BEHAVIOUR OF TITANIUM ALLOY TESTING UNDER CRYOGENIC CONDITION USING ACOUSTIC EMISSION TECHNIQUES

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Abstract

Titanium (Ti) alloys are strategic aerospace materials used in relatively severe working environment. Owing to the excellent properties such as high rigidity to weight ratio, elevated temperature strength, corrosion resistance and toughness in ambient as well as cryogenic environment, Titanium alloys find high technology applications in aerospace industries. As the Ti alloy find application in aircraft engines, compressor blades and gas turbines, it is necessary to characterize the performance of this material under stress conditions. Acoustic Emission (AE) is a high sensitivity technique for detecting active microscopic events in a material under stress. The processes that are capable of change the internal structure of a material such as dislocation motion, directional diffusion, creep, grain boundary sliding and twinning which are usually associated in plastic deformation and fracture are the sources of Acoustic Emission. Thus, using AE signals, it is possible to evaluate the performance of material under stress. The data acquired can be used to predict the performance of products made of Ti alloy. With this view, the acoustic emission responses of Ti alloy subjected to tensile testing under cryogenic condition have been studied. The fractured surfaces are examined through Scanned Electron Microscopy (SEM) and corresponding micrographs are also compared and the results were presented.

Keywords: *Acoustic Emission, AE signals, tensile testing, cryogenic condition.*

1. Introduction

Performance of a product is largely dependent on design, manufacturing and maintenance. Material characteristics influence significantly on the three aspects. Any material under stress will respond according to the nature of stress and environment. Material response is to be carefully monitored, especially in the case of critical parts such as part in aerospace and related applications.

Acoustic Emission (AE) as the transient elastic wave generated by the rapid release of energy from a localized source or sources within a material when subjected to a state of stress. This energy release is associated with the abrupt redistribution of internal stresses and as a result of this, a stress wave is propagated through the material [1–3]. The definition of AE given above Indicates that processes that are capable of changing the internal structure of a material such as dislocation motion, directional diffusion, creep, grain boundary sliding and twinning, which result in plastic deformation, phase transformations, vacancy coalescence and decohesion of inclusions and fracture are sources of acoustic emission; of processes said above, only plastic deformation and fracture are of significance in metal cutting. Out of the four plastic deformation processes mentioned, generally, dislocation motion is the dominant mechanism in crystalline materials which are widely used in practice [4].

AE study is used as a condition monitoring process by different researchers [5] studies the acoustic behavior of screws under tensile load. The significance of the results for the in-process monitoring of screws is explained in this work. AE technique for the integrity evaluation of aerospace pressure chambers made of M250 Maraging steels is carried out [6].

Due to the excellent properties to titanium alloy, such as good ductility, high temperature strength, corrosion resistance and lower density, this alloy finds under high technology application aerospace, chemical and petrochemical industries, it is necessary to acquire a thorough knowledge on the behavior of the material explained [7]. The acoustic response of titanium alloy subjected to a tensile testing reveals the behavior of the material during fracture. Only limited literature is available in this area. The AE response of the material can indicate microstructure – property relationships.

Roman et al [8] studied the AE produced during tensile straining and fracture to have a better understanding of the titanium aluminide alloy behavior [9] investigated the effects of matrix microstructure and interfacial properties on the fatigue and fracture behavior of a Meta stable titanium matrix composite. The damage behavior of the titanium matrix composite, during monotonic and cycle loading were studied through AE.

Bakuckas et al [10] conducted AE studies to locate and to observe the damage of the titanium matrix composite. The results were supported by SEM analysis carried out on the fractured surfaces. The relationship between microstructure and AE of Ti-641 – 4v has been studied [11]. Different microstructures of Ti-641-4v alloy have been obtained through different grain sizes and different heart treatment procedures. The AE response of these different microstructures subjected to mechanical deformation rest has been studied.

A detailed study on the micro fracture mechanism in fracture toughness test of Ti-8A1-1Mo-1v alloy was examined by AE wave analysis [12]. The wide spread use of cryogenic fluids for several industrial applications such as frozen food, metal industry, space application, superconductors and biomedical applications have to be studied. Suitable materials have to be selected, in such a way that selected material should have toughness, ductility and weld ability at this low temperature. Titanium by its inherent properties meets the requirements of cryogenic technology [13–14].As the titanium alloy finds application in aerospace and cryogenic in industries, the behavior of this material under both the working conditions such as ambient and cryogenic conditions has to be investigated. In this recent study, the acoustic response of the titanium alloy has been studied during the mechanical deformation, subjected to varying working environment such as ambient and cryogenic condition.

