Acoustic Emission Signal Analysis to Study the Yield Behaviour of AA2219 Aluminium Alloy Material

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Abstract

AA2219 aluminum alloy is widely used for aerospace applications due to its good strength at high temperature as well as cryogenic temperatures. It is used for the fabrication of launch vehicle components such as propellant tanks, engine casings & structural components like heat shield and interstages. Acoustic emission (AE) is widely used in the aerospace industry for the real-time structural integrity evaluation of pressure vessels and structures made of AA2219 alloys. Since AE is a material dependant phenomenon an acceptable criteria based on the characteristics of AE signals corresponding to various source mechanisms in parent metal and weldments of 2219 material is used for the assessment of the pressure vessels made of that material. The weld regions of metallic pressure vessels are more critical in view of the possible failure due to defect growth under loading. More than 80% of energy expended on fracture in 2219 alloy material goes to development of plastic deformation. Hence the AE signature corresponding to the plastic deformation of the material is studied through the testing of Plain and welded tensile specimens. The major challenge for the signature analysis of specimen is the discrimination of genuine AE signals corresponding to yielding from noise signals due to the machine operation and also the rubbing of the specimen in the grips of the UTM machine. Various signal analysis methods are used for this and the process is very involved. An effective method to segregate the signals from the gauge length of the specimen from those from the rest of the regions is by extraction of located events in the gauge length region using a linear array mode is discussed in this paper. This paper gives the methodology used for the analysis carried out on AA2219 Aluminium alloy tensile specimen test data for the discrimination of noise signals and the characterization of the yield behaviour of the material from the genuine AE data in detail.

Keywords: Acoustic Emission (AE) technique, Structural Integrity, AA2219 Aluminium Alloy, Tensile Specimen

Introduction

Acoustic emission (AE) is a phenomenon in which elastic or stress waves are emitted from rapid, localized change of strain energy in material. The practical application of the AE first emerged in the 1950's, through the research work of Joseph Kaiser (Germany). The result from his investigation was the observation of the irreversibility phenomenon that now bears his name, the Kaiser effect as shown in Fig.1, which is absence of AE during repeat loading up to the previous maximum load [1]. In case of composites “Felicity ratio” is applicable, which is the
ratio of the load at which AE starts during repeat load cycle to the previous maximum load. In 1957 after performing extensive laboratory studies, Clement A. Tatro, suggested to use AE as an NDT method [1]. Currently AE has become one of the most important non-destructive testing techniques, which is widely applied for fatigue crack detection and location in pressure vessels and pipelines, partial discharge sources detection and location in power transformers and rotating machinery, damage assessment in fiber-reinforced polymer-matrix composites, monitoring welding applications and corrosion processes, on-line monitoring of civil-engineering structures etc [2]. The sensors used for this technique are piezoelectric sensors, with elements made of special ceramic elements like lead zirconate titanate (PZT). Mechanical strain of a piezo element generates an electric signal [3].

Due to the desirable aerospace properties like good specific strength, high ductility, formability and corrosion resistance, heat treatable aluminum alloy AA2219, with 5.8-6.8% copper as the main alloying element is widely used for the fabrication of launch vehicle components such as propellant tanks, engine casings & structural components like heat shield and interstages [4]. Acoustic emission (AE) is widely used in the aerospace industry for the real time structural integrity evaluation of pressure vessels and structures due to its great potential in locating and characterizing the flaws and evaluating their severity in real time during the loading [5]. Pressure vessels are evaluated through AE based on an acceptance criteria evolved from the characteristics of the AE signal parameters during various failure modes. This led to an increased emphasis on the study of the failure modes of the material. The most probable and most expected failure mode of the AA2219 hardware is the yield failure. As apart of the criteria development, experiments were carried out on AA2219 plain and welded tensile test specimens to determine the AE signature corresponding to pre and post yield phases of the parent metal and weldments. Specimen test results were corroborated with a subscale AA2219 tank burst test data for validation and thereby evolve an online AE criterion [5]. In the post yield conditions of plain specimens, the reduction in AE activity with lesser magnitude in AE parameters has been observed as per the fundamental AE theory [6]. Acceptable limits of the AE parameters viz. amplitude, duration and energy are shown in Fig.2. has been evolved for the evaluation of 2219 pressure vessels. This report brings out the methodology adopted for the AE data analysis and the AE response of AA2219 plain and welded tensile specimens with respect to yield.

**Theory**

The macroscopic sources of AE in metal are crack jumps, plastic deformation developments, fracturing and de-bonding of hard inclusions as shown in Fig.3 [2]. The microscopic sources include the dislocation movement, interaction, annihilation, slip formation and voids nucleation.
More than 80% of energy expended on fracture in common industrial metals goes to development of plastic deformation. Plastic deformation development is accompanied by the motion of a large numbers of dislocations shown in Fig.4. The process by which plastic deformation is produced by dislocation motions is called slip [2]. The motion of a single vacancy and a single dislocation emits a signal of about 0.01-0.05eV. Cracks, inclusions and other discontinuities in materials concentrate stresses. At the crack tip stresses can exceed yield stress level causing plastic deformation development. Being a highly sensitive technique, AE is capable to capture these micro level changes occur in the material. The variation in the magnitude of the fundamental AE parameters of amplitude, duration and energy during the pre and post yield condition of the tensile specimen show how sensitive the technique is for capturing the micro level changes in the material. The load vs extension curve obtained during the test is used to obtain the yield point of the specimen. Evaluation of the magnitudes of these parameters gives the AE signature corresponding to the yielding of the material.

