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Online Acoustic Emission Monitoring of Cyclic Ball Indentation Testing - Correlation with Hysteresis Area Response

Raghu V Prakash[a,*], Manuel Thomas[a], Anirudh R. Prakash[b] and C. K. Mukhopadhyay[c]

[a] *Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600 036, India*
[b] *Department of Mechanical Engineering, Politecnico di Milano, Bovisa Campus, Milano 20156, Italy*
[c] *Homi Bhabha National Institute,Kalpakkam 603 102, India*

Abstract

Fatigue has been one of the most researched subjects as most of the critical component failures are traced to fatigue. While fatigue data generation for design purposes is carried out using ASTM or equivalent standard specimens, the use of miniature or small specimens to estimate the fatigue properties is considered as a tool for extending the remaining life of in-service components. Cyclic automated ball indentation (Cyclic ABI) is one of the non-conventional test techniques used for fatigue performance assessment of pristine and in-service damaged materials. This method uses compression-compression cyclic loading of a flat specimen using a tungsten carbide spherical indenter; continuous monitoring of load-displacement (measured close to the indentation location) data provides an idea about the fatigue life of the material. Apart from this, hysteresis in load-displacement is used as an indicative energy parameter to detect fatigue failure in an Inconel 617 alloy using an off-line data analysis. To ensure on-line tracking of failure events, a specially tuned, miniature acoustic emission (AE) sensor was used during cyclic indentation testing. The AE parameters were extracted in the format of counts, absolute energy; the result processed in terms of cumulative counts, cumulative energy as well as first derivative of acoustic emission counts vs. fatigue cycles was used to cross-correlate failure events with other sensor responses. The failure cycles identified from AE were found to be in good agreement with the hysteresis area under the load-displacement curves, as well as extensometer displacement during cyclic loading.

* Corresponding author. Tel.:+91-44-2257 4694; fax: +91-44-2256 4652.
E-mail address: raghuprakash@iitm.ac.in; raghu.v.prakash@gmail.com

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1. Introduction

Fatigue has been one of the most researched subjects as most of the failures related to critical components are traced to fatigue. This is despite nearly 150 years of research in to fatigue. In this context, it is pertinent to note that designers work with fatigue data generated at the start of the design and development of the product and assess the durability of the component using well known life prediction methods. It is noted that fatigue life is dependent on material, geometry, loading conditions and the environment in which the system is operating. Practicality of operation of systems suggests that many of them do not work under the ideal loading conditions or environment, which results in accelerated fatigue damage, causing premature failures. While fatigue data generation for design purposes is carried out using ASTM or equivalent standard specimens, such as, ASTM E-606 or E-647, when one needs to assess the remaining life of a critical component, for e.g., mid-way through its operation, it is essential to gather information about the current state of the material. It is in this context the use of miniature or small specimens extracted from small scoop of material from a working component is practiced to estimate the fatigue properties of the material. In essence, the fatigue properties are either assessed in-situ or derived from small volume specimens. Review of literature on small specimen testing, suggests that majority of the life extension studies use miniature tensile, impact or fracture toughness specimens, but very little effort is devoted for fatigue studies. In some cases, sub-size cylindrical low cycle fatigue specimens are used for fatigue life estimation [Nogami et al, 2010]. The problem when one reduces the size of the specimen is that the data has enormous scatter due to local microstructure influence, esp., when the size of the specimen is comparable to the grain size of materials.