The finite element analysis and modeling of fractured bone are used in acoustic emission [16]

2. Acoustic Emission Technique

Acoustic emission (AE) is the class of phenomenon where transient elastic waves are generated by the rapid release of energy from localized sources within a material, or the transient elastic waves so generated. In other words, AE refers to the stress waves generated by dynamic processes in materials. Emission occurs as a release of a series of short impulsive energy packets. The energy thus released travels as a spherical wave front and can be picked from the surface of a material using highly sensitive transducers, (usually electro mechanical type). The picked energy is converted into electrical signal which on suitable processing and analysis can reveal valuable information about the source causing the energy release. The load applied on the material results in the transient energy release from the source. It obviously travels as a spherical wave front. As this pressure waves propagates through the material it undergoes distortion and attenuation. The volume and characteristics of AE generated are dependent on the nature. Type and characteristics of the source: the main characteristics being its initial severity, present state, local metallurgical structure and the environment. These are converted in to electrical signals by mounting Piezo electric transducer in suitable locations on the material by pasting them with complaints. As the stress waves pass through the compliant and transducers they further undergo distortions depending upon their transfer function characteristics. In order to increase strength of the signals, a preamplifier with filter leads the AE signals to the signal processor where ambient noise and unwanted frequency comportment of the signal are eliminated. This also helps to increase the signal to noise ratio. It further leads to data acquisition unit for analysis.

3. Experimental Work

Acoustic Emission (AE) is the stress waves produced by sudden movements in stressed materials. The classic sources of AE are defect related deformation. Elastic waves are generated due to the local changes in source region. These waves propagate as mechanical disturbances through the structure causing a time varying surface displacements/in this experiment using Titanium Alloy under tensile load in Universal Testing Machine (UTM) has been carried out for the AE Study.

3.1 The Material

The tensile specimens used have been machined out from Titanium Alloy (Ti-6A1-4V) Plates, which were in received condition, are subjected to annealing before the machining process. The axis of the specimen has been kept coinciding with the rolling direction of the plate. Care has been exercised to ensure that the radius of curvature at the gauge end has been as smooth as possible. The major interests in this class of specimens are toe study AE signature at the pre – yielding onset of yielding.

As such no strict quality control measures have been affected to control the width or thickness of the specimen within close tolerance at the gauge length portion.

Figure 1. displays the machined specimen with the general configuration. Figure 2. shows the photographic view of the fractured tensile specimen in cryogenic condition.

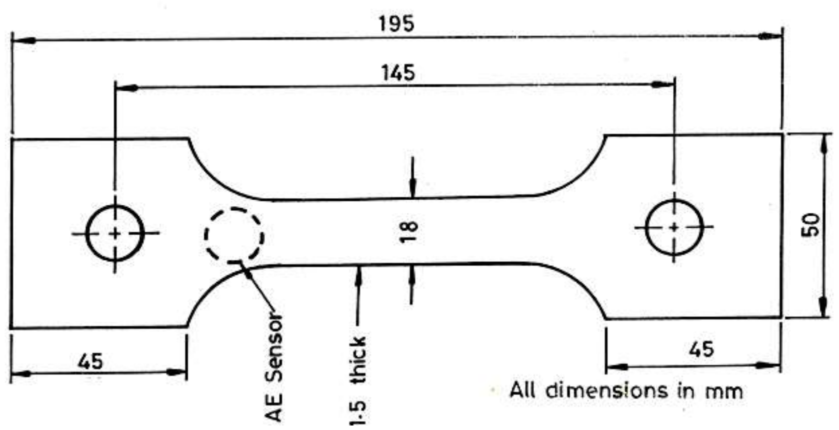


Figure 1. Tensile test Specimens

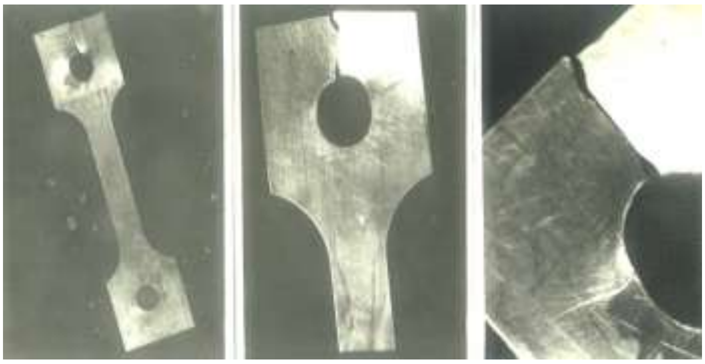


Figure 2. Typical fractured tensile specimen

3.2 Loading Machine

The tensile specimen is subjected to the required loading / load cycle on Servo controlled SCHENCK TREBEL RM 250 Universal Testing Machine, 250 KN Capacity with the provision for fatigue cycling as well as displacement controlled loading machine cells for necessary screening if the genuine emission events from the specimens under test are to be acquired. Board specifications for the loading machine are listed below.

Model	:	AET5500
Oscilloscope model	:	Hewlett 5460 B 60 MHz Packard Oscilloscope Measurement / Storage Module
Intelligent Graphic Display Terminal (IGT)		
Operating System	:	MS DOS Version 3.3
Pre-amplifier	:	160 B Model ; Gain – 60 dB 140 B Model ; Gain – 40 dB
Filter	:	30 kHz-2 MHz 500 KHz – 2 MHz
Sensor Model	:	FAC 500

Photograph view of the cryogenic experimental set up is shown in Figure 3.