In a typical tensile test one tries to induce uniform extension of the gauge section of a tensile specimen. The gauge section of the tensile specimen is normally of uniform rectangular cross-section. The two ends of the specimen are used for fixing into the grips as shown in Fig.5, through which the load is applied. The load in the gauge section is the same as the load applied by the grips. Two acoustic emission sensors were fixed on the gauge length of the specimen for an equal distance from the centre of the specimen. The acoustic emission data acquired during the tensile testing is the combination of genuine AE signal generated due to the plastic deformation of the material and the noise signals generated due to the rubbing of the specimen in the grips of the machine and the machine noises due to operation. The primary operation in the data analysis is the segregation of genuine AE signals corresponding to yielding from the noise signals. For this the emissions from all sources away from the gauge length of the specimen is to be removed. An effective method to segregate the signals from the gauge length of the specimen from those from the rest of the regions is by extraction of located events in the gauge length region using a linear array mode.

Location is the process of collecting incoming hits into events and analyzing the arrival times of the hits in an event to compute source location. The fundamental basis for the location is just the time-distance implied by the velocity of the acoustic wave. Linear location is a time difference method commonly used to locate AE source on linear structures. The linear location uses two hits and the time difference in their arrival times to calculate the source location using linear interpolation of the coordinates for the two sensors. Linear location only forms events between
adjacent sensors, so there are only two possible second hit sensors for any first hit sensor. When there are hits on both, it decides which hit to be used based on the ratio of the $\Delta t$ value of the hit divided by the maximum $\Delta t$ calculated from the sensor spacing and the user entered velocity [7]. If two sensors are placed at a known distance of $D$ as shown in Fig.6, then the source location of the event can be calculated based on the equation given below [2].

$$d = \frac{1}{2} \left( D - \Delta T \cdot V \right)$$

$d =$ distance from first hit sensor
$D =$ distance between sensors
$V =$ wave velocity

The factors which control the event formation are mainly the event lockout value and effective wave velocity. The event lockout value is the physical length between the first and the last hit sensor of an event. If the event lockout value is the distance between two sensors, then all the AE bursts captured by both the sensors will be formed as an event. So the best way to avoid the source events from outside the array is to use lockout value lesser than the distance between two sensors. The same principle is used to remove the data corresponding to noise from the grips and other extraneous sources during the tensile specimen test. The material velocity is calculated based on the arrival time of hits in pencil lead break calibration. The source location of the pencil break is to be verified before the final data segregation. The attenuation between the two sensors was found to be less than 5dB, which assures all the AE bursts with an amplitude range of 35dB is recorded with the threshold of 30dB applied during the test.

**Experiment**

The material for specimens was in T-87 heat treatment condition. The specimens are rectangular in cross section (15x7.5mm) as shown in Fig.7 and the dimensions of the specimens are generated in view of the capacity of the testing machine and ASTM guidelines. The specimens were fabricated in-house at RFF/VSSC. The tensile tests were conducted at an in-house facility of HPDD/VSSC using a Lloyd make universal testing machine which is having a maximum capacity of 100 kN. Loads were applied in axially. The maximum cross head movement of the machine is 1.2metres and is controlled with stepper motor. The rate of cross head movement controlled at 0.5mm/minute was used for testing.
A pair of single ended AE sensor model R15 having 150kHz resonant frequency was used for the test. Highly viscous ultrasonic couplant was used to acoustically couple the sensor to the specimen. PAC 1220A type pre-amplifier (20-1200kHz bandwidth) was used for amplification. The preamplifiers are connected to the DAC through RG-58 Belden make co-axial cables. PAC Disp AE win system has been employed to monitor the AE data during the tensile testing. The sensors were mounted 25mm away from the centre of the specimen. The threshold applied was 30dB during the test. The sensors were calibrated through Hsu-Neilsen pencil lead break [5] and the attenuation between the sensors was estimated. The wave velocity of the material was calculated from the calibration data based on the difference in time of arrival and distance between sensors.

Results & Discussions

The sensors are showing an attenuation of maximum 1dB during the pencil break calibration on plain specimen. The $\Delta t$ is found to be 9µsec. The wave velocity in the material is estimated as 6200m/sec. Acoustic emission data acquired during the tensile testing of plain specimen is shown in Fig.8. A total of 3007 hits were recorded by the system which was formed by putting a lockout value of 60mm as shown in Fig.10a. Amplitude vs sensor position plot of the total events formed are shown in Fig.10b. These events are the combination of all genuine AE burst and some events from outside the array. During the test, the sample failed at the centre at a load of 1530kN. The Amplitude vs sensor position plot of the source events formed at the centre of the specimen for a distance of 30mm is shown in Fig.9. These events are formed by putting lockout value of 45mm. These events represent the genuine AE from the material during elasto-plastic deformations and final rupture. Total 113 source events were segregated which include 226 individual AE hits.

