stress amplitude (MPa) plotted as a function of cycles. It is seen in this figure that the degree of cyclic hardening and resultant cyclic softening is less extensive for the transverse specimen than for the longitudinal specimen. The increased low cycle fatigue life and cyclic ductility of the transverse specimen is attributed to a fewer agglomeration sites of the hard and brittle SiC particles in the transverse direction of the as-cast ingot. The increased size and number of agglomeration sites of SiC_p in the longitudinal direction promotes dislocation-particle (SiC_p) interaction, thereby, contributing to the hardening observed. An increased interaction of mobile dislocations with the SiC_p, during cyclic deformation, is detrimental to cyclic strain resistance and low cycle fatigue life. The observed hardening at the higher cyclic strain amplitudes occurred by an increase in stress in both the tension and compression parts of the LCF test (Fig. 7). The cyclic stress response curve at the higher cyclic strain amplitude can be considered as comprising of three stages: (i) an initial few cycles of rapid hardening, followed by (ii) progressive hardening, and then prior to failure, (iii) rapid softening of the material

Fig. 7 Stress response curves showing the variation of tensile stress and compressive stress with cycles at a fixed plastic strain amplitude.

due possibly to the effects of multiple crack initiation and rapid macroscopic crack growth. Microscopically, the initiation of macroscopic cracks during low cycle fatigue has been found to occur much later in the fatigue life of many components when compared with their constituent matrices. It seems plausible that while the particle [SiC_p]-matrix interface is a preferred site for crack initiation in this composite, subsequent small crack growth to form a macroscopic crack is inhibited till a later stage in the fatigue life.

The micromechanisms which control variation of stress amplitude with fatigue cycling are dependent on both the microstructure and the strain range. In the as-cast condition (absence of heat treatment and resultant strengthening contributions), the possible micromechanisms controlling the initial hardening behavior during cyclic straining are:

- (i) a pre-existing high dislocation density in the matrix caused by the presence of SiC particles,
- (ii) dislocations ascribed to the large difference in thermal expansion coefficients between the matrix (aluminum alloy) and the reinforcing particles (SiC)⁽²⁵⁾⁽²⁶⁾. These dislocations are distributed at random throughout the matrix of the A356-SiC_p composite. Hardening during cyclic straining results from an increase in:
 - (a) dislocation density already present in the matrix by dislocation multiplication,
 - (b) dislocation-SiC particle interactions, and
 - (c) dislocation-dislocation interactions.

The interaction of mobile dislocations with the particles dominates during initial stage of cyclic deformation. When the local stress concentration caused by dislocation build-up at a particle [SiC_p] exceeds a critical value, crack initiation occurs through rupture of the hard and brittle particle. Also, with continued cyclic deformation numerous such particles crack on account of their intrinsic brittleness. With progressive cyclic straining the microcracks, initiated at neighbouring particles, rapidly link to form a macroscopic crack, resulting in drop in load carrying capability or softening of the material prior to failure.

3. Plastic strain-fatigue life response

Cyclic plastic strain is a measurable physical quantity that can be related to fatigue damage. Progressive fatigue damage due to cyclic plastic strain helps relate the fatigue life to plastic strain amplitude. The empirical relationship between plastic strain amplitude and number of cycles to failure, known as the Coffin-Manson relationship, was determined for the low cycle fatigue regime ($N_f < 10^4$ cycles) and predicts that⁽²⁷⁾⁽²⁸⁾

$$\frac{\Delta \epsilon_p}{2} = \epsilon'_f (2N_f)^C \quad (1)$$

where $\Delta \epsilon_p / 2$ is the plastic strain amplitude and $2N_f$ is the number of reversals to failure. The above relationship is plotted on bi-logarithmic co-ordinates on the basis of plastic strain amplitude and reversals to failure. The best straight line fit for the plastic strain-fatigue life curve is obtained by linear regression analysis. An extrapolation of the best fit is made to determine the plastic strain amplitude at $2N_f = 1$. This point in the plastic strain-fatigue life curve is the fatigue ductility coefficient and is related to the cyclic ductility of the material. The slope of the plastic strain-fatigue life curve gives the fatigue ductility exponent, C .

