In situ microstructural observations on slip lines and microfracture processes have been coupled with mechanical deformation to investigate the acoustic emission of Ti–6Al–4V, a two-phase alloy. The material has been subjected to several different heat treatments to produce various microstructures and grain sizes. The dependencies of acoustic emission (AE) characteristics, such as the AE events amplitude, the rate of AE, location of the AE sources and the total events of AE in each deformation test, on work hardening, grain size, second phase content and morphology, and strain rate have been explored. The presence of the second phase, beta, existing in either an intergranular network or thin plates, was found to have little influence on the AE of this material. Furthermore, it was found that the dependencies of the AE characteristics on work hardening, grain size, second phase and strain rate could be explained in terms of the operation of Frank–Read dislocation sources.

1. Introduction

During the last two decades acoustic emission (AE) from composite materials has been utilized to detect initiation and the location of the source of damage, to monitor damage accumulation, to track damage progression, to determine damage severity, and to identify the major failure mechanisms and processes. The attractiveness of the AE technique results from these multiple applications and the fact that results can be obtained in real time. Each of the applications listed above has been extensively investigated on a variety of composite systems including metal–matrix [1–4], ceramic–matrix [5–7], and polymer–matrix [8–12] composites with varying success. Among these applications, the identification of specific failure mechanisms and processes has been the most challenging task in the application of the AE technique. The complexity in this area is due to the fact that many damage mechanisms (e.g. plastic deformation of matrices, matrix cracking, matrix twinning, interfacial debonding, interfacial friction, delamination, fibre breakage, etc.) cause AE and may occur simultaneously. This is further complicated by similar AE characteristics for some different damage processes and by the anisotropic properties of composites. Notwithstanding these difficulties, several attempts have recently been made to identify mechanisms of AE in composite materials [1, 11, 13, 14]. For example, using in-situ AE monitoring with simultaneous scanning electron microscope recording, Siegmann and Kander [13] have divided AE amplitude distribution of a polymer-based composite into three ranges corresponding to matrix damage, fibre–matrix debonding and fibre breakage. Working with replicates and a closed-circuit television system for in-situ monitoring of the damage evolution, Bakuckas et al. [1] attempted to relate AE to the failure mechanisms in titanium β21S–SiC composites and suggested that direct correlations between damage mechanisms (i.e. matrix plastic deformation, matrix cracking, fibre-matrix debonding, cracking of brittle reaction zone and fibre breakage) and AE events amplitude do exist in this composite system. Despite these efforts, the identification of the major failure mechanisms and processes through the AE technique is still in its early stage of development.

Obviously, one approach to establish the correspondence between AE events and composite failure mechanisms is to diagnose the composites by investigating the AE characteristics of matrices alone, comparing these with the AE response from model composites such as single-fibre composites, and finally addressing real composites. The first two phases are necessary for establishing the basic response characteristics for prediction of the acoustic response from the real composites. Hence, a program containing these three phases aimed at monitoring the damage progression in Ti-based continuous-fibre reinforced composites using AE technique has been developed. Such a three-phase program is necessary, especially for metal–matrix composites because AE during the deformation of metals alone could be quite complicated. Sources of AE during the deformation of metals include moving dislocations, twinning, grain boundary sliding, the fracture and decohesion of inclusions, intergranular microfracture, cleavage microfracture,
and microvoid coalescence [15]. Because of the complexity of matrix deformation alone, this study, as the first phase of the program, reports only the AE response of Ti-6Al-4V matrix (a two-phase alloy) with various processing conditions and microstructures at a fixed composition.

2. Experimental procedure

Ti-6Al-4V sheets with a thickness of 1.524 mm (0.06 inch) were supplied by RMI Titanium. The as-received sheets were in an annealed condition (i.e. hot rolled starting at 927 °C, annealed at 730 °C for 4 h and furnace-cooled). The sheets received were first cut, using an electro-discharge machine, into dog-bone shaped tensile specimens with a gauge length of 22 or 28 mm, and then subjected to heat treatment to examine the microstructure effect on the AE of this material. The heat treatment temperatures and cooling rates were selected in such a way that various grain sizes and second-phase morphologies could be obtained and evaluated. The heat treatment was conducted using a box-type furnace. The specimens, which were wrapped with tantalum foil and encapsulated in quartz tubes with back-filled argon, were subject to one of the following heat treatments: (a) annealed at 925 °C for 1.5 h and furnace-cooled to room temperature (with a cooling rate of ca. 8 °C min⁻¹); (b) 960 °C for 1.5 h and furnace-cooled; (c) 1010 °C for 1.5 h and furnace-cooled; and (d) 1100 °C for 1.0 h, cooled to 700 °C at 2 °C min⁻¹, and then furnace-cooled to room temperature. In order to avoid acoustic noise from any oxide layer on the surface of the dog-bone specimens, each specimen, after heat treatment, was ground with SiC abrasive paper to 320 grit and cleaned with acetone. Some specimens were further polished to 1 μm diamond paste and then electropolished in an electrolyte (6% perchloric acid in a mixture of methanol and 2-butanol) with a 20 V d.c. at - 50 °C for 30 min. The polished surface allowed in situ optical observation of the slip lines and various microfracture processes during tensile tests.

Tensile tests were performed using a servo-hydraulic machine at ambient temperatures. The tests were displacement controlled with a nominal strain rate of 2.9 x 10⁻³, 2.9 x 10⁻⁴ or 3.8 x 10⁻⁵ s⁻¹. A knife-edge extensometer was mounted to monitor the strain within the gauge as a function of load throughout the test. In order to relate the microscopic damage of the tested materials to AE, some tensile tests were conducted using a micro-straining stage built in this laboratory. This micro-straining stage allows in situ observation of the slip lines and various microfracture processes during testing with an optical microscope.

AE was monitored using an AE Data Acquisition System. Care was taken to standardize all experimental procedures so that valid comparisons could be made between different tests. Two piezoelectric transducers, sensitive to acoustic signals with frequencies from 10 KHz to 1 MHz, were attached to the shoulders of the specimens by a thin layer of vacuum grease, under a constant pressure applied by a rubber band. The output signals from the sensors were amplified by pre-amplifiers with a gain of 40 dB and a 100-400 KHz bandpass filter. The post-amplifier gain was 20 dB and the hit definition time used to distinguish between separate events was set to 200 μm for the dimension of the present specimens. After the installation of the transducers, a pencil lead break procedure (ASTM E976) was used for AE location calibration. A mechanical pencil with a 0.5 mm diameter 2H lead was used and the lead was broken at three locations within the gauge length of the specimen with one location near sensor 1, another near sensor 2 and the last one at the centre of the specimen. The location of AE events with the origin designated at sensor 1 was calculated as follows:

\[ x = \frac{(L + \Delta t \cdot V)}{2} \]

where \( L \) is the distance between the two sensors, \( \Delta t = t_1 - t_2 \) with \( t_1 \) and \( t_2 \) being the arrival time of sensors 1 and 2, respectively, and \( V \) is the acoustic velocity.

Several precautions were taken to avoid extraneous acoustic noise. First, the amplitude threshold was set at 45 dB, which was found to be very effective in limiting the acoustic noise because most of the noise had amplitudes < 45 dB. Second, the spatial filtering of AE events through post-test data reduction was performed to exclude the AE from outside the gauge

![Figure 1](image-url)