To address this aspect, non-conventional experimental techniques to determine the fatigue performance of in-service components or their scooping have evolved over the years. Cyclic ball indentation (Cyclic ABI) [Prakash et al, 2008] is one of the test techniques used for fatigue performance assessment of pristine or in-service or even failed/damaged materials and the results have been correlated with standard specimen fatigue test data [Prakash et al, 2018]. From a simple view point, use of cyclic compression-compression loading using a spherical indenter and continuous monitoring of load-displacement (measured close to the indentation location) data provides an idea about fatigue life of the material. The depth of penetration increases as a function of the applied cycles of compression-compression loading and reaches a steady state after some cycles. But in view of the tensile component of stresses that exist underneath the indenter area (as confirmed through finite element studies of Arunkumar and Prakash, (2016)), the material fails after some cycles through the formation of a sub-surface crack. As a consequence, the depth of penetration shows instability in output with a sudden increase in depth of penetration. This perturbance in penetration depth has been used to identify failure cycles during cyclic ball indentation. Thus the detection of exact cycles at which the failure occurred in the material underneath the spherical indenter is not straightforward. Fatigue life estimation using cyclic ball indentation is feasible off-line after the test is complete. To address this aspect, Bangia and Prakash (2012) explored the option of equating the strain energy (represented by the area inside the hysteresis loop during a low cycle fatigue test) to the hysteresis area during cyclic ABI test. The premise is that the failure or creation of new surface is based on energy balance. The results were found to correlate reasonably well, though there is a difference in failure life cycles due to the difference in state of stress between the conventional low cycle fatigue (LCF) test specimen and cyclic ABI test specimen. The conventional LCF specimen experiences a uni-axial load and associated stress components whereas the cyclic ball indentation test specimen experiences a tri-axial state of stress and constraint to plastic deformation. Research carried out on the ball indentation test methods suggests that there is a minimum thickness of the specimen that is required underneath the spherical indenter to avoid local microstructural effects. Equating the hysteresis area or hysteresis energy is yet another method to identify failure in small specimen fatigue testing.

To examine, if one can use an on-line technique to detect crack initiation during cyclic indentation and to correlate the findings with post-processed data, this study was carried out. Acoustic emission (AE) technique is a promising on-line non-destructive test (NDT) technique used for the detection of damage and its progression [Huang et al, 1998)]. Materials during failure emit acoustic signals, like the way one hears the creek noise during failure of wooden beam. If such noise signals can be picked up on-line, it could help identify the crack initiation. For this purpose special acoustic sensors that can pick-up the feeble noise signal during cracking needs to be employed. In this study, specially tuned, miniature AE sensors were employed to detect on-line the fatigue cracking in a structural Inconel alloy subjected to cyclic ball indentation loading. A piezoelectric sensor, along with a series of preamplifiers and signal conditioners are used for the monitoring of acoustic waves generated from the material to be tested. A typical AE waveform and the AE parameters from the waveform are provided in Figure 1. The AE parameters are logged in the format of acoustic counts, absolute energy of signals.

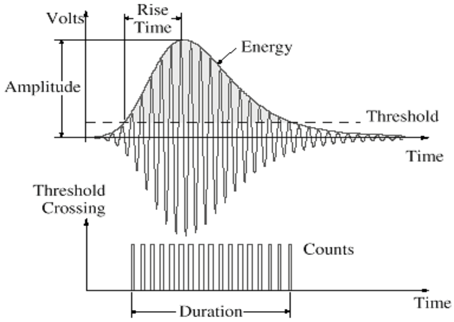

Fig.1 – Typical AE burst signal [Huang et. al, 1998].

The AE results are processed in terms of cumulative counts, cumulative energy as well as first derivative of acoustic emission counts vs. fatigue cycles. The failure cycles thus identified were correlated with the hysteresis area under the load-displacement curves during cyclic loading. It is to be noted that since the fracture results in feeble acoustic wave propagation, the results are dependent on the placement location of the sensor. For this purpose a ABAQUS® simulation was carried out to identify the preferred location of AE sensor placement, which is a separate and stand-alone investigation. Upon proper placement of AE sensors, a fair degree of agreement in failure cycles data is seen between the hysteresis area method and AE sensor method.