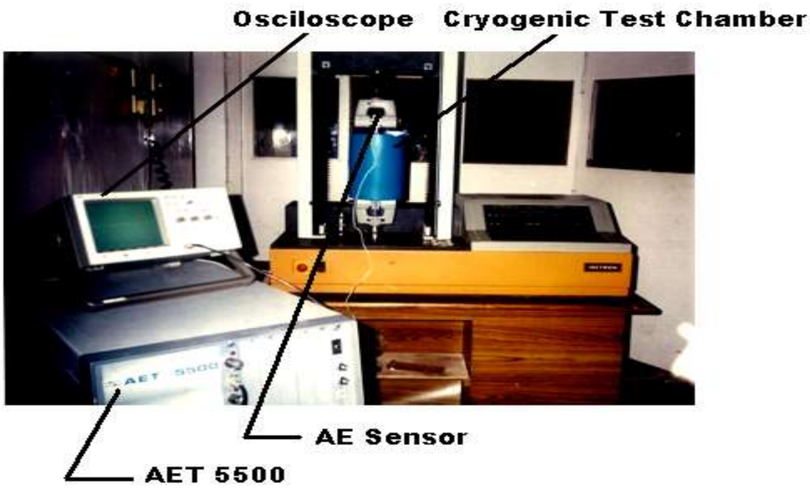


Figure 3. Experimental Set Up

4. Experimental Procedure

Tensile test specimen of 1.5 mm thickness and 18 mm width, made of 6% Aluminum and 4% Vanadium, 9% of Titanium alloy is tested with tensile loading in a universal testing machine of 250 KN capacities. It is seen that as the load increases there is a steady improvement in activity; around certain critical/threshold load, the test material becomes active, associated with deformation and dislocation movements, the material exhibiting permanent set. This is associated with emission of continuous AE signal. As the load applied increases, the material tries to attain the threshold/permissible stress beyond which degradation/failure sets-in. Hence, as the material is subjected to increasing loading, acoustic stability is attained; with the result the material may even become inactive over the permissible stress region. Beyond that stress, failure of material sets-in associated with localized burst signals.

4.1 Data Acquisition

An Oscilloscope has been used to acquire the amplified and filtered data. The 2 K pts resolution of the Oscilloscope and the storage duration of second/signal limited the signal rate and precision. The trigger threshold was adjusted exactly to just above the noise level. The signal exceeding this threshold (together with the elongation, load and speed of the crosshead) was recorded and the signal from the sensor was magnified by a pre-amplifier for increasing load. The raw signals were monitored using a data-logger. The acquired signal was analyzed separately using a suitable PC based data acquisition system at a sampling frequency of l MHz for spectrum analysis. The time duration signal consisting of 25 and 50 observations were considered for the purpose of analysis. The recorded data were used to calculate the AE rate and the frequency spectra. The AE signals were obtained under the cryogenic conditions.

4.2 Fatigue life of Ti-6Al-4V alloy

The experimental results of the high-cycle fatigue bending tests and the S–N diagram of titanium alloy are shown in Figure 4. The aim was to evaluate the fatigue behavior in L and T orientation and determine approximately the fatigue limit at N = 108 cycles. It can be seen that presented results of the fatigue tests show the impact of structural orientation for tested materials less distinctive and the orientation factor does not play the main role. The fatigue limit was found to be about 561 MPa for direction L and 550 Mpa for direction T (at 108 cycles).

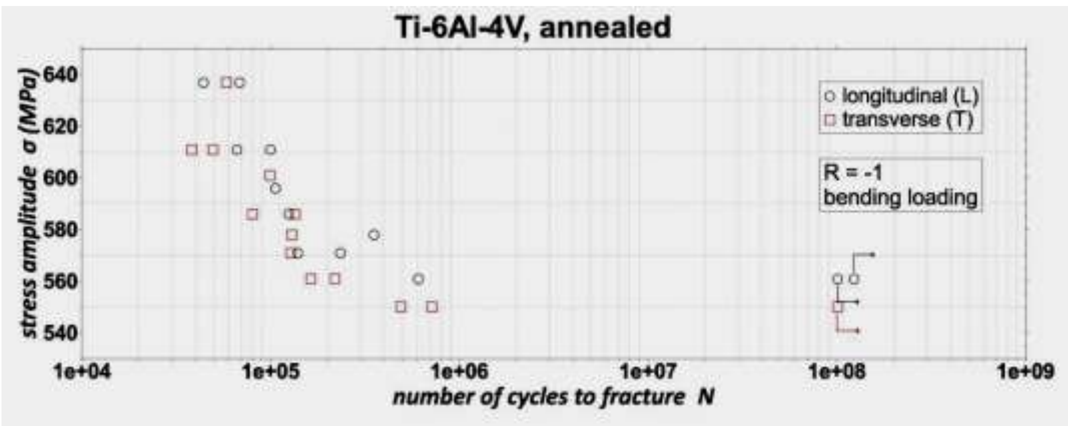


Figure 4. S-N diagram of specimens cyclically stressed in direction L and T of Ti-6Al-4V alloy

5. Results and Discussion

5.1 Acoustic emission response during fatigue

As suggested above, an AE measurement was carried at stress amplitude levels from 611 to 550 MPa (5x104 to 2x106 cycles). As we can see in Figure 7, all records have three similar features. In the first quarter of the fatigue life the activity of AE signal emitted by changes of mechanical properties and surface relief formation is increased. The next area is characterized by low activity that leads to fatigue micro crack initiation.

