Sensing and clustering analysis of acoustic emission due to crack rubbing/clapping in fatigue-cracked thin metal sheets
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ABSTRACT
Fatigue cracks in metallic structures can cause catastrophic failure to the structure if it is not detected during its early stage. Rubbing and clapping of crack faying surfaces are a potential source for acoustic emission (AE) signals. The vibration of fatigue cracked sheet metal samples were used to induce rubbing and clapping of crack faying surfaces to generate AE signals. The AE signals generated were captured by multiple piezoelectric wafer active sensors (PWAS) bonded to the sheet metal sample in a linear configuration, and source localization was performed to confirm the origin of the AE signals. In some practical cases, the structure would be subjected to external loading while undergoing crack rubbing and AE generation. The sheet metal sample was first axially loaded, then rubbing/clapping was induced through the vibration of the specimen and AE signals were recorded to study the influence of external loading on the AE signals. A large number of AE signals was captured through various cases of AE experiments. To understand the consistency or similarity of the signals, it is necessary to perform a statistical analysis of these AE signals. Pearson correlation was performed for all AE signals in the time domain as well as in the frequency domain to understand the similarity of AE signals. A 2D plot of time domain as well as frequency domain correlation was obtained to depict the similarity in the AE signals.

Keywords: Acoustic emission, AE signal processing, Crack rubbing AE, Correlation of AE signals

1 INTRODUCTION
Acoustic emissions (AEs) are the stress waves produced by the sudden internal stress redistribution of the materials caused by the change in internal structure possibly due to crack initiation and growth, dislocation movement, twinning, phase transformation in monolithic materials, fiber breakage, fiber-matrix deboning in composites, etc.[1]. AE signal characteristic is strongly influenced by the source mechanism of the AE. The mechanism of the source is significantly influenced by the composition of the material[2]–[5]. Many researchers studied AE due to various kinds of sources. Wang et al.[6] performed acoustic emission due to rubbing in a rotor-bearing and source localization. Acoustic emission due to progressive damage in a polymer-based composite[7] as well as clustering of AE signals obtained from failure on carbon fiber reinforced plastic (CFRP) specimens was studied[8]. Acoustic emission during various fracture activities was studied to relate the fracture and AE signals [9].

Acoustic emission during fatigue a crack growth event attracted many researchers. The detection of fatigue crack growth can prevent catastrophic failure of structures. Many researchers have studied the AE due to fatigue crack growth[10]–[13]. Zhang et al.[14] studied the acoustic emission signatures of fatigue damages in an idealized bevel gear spline and identified two different AE signal signatures for plastic deformation and crack jump. Bhuiyan et al. [15]–[17] studied the AE signal signatures recorded by PWAS sensors during a fatigue crack growth experiment. Roberts and Talebzadeh [10] discussed the correlation between acoustic emission count rates and crack propagation rates.

The AE signals are generated when a crack growth in metallic structures occurs and several studies have been reported on this, similar to the works presented in the previous paragraph. It
is not obvious that the crack will be always growing and producing the AE signals. If the fatigue loading on the structure is not enough for the crack advancement, the crack may not grow. But, any kind of vibration or fatigue loads which do not cause any crack propagation can produce AE signals when the crack surfaces rub and clap each other. No research works have been reported yet to study the signals generated due to rubbing and clapping of crack faying surfaces of thin metallic plates. This paper discusses AE signal signatures when the faying surfaces of crack rub and clap each other.

The organization of the paper is as follows. Section 2 discusses the experimental setup and methods. The experimental set up for generating the fatigue crack in a 1-mm aluminum plate and the experimental set up for measuring AE signals due to rubbing and clapping of crack faying surfaces are explained in this section. In section 3, the results of Finite Element Method (FEM) analysis of the specimen, as well as the AE signal signatures due to rubbing and clapping of crack faying surface, have been discussed. The paper ends with a summary, conclusions, and future work.

2 EXPERIMENTAL SET-UP AND METHODS

2.1 Experimental setups

Aluminum 2024-T3 specimen was chosen for manufacturing the test specimen material. The material properties of the specimen were 73 GPa modulus of elasticity, 2767 kg/m3 density, and 0.33 Poisson’s ratio. The aluminum coupons manufactured had dimensions 103 mm width, 305 mm length and 1 mm thickness. A 1 mm hole was drilled at the geometric center of the specimen for initiating the fatigue crack. The hole would cause stress concentration at the edges of the hole, and the crack initiation would happen at the hole. Fatigue loading was applied to the specimen to generate the pre-crack. For the pre-crack generation fatigue loading from 22 kN to 2.2 kN at a frequency of 4 Hz was applied. Crack initiation started at approximately 40,600 cycles. The crack grew 20 mm in 400 cycles. After generating the crack in the specimen, four PWAS sensors were bonded on the specimen (Figure 3). One PWAS was bonded very close to the crack at a distance of 6 mm from the crack. This PWAS was bonded at such a close distance so that it can pick up even the weak AE signals originating from the crack. Two other PWAS were bonded at 25 mm distance from the crack in opposite directions, and another PWAS was bonded at 50 mm from the crack. The PWAS bonding configuration, the time of arrival, and amplitude of the signals reaching these PWAS would confirm the AE signal source and geometric spreading of the AE signals.