2. Experimental details

Inconel alloy IN 617 supplied in the form of a forged disk was used for carrying out the cyclic ball indentation studies. A small test section of nominal dimensions 15 mm x 15 mm x 10 mm thickness was extracted from the disk and was machined, ground and polished as part of surface preparation. Testing fixtures consisted of a flat compression platens and a special holder to accommodate a 1.57 mm diameter tungsten carbide (WC) spherical ball in a small conical cavity. Cyclic ball indentation experiments were carried out on a 100-kN MTS 810 servo-hydraulic testing system interfaced to a computer control. The special holder was fixed to the upper grips of the test system while the specimen as placed over the compression platen. The load cell placed on the upper cross-head and in-line to the load train senses the load when the specimen comes in contact due to the movement of lower end servo-actuator. The load range was electronically scaled down to ± 10 kN and the displacement range was scaled down to one-tenth of its full scale range (of ± 75 mm). A MTS crack mouth opening displacement gage having a travel of +3 mm/-1 mm was used for local displacement measurements. Experiments were carried out under load control and Table 1 presents the details of test matrix. A Nano-30, a medium frequency resonant response (@ 300 kHz) acoustic emission sensor provided by Physical Acoustics Corporation, USA was used for the pick-up of acoustic signals. This AE sensor has a good frequency response over the range of 125-750 kHz and was mounted using an acoustic couplant (vacuum grease) on the side of the test section that was used for cyclic indentation experiments. Figure 2 presents the photograph of the test set-up both in general view and close-up view.

A dummy specimen of the same material was tested for eliminating external noise produced using the testing. The sources of external noise signals include hydraulic noise, noise generated due to cyclic loading and other outside disturbances. Based on the test conducted on dummy specimens, a signal threshold of 50 dB was selected. Also, a preamplifier gain of 40 dB, along with a bandpass filter of 100-600 KHz was used for the AE data acquisition. The acoustic signal parameters such as signal amplitude and duration, signal rise time, and total ring down counts were monitored during the testing from the software interface. The AE data was then filtered using the Amplitude duration criteria [Chai et al, 2017]. According to this criterion, both low amplitude, high duration signals and high amplitudes low duration signal can be eliminated to ensure data quality. In general, the signals with higher strength will have a higher duration and corresponding low amplitude signals decay fast [Nemati et al, 2015]. Signals having duration greater than 1200 μs and amplitude less than 60 decibels were filtered out. High amplitude signals (>65 dB) having a duration of less than 1000 μs was eliminated.

Table 1 - Test matrix for cyclic indentation studies on IN 617.

Specimen/Test ID	Max. Compression Load (N)	Min. Compression Load (N)
15-Feb-2020-01	1250	125
15-Feb-2020-02	1250	125
19-Feb-2020-02	1250	125
19-Feb-2020-01	2000	200
21-Feb-2020-01	2000	200
21-Feb-2020-02	2000	200
20-Feb-2020-01	2250	225