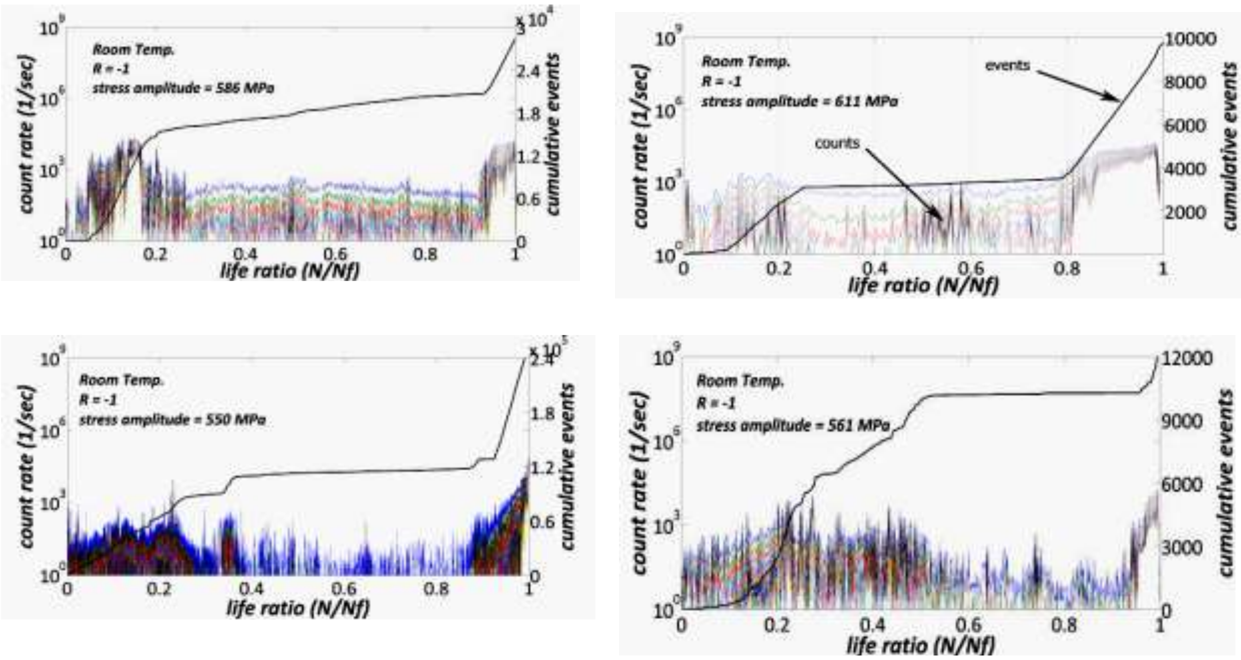


Figure 5. Count Rate and cumulative events behavior at different stress amplitude levels

In the last quarter of the life ratio the activity of AE signal emitted by stable and unstable crack propagation increases rapidly and does not decrease up to specimen failure. In our traditional AE testing, AE signal has been correlated with a record of resonant frequency of loading RUMUL machine and then used to characterize material fatigue behavior. Using this approach, the transition zones of fatigue damage with the changes in AE signal and resonant frequency is possible associate during the whole fatigue test. The source location of AE events (location distribution histogram) are plotted in Figure 6 above. The record of cumulative number of AE events and resonant frequency of RUMUL machine versus time is shown in Figure 6 below. The total localized events (red) and events coming from the notch (blue) are shown in this graph. The whole record is divided into four sections for detailed analysis of AE signal, i.e. 0 - 15, 15 - 35, 35 - 50 and 50 - 61 minutes.

