Damage Evolution and Dynamic Mechanical Properties in a SiC Fibre Reinforced Ti Alloy Composite

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Damage evolution in a SiC fibre reinforced Ti alloy composite (SCS-6/Ti-6Al-4V) has been assessed by modulus loss, change in internal friction (mechanical damping) and acoustic emission (AE). Damage was introduced into unidirectionally reinforced unnotched specimens by four point bending using constant cyclic amplitude loading. Dynamic Young's modulus and internal friction were measured by a flexural resonant method after a predetermined number of cycles, and AE signals were also monitored during the tests. Damage induced in the composites changed progressively primarily as a function of the applied maximum stress levels ($\sigma_{\max}$). Fibre fracture dominated at $\sigma_{\max}$ values greater than $0.5\sigma_B$ (where σ_B is the flexural strength of the composite). High amplitude AE signals associated with fibre fracture were observed, and internal friction measurements increased rapidly just before failure of the specimen. In contrast, matrix cracking dominated at $\sigma_{\max}$ values lower than $0.35\sigma_B$. As matrix cracks (bridged by intact fibres) grow in these composites, internal friction measurements increase. Small amplitude AE signals were observed to be associated with matrix crack growth. Also, fibre fracture occurred in the bridged zone at $\sigma_{\max}$ values between 0.35 and $0.5\sigma_B$. In all tests, the Young's modulus decreased by only 1% of its initial value until just before failure of the specimen. However, internal friction measurements increased rapidly prior to catastrophic failure of the specimen at all stress levels investigated in this study. This result shows that an increase in internal friction is related to damage accumulation in the composites, and suggests that measurement of changes in internal friction may be applicable to the assessment of damage in such composites.

Keywords: composite, MMC, damage, fatigue, Young's modulus, internal friction, mechanical damping,
acoustic emission, non-destructive inspection

I. Introduction

Metal matrix composites are considered to be favourable candidate materials for aerospace structures or engine components because of their high specific strength and high temperature strength. In particular, Ti alloys reinforced with continuous SiC fibre are some of the most promising composites which offer an excellent combination of moderate temperature strength, stiffness and toughness⁽¹⁾. For in service application of these composites, non-destructive inspection techniques are required for the determination of component quality after fabrication, and for the assessment of damage throughout service. Damage processes in composites involve various microfracture modes, such as fibre failures, debonding between fibre and matrix, fibre sliding and pull out, and matrix cracking⁽²⁾. Since these fracture modes interact with each other, it is difficult to assess damage progression and the amount of damage in such composites.

It is expected that damage may cause both modulus loss and an increase of internal friction (mechanical damping) of composites. This suggests that both modulus loss and internal friction may be applicable for damage assessment in composites. In addition, The acoustic emission (AE) technique is also one method for assessing damage in compos-

ites. Since AE signals contain information on source phenomena, the AE technique has potential for discriminating each microfracture event in composites by suitable AE wave analyses. However, most studies of modulus loss, internal friction and AE measurements during damage evolution in composites have been carried out on fibre reinforced polymers⁽³⁾⁽⁴⁾ and ceramic matrix composites⁽⁵⁾⁽⁶⁾, and there are relatively few studies to date which have been applied to Ti alloy based composites⁽⁷⁾⁽⁸⁾. In this present study, damage introduced by cyclic loading in a SiC fibre reinforced Ti alloy composite (SCS-6/Ti-6Al-4V) has been assessed by modulus loss, internal friction (mechanical damping) acoustic emission (AE).

II. Experimental Procedure

1. Material

The material used in this study was a Ti-6Al-4V alloy unidirectionally reinforced with continuous SCS-6 (SiC) fibres (of 140 μm in diameter) fabricated by a foil-fibre-foil consolidation technique, and available commercially. Specimens with dimensions of 75mm in length, 4mm in width, and 2mm in thickness were cut from 8-ply composites panels by electrical discharge machining. The fibre orientation to the

Table 1 Elastic moduli and the internal friction values obtained for the SCS-6/Ti-6Al-4V composite.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12}	ν_{21}	ν_{23}	Q_1^{-1} (10^{-4})	Q_2^{-1} (10^{-4})
194.5	140.7	79.1	52.9	0.23	0.17	0.33	2.25	5.07

Table 2 Number of cycles to failure as a function of applied stress and type of damage developed in the composites.