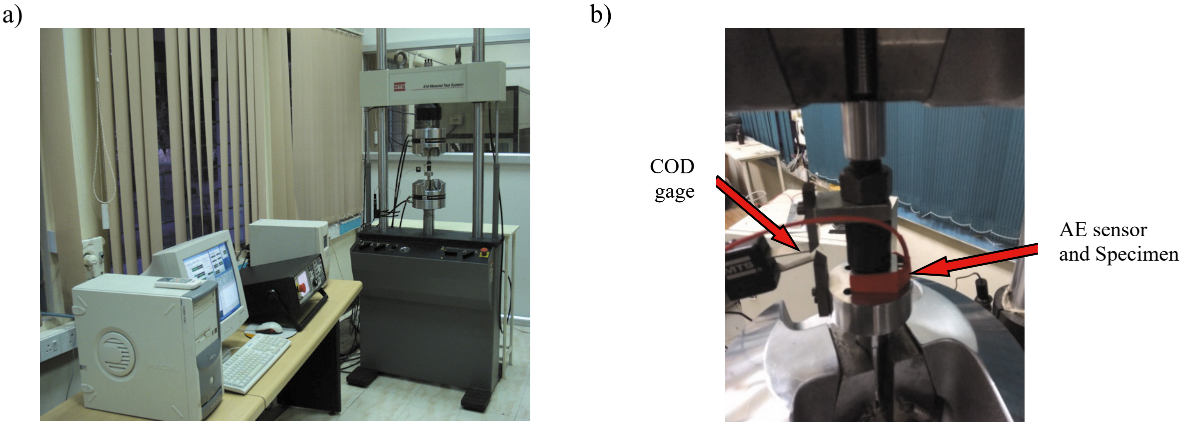

Fig. 2 – Photograph of: a) general test set-up and b) close-up view of cyclic ABI with COD gage and AE sensor.

3. Results and discussion

Figure 3(a) presents the typical displacement response as a function of the number of fatigue cycles of compression-compression fatigue loading. It can be seen that after the initial set-in of indenter response, the same settles down at about 1000 cycles (or 2000 segments). Further, a perturbance in displacement data is seen at approx. 2958 cycles and the displacement value increases thereafter. Figure 3(b) presents the load-displacement data extracted for a single cycle of loading-unloading. It can be seen that the loading and unloading paths are different, thus resulting in hysteresis in response. The energy stored during the hysteresis response causes cracking of the specimen underneath the indenter once the critical energy level is reached. Figure 4 presents the graph of hysteresis area (expressed in terms of kN-mm) as a function of the number of cycles of loading. It can be seen that there is a perturbance in hysteresis area and the maximum perturbance is seen at approx. 2977 cycles of loading.

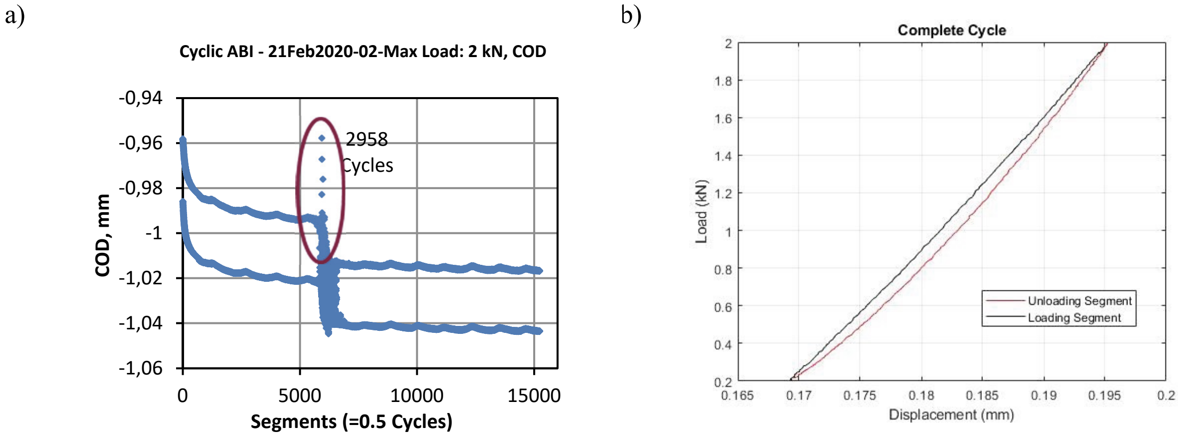

Fig. 3 – (a) COD (displacement near indenter) response as a function of number of cycles of cyclic ABI loading; (b) Load-COD (displacement near indenter) response for a single cycle of cyclic ABI loading; Specimen ID: IN617-21Feb2020-02, tested at a maximum compression load of 2 kN.