Fig.8. AE data acquired from a Plain AA2219 Tensile Specimen

Fig.9. Source events and hits for 15mm on either side of failure.
Acoustic emission data acquired during the tensile testing of the welded 2219 specimen is shown in Fig.10. Total 7608 hits were recorded by the system. Similar filtration has been carried out on the data and the events corresponding to the failure region has been segregated. Total 1212 source events were segregated which include 2424 individual AE hits.

The load curve of the plain tensile specimen combined with the amplitude vs time plot is shown in Fig.11. The curve is linear upto 80% of ultimate load. The load is increasing non-linearly beyond that and then decreases beyond the ultimate load. This shows that the plastic deformation of the specimen is initiated around 80% of ultimate load. The figure shows, before reaching the yield point not much acoustic emission signals are emitted from the specimen. This indicates that the acoustic emissions in the elastic range are of low energy content having amplitude below the threshold value of 30dB. AE signals with amplitude above 30dB are emitted from the specimen at the initiation of plastic yielding and gradually the amplitude increases and reaches to a maximum value. Then a declining trend is seen in the number of emissions and the amplitude levels and it goes below 30dB beyond the ultimate load. The load curve and the load vs time combined with the amplitude vs time plots of welded tensile specimen are shown in Figs.12 & 13.
In the case of welded specimen the non linearity of the curve started around 70% of the failure load, showing the initiation of elasto-plastic deformation. The decreasing trend is not seen in the curve like plain specimen. AE signals with 65dB amplitude were detected from the specimen around 30% of failure load. This indicates that the welded specimens are emitting signals even in the elastic deformation phase at the heat affected regions near to the weldments. The rate of acoustic emission signals are increasing beyond the yield point upto the failure time. Before failure a rapid change in the acoustic emission parameters are observed.

The cumulative plots of duration and energy of plain and welded specimen are shown in Fig.14. For the plain specimen the curve became saturated when the load reached the ultimate load while in the case of welded specimen increasing trend is observed. This shows that there is no detectable AE after the ultimate load in case of plain specimen but there is an increase in the magnitude of AE parameters in the case of welded specimens.

The behavior of AE parameters amplitude, duration and energy from plain and welded specimens with respect to time is shown in Fig.15. No detectable level AE was observed in the elastic regime of plain specimen but from the welded specimen, signals with 65dB amplitude, 1500μsec duration and energy upto 20 has been observed. Beyond the yield point the plain
specimen emitted AE signals with amplitude less than 40dB, duration <100 µseconds and energy less than 10. An increasing trend in AE parameters was seen further and reached a maximum value of amplitude 46 dB and duration 500 µseconds before starting to decrease. Around 10 seconds before rupture, AE started again and the parameters suddenly went up and the specimen failed. At the time of failure, the amplitude went to 100dB, duration became 90000µsec and energy was 40000. In welded specimens the rate of acoustic emission signals are increasing beyond the yield point upto the failure time. Before failure a rapid change in the acoustic emission parameters are observed. The comparisons of AE parameters recorded by plain and welded specimen are shown in Fig.16.

Total four numbers of plain and welded specimens were tested. The results show a good match. A combined table showing the AE parameters of all the tested plain and welded specimens during pre and post yield conditions are given in Table.1.

<table>
<thead>
<tr>
<th>Spn No.</th>
<th>Plain Specimen</th>
<th>Welded Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Yield</td>
<td>After yield</td>
</tr>
<tr>
<td></td>
<td>Amp (dB)</td>
<td>Dur (µsec) Enr</td>
</tr>
<tr>
<td>1</td>
<td>35dB 300 1</td>
<td>30-45 0-400 10</td>
</tr>
<tr>
<td>2</td>
<td>No hits No hits No hits</td>
<td>30-46 0-500 20</td>
</tr>
<tr>
<td>3</td>
<td>37 300 1</td>
<td>30-40 0-200 5</td>
</tr>
<tr>
<td>4</td>
<td>No hits No hits No hits</td>
<td>30-54 0-250 15</td>
</tr>
<tr>
<td>5</td>
<td>No hits No hits No hits</td>
<td>30-54 0-400 15</td>
</tr>
</tbody>
</table>

Table.1

For plain specimen, the average parametric values after yield are Amplitude 50dB, duration 350 µseconds and energy 15. In the welded specimens the average parametric values before yield are Amplitude 71dB, duration 1150 µseconds and energy 15 and after yield are Amplitude 63 dB, duration 1500 µseconds and energy 8.
Conclusion

The acoustic emission behaviour of AA2219 Aluminium alloy material under loading is studied. The material emits detectable level of Acoustic emission signals during elastic to plastic deformation phase. The magnitude of the fundamental AE parameters under yielding on the parent metal and near to the weldments is evaluated through the study. The corroboration of this data with a subscale AA2219 chamber burst test data can be utilised for evolving the acceptance criteria for the real time monitoring of AA2219 tanks.

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