Maximum bending stress (MPa)	Ratio to bending strength	Cycles to failure	Dominant damage mode
1900	0.72	2,512	Fibre fracture
1400	0.53	15,267	Fibre fracture
1000	0.38	51,780	Mixture of fibre fracture and matrix cracking
950	0.36	100,538	Mixture of fibre fracture and matrix cracking
850	0.32	268,005	Matrix cracking

longitudinal direction was 0° . The fibre volume fraction in these composites was approximately 0.35. One side of the specimen surface was polished with diamond paste to reveal the cross section of fibres in the first ply, and which enables direct observation of damage in the composites. All specimens were tested in the as-fabricated condition, and no heat treatment was performed prior to testing.

2. Fatigue tests, dynamic mechanical property and AE measurements

Damage in the composite was introduced by four point bending through cyclic loading under a constant load range. Fatigue testing was conducted at room temperature in air using a servo-hydraulic testing machine at a frequency of 1Hz and a stress ratio (the ratio of the minimum to maximum stress applied over the fatigue cycle) of 0.1. The maximum stress ($\sigma_{\max}$) over the fatigue cycle was controlled in the range from 0.35 to 0.75 σ_B , where σ_B is the flexural strength measured in a static bending test and has been measured as 2630 MPa for the present composite system.

Young's modulus and internal friction were measured by a free-free beam method. Young's modulus was determined from a fundamental flexural resonant frequency, and internal friction was measured by both a resonance peak-width method and a free decay method. Table 1 shows elastic moduli and internal friction values of the composite in the as-received condition measured by this method. Young's modulus and internal friction were measured after a predetermined number of cycles, and the specimen surface was also observed optically to examine the development of damage in the composite periodically.

In all fatigue tests, AE sensors were attached to both ends of the specimen using silicone grease. The AE sensors used were M53 (Fuji Ceramics Co.), and their resonant frequency is approximately 300kHz. AE signals detected during tests were amplified by a pre-amplifier and analysed by an NF

9502 AE measurement system. The gain of the pre-amplifier was 40dB. The threshold level was 60dB with reference to $0.1\mu\text{V}$ at the output of the sensor. In this study, only AE events generated within the central loading span (constant bending moment region) were measured by using spatial filtering techniques.

III. Results

1. Damage development during fatigue tests

Table 2 summarises the applied maximum surface stress ($\sigma_{\max}$), the number of cycles to failure and the dominant type of damage in the composite. Damage in the composites changed progressively depending on the level of $\sigma_{\max}$ as shown in Fig. 1. Figure 1(a) shows an optical micrograph of the specimen near fracture and tested at a $\sigma_{\max}$ value of 0.72 σ_B . Fibre fractures dominate at this stress level, and debonding between fibre and matrix is also visible. This type of fibre fracture was observed at $\sigma_{\max}$ values greater than 0.5 σ_B . At $\sigma_{\max}$ values between 0.35 and 0.5 σ_B , matrix cracking is observed in addition to fibre fracture, as shown in Fig. 1(b). Matrix cracking dominates at stress levels, lower than 0.35 σ_B , as shown in Fig. 1(c), where matrix cracks are bridged by intact fibres. No fibre fracture is seen at this level of loading in these tests until just prior to catastrophic failure.

2. Dynamic mechanical property and AE measurements

Figure 2(a) shows changes in Young's modulus and internal friction during fatigue, and tested at a $\sigma_{\max}$ value of 0.5 σ_B . Young's modulus and internal friction values are normalised by their measured values for the undamaged condition. Fatigue failure occurred after approximately 15,000 cycles. The reduction of Young's modulus after 10,000 cycles (corresponding to 67% of the fatigue life of this specimen) is only 1%. Internal friction begins to increase from the

Fig. 1 Optical micrographs of specimen surface tested at $\sigma_{\max}$ of (a) 1900 MPa ($0.72\sigma_B$), (b) 950 MPa ($0.36\sigma_B$) and (c) 850 MPa ($0.32\sigma_B$).

first loading cycle, and continues to increase upto 100 cycles. Although the internal friction does not increase from 100 cycles to 5,000 cycles, the internal friction again increases suddenly between 5,000 cycles and 10,000 cycles. This suggests that damage evolves rapidly during this period. Figure 2(b) shows the relation between cumulative AE event, AE energy and the number of cycles. In this study, the AE energy was defined as the square of the event peak amplitude. AE events are generated during the first loading cycle and increase gradually with increasing number of cycles. Sudden increases of AE events are found just before final failure, and the AE energy associated with these events also increased rapidly. Figures 3(a) and (b) show the amplitude distributions during first 10 cycles and 5,000 to 15,000 cycles, respectively. Event amplitudes are classified into two groups. Amplitude of one group is distributed from 60 to 90 dB, and the other is over 100dB. In our previous investigations⁽⁸⁾, AE events with 60~90 dB were associated with debonding between fibre and matrix, and high amplitude events over 100 dB were confirmed to be correlated with fibre fracture.