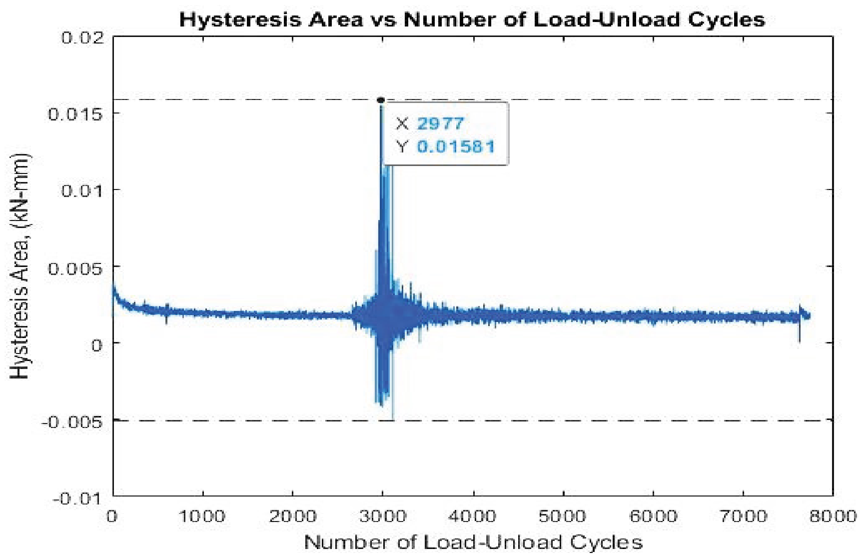

Fig. 4 – Hysteresis area as a function of cycles of loading – area calculated from individual cycle hysteresis loops (as shown in Fig. 3(b)). Perturbance in hysteresis area is indicative of failure due to fatigue cycling. Material: IN 617 alloy.

Figure 5(a) presents the cumulative acoustic count vs. time for the same specimen whose data was acquired online. It can be seen that the data shows a step response and the steep increase in cumulative count can be seen at approx. 2950 cycles. Figure 5(b) shows the cumulative absolute energy graph for the same specimen. A step response in cumulative absolute energy with the maximum change at approx. 2950 cycles was noticed. To identify clearly the AE sensor response for the peak variation due to cracking underneath the specimen indenter, the first derivate (dc/dN) was estimated and the same plotted as a function of cycles of loading (Fig. 6). The derivative response clearly identifies the cycles at which the fatigue failure took place. Since this is an experiment conducted under compression-compression cycling, physical growth of crack cannot be expected, like in the case of plates/panels subjected to tension-tension fatigue loading. So it would be appropriate to assume this AE event to be due to crack initiation under compression-compression cycling.