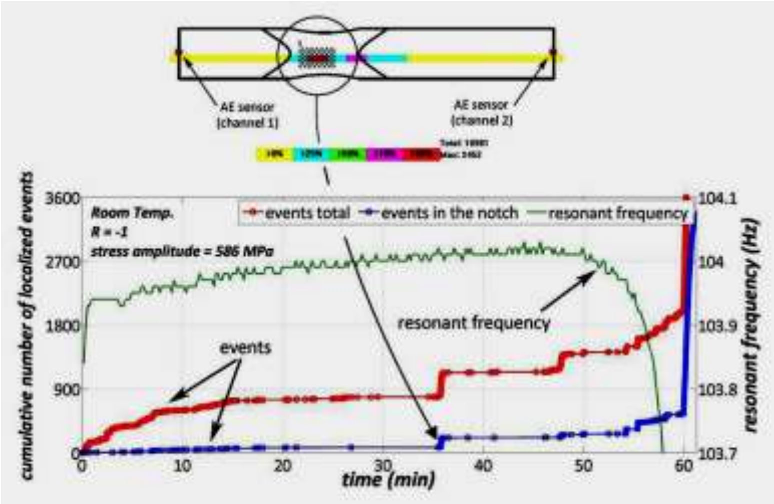
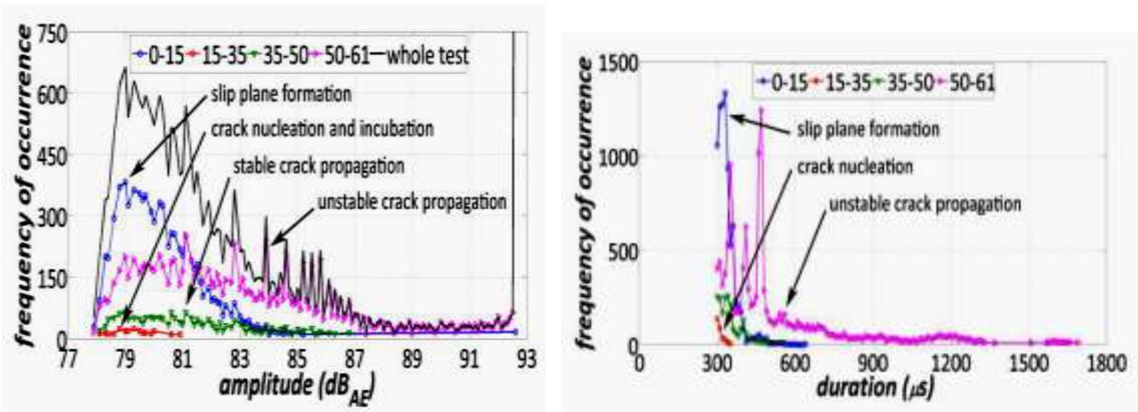


Figure 6. Events and resonant frequency of RUMUL machine during fatigue test (Nf = 3. 84 x 10^5 cycles)

It is common knowledge that when a resonant frequency begins to decrease (the specimen stiffness decreases as well), a main crack already propagates in the specimen and fracture occurs. This moment occurs in the 15 minute (in Figure 6). The onset of unstable crack propagation is seen from the rapid increase in the localized AE events rate since the 55 min of the fatigue test. The location distribution histogram of all events accumulated during the whole fatigue test shows that initially most of events were generated outside the notch and since the 35 min to a region near the notch. It should be noted that the few events generated away from the notch during may have been caused by surface imperfections. Figure 7. shows the diagrams of amplitude and duration distribution at each time stage. These diagrams show that events are distributed in amplitude with a higher frequency of occurrence from 78 to 81 dBAE in the case of the pre- and initiation stage (0 - 35 min.) and from 80 to 85 dBAE in the case of the crack propagation (35 - 61 min). However, the amplitude distribution in the case of events in the notch (in Fig. 8 above right) is slightly different. Here is a higher frequency of occurrence up from 83 to 86 dBAE in the case crack propagation; the events have not been detected in the previous stages. These results suggest that fatigue damage modes generate signals at low amplitudes. The distribution of events in duration ranged between 0 to 50 s for first two stages and unstable crack propagation stage was between 50 to 200 s. A similar picture is also the case of events in the notch. Note that the duration in the diagrams also includes a dead time of 300 s.



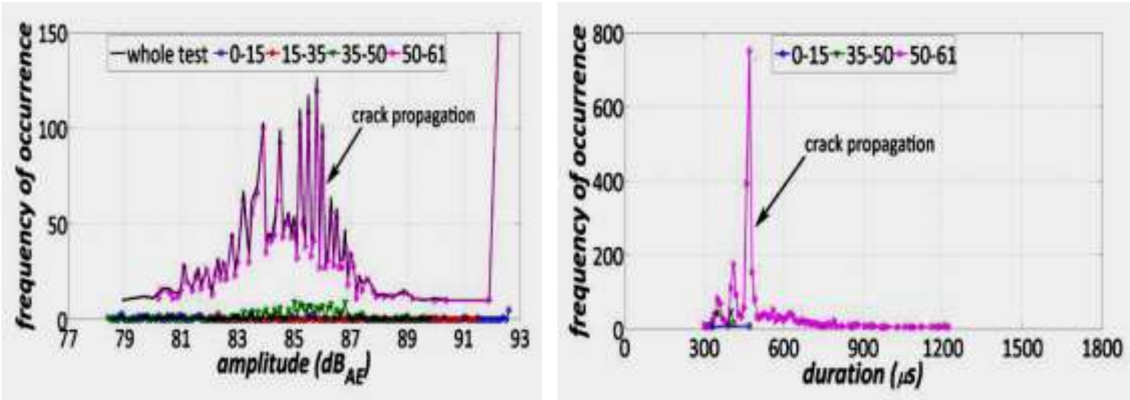


Figure 7. Amplitude (above) and duration (below) distribution of events during the fatigue test.

Overall, no damage activity occurs at the beginning of the test, but this is then followed by a sharp increase in cumulative AE events (in Figure 7. in the first quarter). These events are characterized by low amplitude (see Figure 10 above left). Mostly it is basically uniform growth and distribution of small sub-grain cracks and slips plane formation. Dislocation motion and interaction across the boundaries and partially also crack nucleation is the major contributor of AE signal in second stage of fatigue process (see Figure 8 above right). The count and events rate emitted by these processes is minimal. Then since the 35 minutes, the areas of developing micro crack as a result of movement of dislocations are sources of AE signals. The AE events measured at this stage are mostly burst type and characterized by a higher amplitude and duration about 50 µs. The final phase of rupture area is sufficiently short and no more than a few minutes. In the last stage were registered AE signals emitted by the smain crack propagation with a high amplitude and duration about 150µs (shown in Fig. 9 below right).