The effects of strain cycling on LCF life of the A356-SiC_p composite is shown in Fig. 8. This curve can be viewed as an indication of the resistance of the material's microstructure to crack initiation and failure. The plastic strain-fatigue life curve is linear and the Coffin-Manson relationship can be used to determine the fatigue behavior. The value of C , the fatigue ductility exponent,

Fig. 8 Variation of plastic strain amplitude with reversals to failure ($2N_f$).

obtained from the plastic strain-fatigue life curve is -1.07 for the longitudinal specimen and -0.60 for the transverse specimen. The fatigue ductility coefficient, ϵ'_f , is 3.02% for the longitudinal specimen and 5.0% for the transverse specimen. These values indicate the transverse specimen to have better cyclic ductility than the longitudinal counterparts, and a concomitant improvement in low cycle fatigue resistance.

IV. Fracture Behavior

Examination of the fracture surface features in the scanning electron microscope of the low cycle fatigue specimens were done at low magnification to identify the fatigue and final fracture (overload) regions, and at higher magnification in the fatigue region to identify

Fig. 9 Scanning electron micrograph of the fatigue fracture surface of the A356+20 vol% SiC_p sample deformed to failure at plastic strain amplitude of 0.05%. (a) cracking parallel to major axis, (b) SiC particles on fracture surface.

Fig. 10 Scanning electron micrograph of the fatigue fracture surface of the A356+20 vol% SiC_p composite sample deformed to failure at 0.02%, (a) agglomerated mass of SiC particulates, (b) cracking in the matrix.

regions of crack initiation and early crack growth. Fracture surfaces revealed near similar topographies at the different strain amplitudes.

At a total cyclic strain amplitude of 0.46% fracture on a macroscopic scale was normal, that is, about 90° to the stress axis. Macroscopic observations revealed the fracture to be brittle (low cyclic ductility) with pronounced cracking along the direction of the stress axis (Fig. 9a). High magnification observation of the intergranular and intersubgranular fracture regions revealed evidence of fine SiC particles (Fig. 9b).

Representative fractographs of the specimen deformed at total cyclic strain amplitude of 0.3% is shown in Fig. 10. The silicon carbide particulates (SiC_p) were found in clusters throughout the fracture surface (Fig. 10(a)).

Fig. 11 Scanning electron micrograph showing an agglomeration of silicon carbide particulates on fatigue fracture surface of the transverse test specimen.

High magnification observation revealed the presence of multiple cracks in the matrix region (Fig. 10(b)). Shallow dimples were found distributed in the matrix. Assuming the 'intrinsic strength' of each SiC particle is inversely proportional to square root of its characteristic dimension⁽²⁹⁾⁽³⁰⁾

$$\sigma_{\text{SiC}_p} = \{\pi E G_{\text{PM}} / 2(1 - \nu^2) d_p\}^{1/2}$$

where E is the Young's modulus, ν is the Poisson's ratio and G_{PM} is the effective fracture energy for propagation of the crack into the matrix. An increase in tensile stress that occurs during cyclic hardening promotes microcrack initiation to occur at the particles. With continued cyclic deformation the cracks propagate into the ductile matrix. Numerous such microscopic cracks eventually link to form a macroscopic crack causing a drop in load carrying capability of the specimen and culminating in fatigue failure. Furthermore, it is also possible that the mismatch that exists between the brittle ceramic particle [SiC_p] and the ductile A356 matrix favors concentration of stress at and near the reinforcement particle causing the matrix in the immediate vicinity to fail prematurely or the particle to separate from the matrix (Fig. 11).

V. Concluding Remarks

Based on a study of the low cycle fatigue response and cyclic fracture behavior of a silicon carbide particulate reinforced cast aluminum alloy composite, the following conclusions are made:

(1) The microstructure of the as-received material revealed an agglomeration of particles. The size and number of agglomerated sites was fewer in the transverse direction than in the longitudinal direction. An agglomeration consisted of particles of varying size and shape.

(2) Cyclic stress response of the ceramic particle reinforced aluminum alloy in the as-cast condition revealed initial hardening followed by cyclic softening at high cyclic strain amplitudes, and cyclic stability and softening to failure at lower cyclic strain amplitudes.

(3) The transverse specimens exhibited better cyclic ductility and low cycle fatigue resistance than the longitudinal counterparts. The improved cyclic strain resistance is attributed in part to fewer agglomeration sites of particles in the transverse direction.

(4) The general fracture behavior at all strain amplitudes revealed brittle failure with separation of the silicon carbide particles from the matrix. The existence of weak constraints at the ceramic particle-matrix interface coupled with stress concentration effects causes the particle to separate from the matrix and the microcracks to propagate into the matrix.

Acknowledgements

This research was supported by The University of Akron under Faculty Research Grant No. 1101 [2-07064]. Material used in this study was provided by DURAL Aluminum Company (California).

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