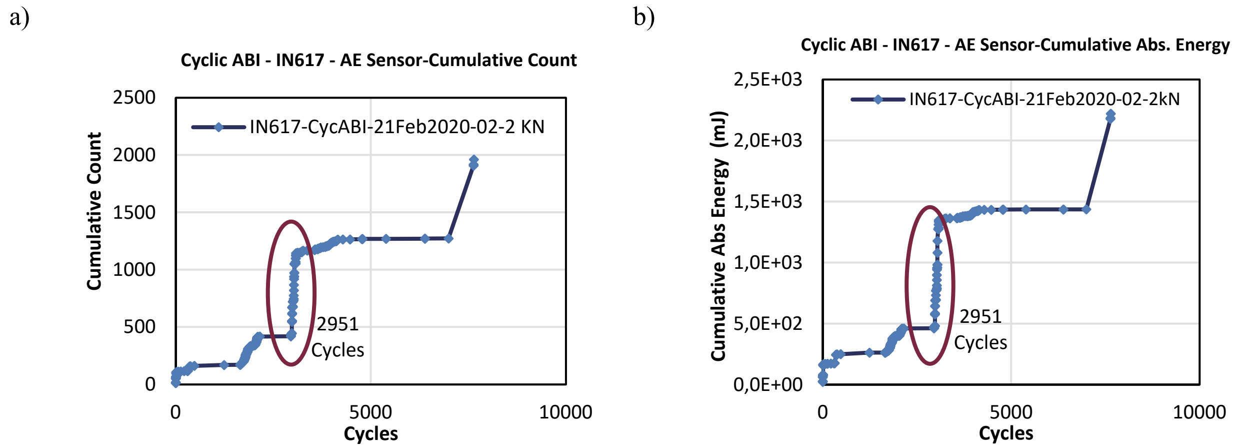

Fig. 5- a) Cumulative count of acoustic signal vs. time for IN 617 alloy specimen during cyclic ABI loading, b) cumulative absolute energy vs time for same specimen. Oval circle indicates the point for maximum change in activity

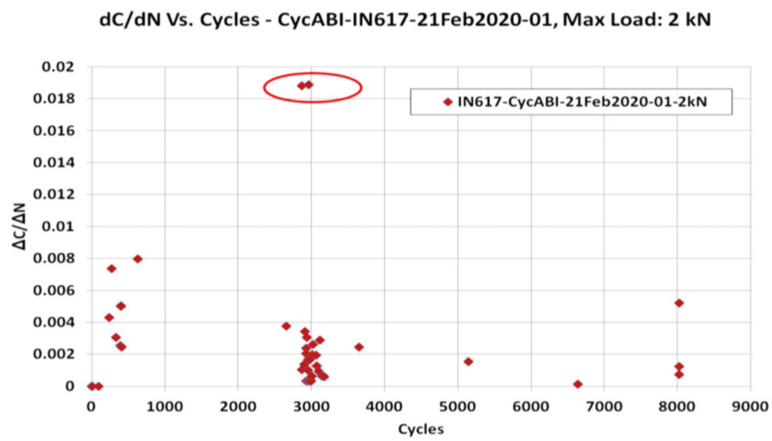

Fig. 6 – First derivative (dc/dN) of acoustic emission counts as a function of cycles to identify the highest change in AE signal response for failure detection.

The failure life data from various cyclic ABI test is compiled and the same is presented in Table 2. It can be seen that in general, there is a good correlation between different experimental methods like AET, hysteresis area and displacement based sensing. Deviations noted in terms of AE response, esp., the ones where the failure has been identified much after the failure identification by the hysteresis area method or COD response method could be due to the positioning of AE sensor with respect to the indentation location and/or crack direction underneath the spherical indenter. These aspects need re-examination and additional experimentation to confirm the findings.

The failure data for selected load ranges is plotted as shown in Fig. 7. It can be seen that this data is similar to the Coffin-Manson plot of fatigue life. Maximum principal stresses or maximum principal strains during cyclic ABI can be estimated using numerical simulations and the same can be used to replot the data to reflect stress vs cycles to failure or strain vs cycles to failure. The test data presented here pertains to a pristine material of Inconel alloy. The applicability of cyclic ABI test method for fatigue life curve has been demonstrated earlier for base metal and weld regions of a stainless steel through an earlier study [Prakash et al, 2018]. Further, the development of slip bands and sub-surface cracks during cyclic ABI is also established through an earlier study on stainless steel SS 304 (Fig 8). In summary, the cyclic ABI test method is capable of estimating the fatigue failure life response of metallic materials in pristine form or in-service condition.

Table 2 – Fatigue failure life data estimated from cyclic indentation studies on IN 617.

Specimen/Test ID	Max. Compression Load (N)	Failure life from AE sensor	Failure life from COD response	Failure life from Hysteresis area
15-Feb-2020-01	1250	2466	2455	2533
15-Feb-2020-02	1250	2455	2533	2455
19-Feb-2020-02	1250	3374	3405	3405
19-Feb-2020-01	2000	2197	1964	1972
21-Feb-2020-01	2000	2870	2866	2901
21-Feb-2020-02	2000	2954	2958	2977
20-Feb-2020-01	2250	1729	2065	2082