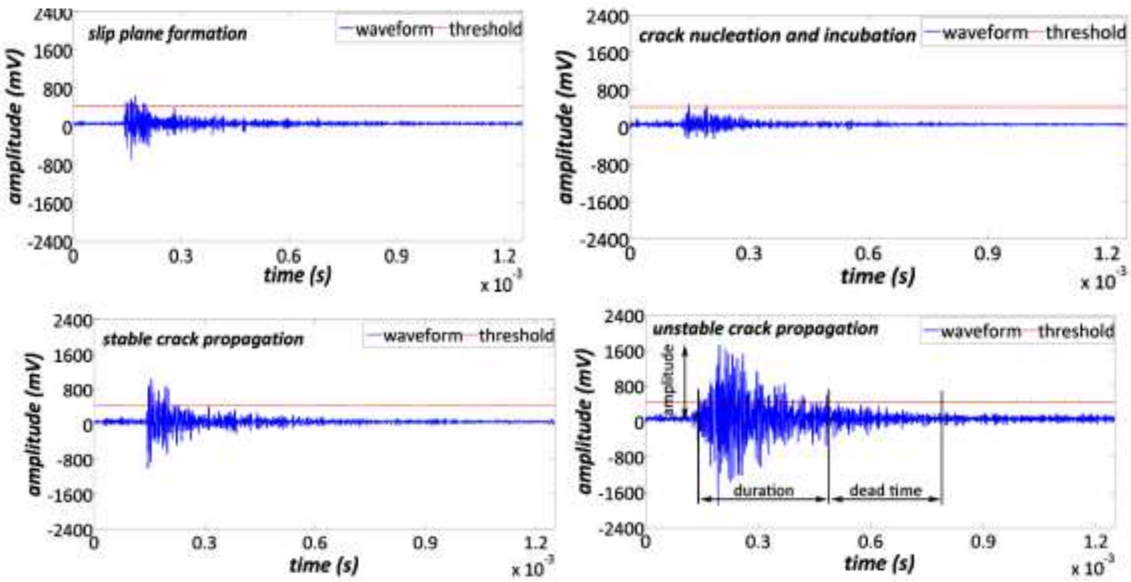


Figure 8. Typical waveforms coming from the different stages

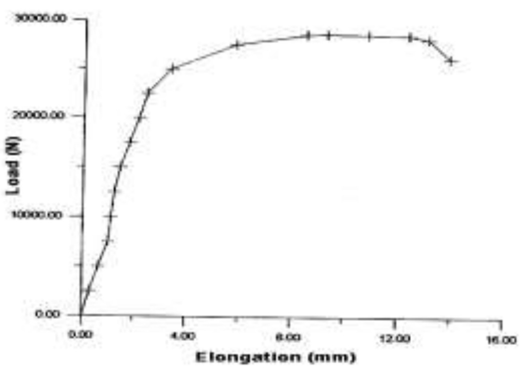
5.2 Data from Test Carried Out at Cryogenic Condition

The titanium material was tested to uni-axial tensile loading. Typical observed load and extension characteristics of the test material are illustrated in Figure 9s. It is seen that up to around 13% (2mm) elastic behavior can be observed; beyond that elongation of the material undergone plastic deformation associated with viscous yielding. This is indicated by the occurrence of staircase type load-extension characteristics. The response of the titanium alloy to tensile loading was monitored on-line by sending the acoustic emission signal emanation from the test specimen by suitably positioning a broad band AE sensor. The recorded signal was characterized in terms of r.m.s value and dominating frequency.

Typical observed r.m.s value of the acoustic emission signal monitored is illustrated in Figure 10. It can be seen that with tensile load on, there is a gradual reduction in r.m.s value indicating that slow degradation of the material with applied load/stress. The r.m.s characteristics is of zigzag nature; from this it can be inferred that after certain cumulative yielding the test material experiences localized bursting associated with a reduction of r.m.s value. Titanium alloy is relatively low strain hardening material; hence it experiences higher order strain before failure. During stressing the test material experiences straining of localized lump of material after certain order of strain, this may experience discrete burst/fissures resulting in the reduced acoustic emission i.e. Titanium alloy under tensile loading experiences localized yielding and burst depending upon the load sequence, till failure, of course with continuous reduction in r.m.s value.

From the recorded raw acoustic emission signal, the dominant frequency was noted. Typical variation of the domination frequency with load is illustrated in Figure 11. Referring to the illustration on r.m.s value and dominant frequency, it can be seen that especially with higher testing load, there is a reduction in the r.m.s value of the acquired acoustic emission signal; the signal acquires for higher loads, indicate the dominant frequency of 120kHz i.e. around 20000N of loading, the material exhibits more of burst emission, indicating there by the occurrence of localized cracking associated distressing the material.