Figure 4(a) shows the changes in Young's modulus and internal friction after cyclic loading, and tested at a $\sigma_{\max}$ level of $0.35\sigma_B$ where matrix cracking dominates. Fatigue failure occurred after approximately 270,000 cycles. Young's modulus decreased slightly after 250,000 cycles (corresponding to 93% of the fatigue life of this specimen), but the reduction is only 2%. In contrast, the internal friction value started to increase after 100,000 cycles, and increased to over three times its initial value after 93% of the fatigue life. Cumulative AE events and cumulative AE energy for

this loading condition are shown in Fig. 4(b). Cumulative AE counts start to increase after 250,000 cycles, and further increase rapidly just prior to final failure of the specimen. However, a rapid increase in cumulative AE energy before final failure was not observed at this stress level. Figures 5(a) and (b) show the amplitude distributions during first 10 cycles and 50,000 to 250,000 cycles, respectively. The range of AE event amplitudes during the first few loading cycles is 60~90 dB and only a few events of high amplitude are observed. In contrast, event amplitude during high loading cycles is relatively low, and few events of high amplitude were observed.

IV. Discussion

The damage developed changes progressively depending on the level of $\sigma_{\max}$ applied. Similar results have also been obtained in fatigue of SCS-6 SiC fibre reinforced Ti alloy composites in tension^{(9), (10)}. In such studies, fibre fracture was observed to dominate when the applied maximum stress in the fibre is higher than approximately 80% of the fibre strength. The fibre strength of fibres in a Ti-6Al-4V has been measured to be 3100 MPa⁽⁹⁾, and the applied maximum stress in the fibre can be calculated using a simple rule of mixtures. If this is applied to the bending test in this investigation, a maximum surface bending stress of over approximately 1200 MPa would be expected to cause this type of damage. This is consistent with the results obtained in this study as indicated in Table 2 in spite of the different type of loading. For this loading condition, AE events are generated

Fig. 2 (a) Relation between normalised Young's modulus, normalised internal friction and number of cycles and (b) relation between normalised cumulative event counts, cumulative AE energy and number of cycles tested at $\sigma_{\max}$ of $0.53 \sigma_B$.

Fig. 3 Amplitude distributions of AE events during (a) first 10 cycles and (b) 5,000 to 15,000 cycles tested at $\sigma_{\max}$ of $0.53 \sigma_B$.

during the first few loading cycles as shown in Fig. 2(b), and the amplitude of most AE events is distributed from 60 to 90 dB but that of some events exceed 100 dB as shown in Fig. 3(a). Therefore, fibre fracture occurs during the early stage of fatigue loading, and the stress concentration in the vicinity of the fractured fibre might be expected to cause further fracture of the adjacent fibres. Sudden increase of AE events are found just before final failure, and high amplitude events are associated with it. Cumulative AE energy began to increase after 1,000 cycles. This energy increase corresponds to the generation of high amplitude events (Fig. 3(b)), and indicates that fibre fracture begins to occur after this number of cycles. A rapid increase in internal friction is also observed between 5,000 and 10,000 cycles. Thus, this increase in internal friction is deduced to be correlated with damage development in the composite, and particularly with fibre fracture events. In contrast, the Young's modulus is almost constant until just

before specimen failure. Fracture surface observation shows that the length of fibre pull out is approximately 100 μm . The fibre debonding length is also the order of 100 μm . In conclusion, cumulative AE energy is sensitive to fibre fracture in the composite. The change in internal friction also gives an indication of such damage, but its increment is only 30% above that for the undamaged condition.