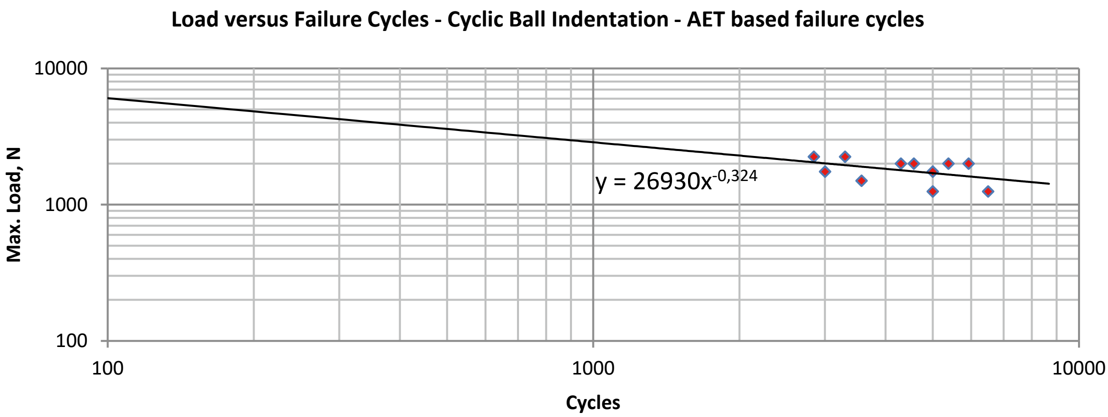

Fig. 7 – Failure life data for IN 617 identified through AE sensor during testing by cyclic ball indentation test method.

a) b)

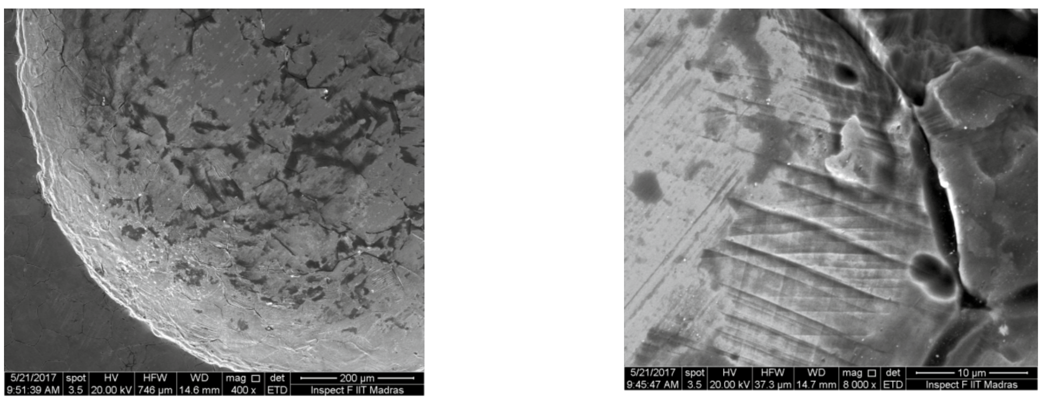

Fig. 8 – SEM images of indentation area which suggests a) presence of slip bands as well as b) secondary cracks.

4. Summary and Conclusions

This paper presented the overview of cyclic indentation test method to evaluate the fatigue failure life of metallic materials. As part of the cyclic ABI testing, two different measurement methods were employed – viz., load-displacement measurement, and acoustic emission measurement. Four different data analysis methods were considered: displacement vs. cycles; hysteresis area during a cycle of loading vs cycles; cumulative count vs. cycles and its first derivative and cumulative absolute energy vs. cycles. Based on the results, it is inferred that a good correlation exists between failure cycles identified by the two experimental methods and associated data analysis techniques. Acoustic emission sensing provides good on-line failure detection, which is preferable compared to post-test data analysis technique like hysteresis area or displacement response. The accuracy of failure cycle identification depends on the location of mounting of AE sensor and care has to be exercised in this regard.

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