Observation on characteristics of raw signal was acquired. Typical illustrations on the acoustic emission signal acquired with one of the sample 15000 N applied load are presented in Fig 13. With applied load of 2500N the acoustic emission signal comprises many different frequency components, with the dominant around 120KHz. As the load is increased to 5000N, only few frequency components were observed with a shift in the dominant frequency towards a lower magnitude. This indicates the occurrence of a relatively more continuous emission. (Also indicated by occurrence of higher r.m.s value)



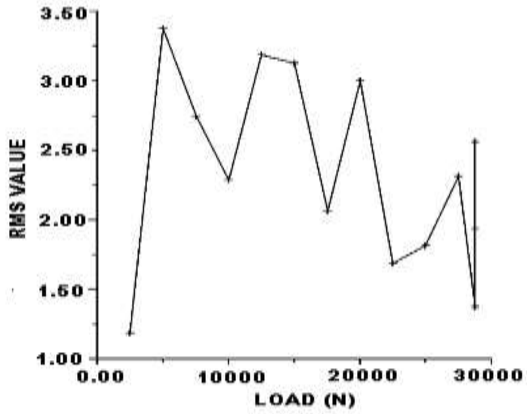


Figure 9. Load Extension Characteristic Figure 10. Variation of the R.M.S value with the load

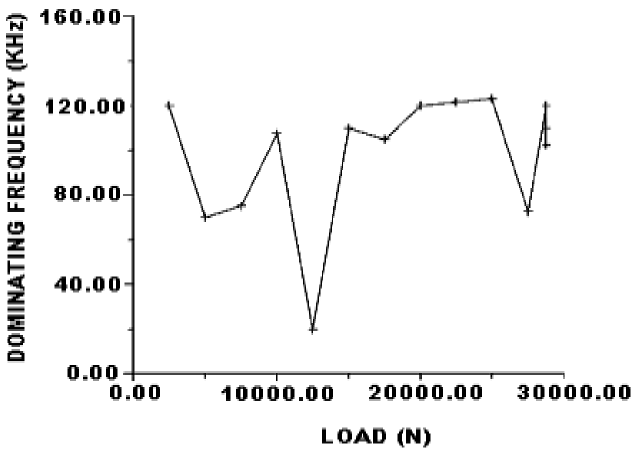


Figure 11. Variation of the Dominating frequency with the load

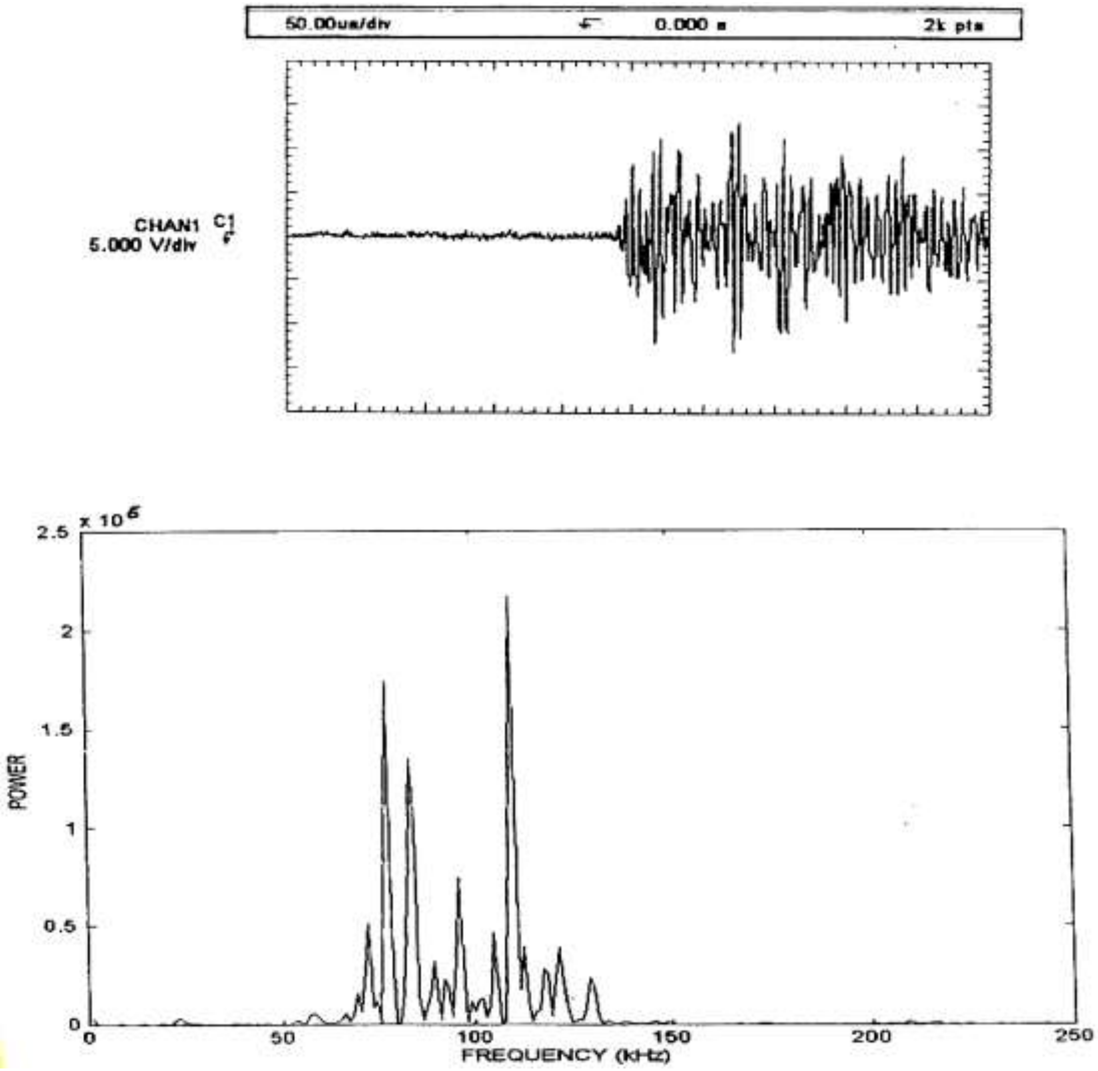
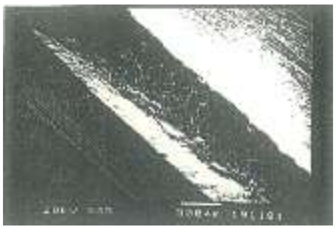