Matrix cracking dominates at $\sigma_{\max}$ values lower than $0.35 \sigma_B$. AE events are also generated during the first few loading cycles as shown in Fig. 4(b), but the range of AE event amplitudes is 60~90 dB and only a few events of high amplitude are observed as shown in Fig. 5(a). Therefore, fibre debonding is deduced to dominate during the early stages of loading. AE events start to increase abruptly after 50,000 cycles. However, their amplitude is relatively low (around 60~70dB) and few events with amplitude over 100 dB are observed (Fig. 5(b)). Optical microscopy observations show

Fig. 4 (a) Relation between normalised Young's modulus, normalised internal friction and number of cycles and (b) relation between normalised cumulative event counts, cumulative AE energy and number of cycles tested at $\sigma_{\max}$ of $0.32 \sigma_B$.

Fig. 5 Amplitude distributions of AE events during (a) first 10 cycles and (b) 50,000 to 250,000 cycles tested at $\sigma_{\max}$ of $0.32 \sigma_B$.

that matrix cracking starts after 100,000 cycles. Thus, AE events are generated by crack growth in the matrix. Optical microscopy observations indicate that the cracks in the matrix initiate from debonded regions between the fibre and the matrix. Internal friction begins to increase coincident with matrix crack growth, as shown in Fig. 4(a), and increases by up to more than three times compared with its initial value prior to catastrophic failure. Once a matrix crack starts to grow, the crack is bridged by intact fibres. If the stress level is high, fibre fracture may occur in the bridged zone. Thus, both fibre fracture and matrix cracking are generated at $\sigma_{\max}$ values between 0.35 and $0.5 \sigma_B$, as shown in Fig. 1(b). The reduction of Young's modulus after 210,000 cycles is only 2% for the specimen tested at a $\sigma_{\max}$ of $0.32 \sigma_B$. Young's modulus is considered to be sensitive to generalised cracking in the matrix (such as is seen for many CMCs). However, only 2 or 3 cracks are generated here in such composites.

This may be one reason that a marked modulus loss is not observed.

From the above discussion, damage evolution and its assessment in this composite system is summarised in Fig. 6. A marked reduction in modulus is not observed for any damage induced in this composite. Thus a measurement of modulus reduction cannot be applied as a sensitive non-destructive inspection tool. Cumulative AE energy or event amplitude is the most suitable tool for the detection of fibre fracture. Changes in internal friction may also be applied, but this is less sensitive to the detection of fibre fracture. Both cumulative AE event counts and changes in internal friction are suitable for the detection of matrix cracking in the composite. From the above considerations, the AE technique seems to be valuable in damage assessment of this composite. However, AE signals have to be monitored during the entire life of the structure, and it is rather difficult if

Fig. 6 Fatigue damage diagram of the SCS-6/Ti-6Al-4V for the bending fatigue test and the comparison of the damage assessment method. Symbols in the figure indicate the potential degree of applicability of the measurement as a non-destructive testing tool: ⊙; very good, ○; fairly good, Δ; fair, ×; poor.

components are operated under normal service conditions. In contrast, the internal friction measurement is suitable for periodical inspection of the component, since changes in internal friction may be assessed only by measuring the decay of elastic vibrations. This suggests that internal friction measurements may be appropriate for the damage assessment of SiC fibre reinforced Ti alloy composite components.

V. Conclusion

Damage evolution in a SCS-6/Ti-6Al-4V has been assessed by modulus loss, change in internal friction (mechanical damping) and acoustic emission (AE). Damage evolved in the composites changes progressively depending on the applied maximum stress levels ($\sigma_{\max}$). Fibre fracture dominates at $\sigma_{\max}$ values greater than $0.5\sigma_B$ (where σ_B is the flexural strength of the composite). High amplitude AE signals associated with fibre fracture were observed, and internal friction increased rapidly, just before failure of the specimen. In contrast, matrix cracking dominates at $\sigma_{\max}$ values lower than $0.35\sigma_B$. After matrix cracks (bridged by intact fibres) grow in such composites, internal friction measurements begin to increase, and to more than three times their initial value prior to catastrophic failure. Small amplitude AE signals were observed to be associated with crack growth. Damage developed at $\sigma_{\max}$ values between 0.35 and $0.5\sigma_B$ was a mixture of fibre fracture and matrix cracking. In all tests, Young's modulus decreased by only 1% of its initial value until just before failure of the specimen. However, internal friction measurements increase rapidly prior to catastrophic failure of the specimen at all stress lev-

els investigated in this study. This result shows that an increase in internal friction values is related to damage accumulation in these composites, and suggests that the measurement of changes in internal friction may be appropriate to the assessment of damage in such composites.

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