Figure 12. FFT Spectra for power vs. frequency at 15000 N Applied load

Summing up; the continuous monitoring of AE has illustrated the deformation of the material, occurrence of local fissures during early phase of loading and continuous deformation as illustrated by higher rms value; further, barring few load stage, the monitored AE signal contains a dominate frequency around 100-120kH. This can be the typical frequency of acoustic emission for titanium alloy tested.

5.3 Fractrography Observation

Fractured surfaces of test samples were observed through JEOL make Scanning Electron Microscope. The typical Scanning Electron Microscope of fractured surface is shown in Figure 13 (a-h). The higher ductility of titanium alloy is clearly illustrated through a textured macrograph, with elongated grains and occurrence of dimpled zones. Further, the flow of material around the dimples indicated that the material has undergone viscous yielding during tensile loading. Closer observation of localized regimes indicate possibility of failure initiation around spherical, second phase particles. Observations also indicate the occurrence of the cracking of the material prior to failure.



(a)

(b)

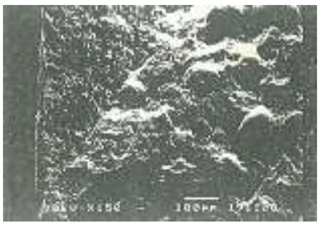
(c)

(d)

(e)

(f)

(g)



(h)

Fig. 13 (a-h). Typical scanning electron Micrographs of Fractured surfaces (Titanium alloy)

6. Conculsion

The main goal of this paper was to evaluate the bending fatigue behavior of Ti-6Al-4V alloy in high-cycle area and to analyze in detail the fatigue damage mechanism using acoustic emission method. It was found that the impact of structural orientation for tested materials (direction L and T) less distinctive and the orientation factor does not play the main role (see Fig. 13). The fatigue limit was found to be about 561 MPa for direction L and 550 MPa for direction T (at 108 cycles). The acoustic emission monitoring during fatigue tests was focused on finding the changes in AE signal that can correspond to transition zones of fatigue damage. Three similar features were found by count rate and cumulative events at four stress amplitude levels (see Fig. 12). It is the uniform growth and distribution of small sub-grain cracks and slip plane formation (high activity), the growth of these micro cracks across the grain boundaries and crack nucleation and incubation (low activity) and final coalescence of these cracks into localized main crack and the stable and unstable main crack propagation (high activity). Typical waveforms were collectsed and correlated with fracture mechanism from different fatigue stages. Study on AE response of titanium alloy, has been carried out with a view to develop an integrity evaluation methodology applicable to aerospace material. Necessary criteria has been evolved and applied to aerospace related application for real time integrity monitoring. The following are the significant conclusions emerging from the studies.

Observation on the tensile specimens bearing possible surface defects indicated that the AE response of titanium alloy subjected to tensile under ambient condition. The acoustic emission acquisition data indicated mixed mode of signal emission in ambient condition. This might be due to occurrence of local fissure during early phase of loading and continuous deformation illustrated by high r.m.s value. Further barring few load stages, the monitored AE signal contains a dominating frequency around 100-120 kHz. This can be a typical frequency of acoustic emission of the titanium alloy tested.

The micrographic studies on fractured specimen clearly indicate the elongated grains or occurrence of dimple zones. Further, the flow of material around the dimples indicated that the material has undergone viscous yielding during tensile loading.

Occurrence of dimpled microstructure indicated ductile mode of failure associated with cracking of the material prior to the failure. Studies on cryogenic environment have been observed; the relatively feeble acoustic signal can be attributed to possible strengthening of the titanium alloy. The studies conducted clearly show the acoustic emission techniques can be used for an effective continuous monitoring system.

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