The experimental setup for generating crack rubbing and clapping in the specimen is presented in Figure 2. For AE generation due to crack rubbing, the fatigue crack grown plate specimen was mounted on a shaker. Continuous sinusoidal excitation was given to the specimen at various frequencies through the shaker. The vibration of the specimen causes the faying surfaces of the crack to rub/clap each other. This rubbing and clapping produce acoustic emission signals.
Figure 1 The specimen with hole mounted on the MTS machine for the generation of crack. Cyclic fatigue loading was applied to generate crack from the hole.

Figure 2 The experimental set up for generation of vibration-induced crack rubbing/clapping AE signals. The sinusoidal excitation for vibrating the specimen was generated by function generator. Sufficient power for the vibrating the specimen using vibration...
exciter was obtained from the power amplifier. Vibration generated AE signals were captured by using the Mistras AE system.

Figure 3 AE measurement test setup in the test cell. Vibration motion is applied to the specimen in the test cell through a shaker. AE signals collected through PWAS bonded to the specimen was passed through pre-amplifier and recorded using Mistras AE system.

For the generation of continuous vibration, a function generator was used. For obtaining sufficient voltage of excitation, the signal is amplified using a power amplifier. The amplified sinusoidal signals are fed to a vibration exciter.

The shaker vibrates the plate in the out-of-plane direction causing rubbing/clapping of crack faying surfaces and generation of AE signal due to the rubbing/clapping. The PWAS installed on the
specimen sensed AE hits. Four identical preamplifiers with a built-in bandpass filter (30-700 kHz) were connected to the sensors. The preamplifier is connected to Mistras AE system. A sampling frequency of 10 MHz was chosen to capture any high-frequency AE signals. AE hits at plate resonance were captured and analyzed. At plate resonances, the possibility of crack rubbing, as well as the threshold of AE signals, are higher, which makes it suitable for AE signal collection and analysis.

In some cases, the cracked specimen may be subjected to external loading. In such cases, the crack would be in an open position. Still, the crack rubbing at the crack tips may induce AE signals. AE signal characteristics in such circumstances need to be studied. A test cell test setup for simultaneously providing axial load and vibrating the specimen was manufactured in house. In Figure 3, a schematic of the setup of the test cell and its important features for mounting AE test specimen and providing axial load is presented. The test cell can arrest two edges of the specimen securely and load the specimen axially through spring loading. The specimen was connected to the spring through a turnbuckle as presented in Figure 3. By using the loading bars, the turnbuckle was turned. Turning the turnbuckle caused extension of the springs and provides the corresponding load to the specimen. The load can be calculated from the spring deflection and the spring constant of the spring. The spring deflection was measured from a knob provided at the spring plate by monitoring its displacement through a measuring scale. After loading the specimen to a specific load, vibration motion was given to the specimen through the shaker attached to it. The AE instrumentation for recording the AE signals is also presented in Figure 3. The AE signals generated by crack rubbing and clapping of the loaded specimen were recorded using a PWAS located 6 mm away from the crack. The signals were fed to the acoustic pre-amplifier with a built-in bandpass filter (30-700 kHz) and then fed to Mistras AE instrument. Recorded AE signals were post-processed and analyzed.

2.2 Pearson correlation coefficient (PCC) of two signals

A large number of AE signals are generated due to rubbing and clapping of crack faying surfaces. Pearson correlation analysis was performed to compare the large number of AE signals. The correlation coefficients of two-time series/frequency series data are calculated using the following PCC expression.

\[
\rho(A, B) = \frac{1}{N-1} \sum_{i=1}^{N} \left( \frac{A_i - \mu_A}{\sigma_A} \right) \left( \frac{B_i - \mu_B}{\sigma_B} \right)
\]

(1)

Where, \(A\) = time domain signal \(A\), \(B\) = time domain signal \(B\), \(\mu_A\) = mean of signal \(A\), \(\mu_B\) = mean of signal \(B\), \(\sigma_A\) = standard deviation of signal \(A\), and \(\sigma_B\) = standard deviation of signal \(B\). Two separate correlation coefficients were calculated, using time domain as well as frequency domain data. 2D scatter plots of time domain PCC vs. frequency domain PCC were constructed.

3 RESULTS AND DISCUSSION

For generating strong AE signals during rubbing and clapping of crack surfaces, there must be active interaction between the crack faying surfaces. The resonant frequencies of specimen vibration are appropriate for the generation of strong displacements in the specimens, which can cause active interaction between the crack faying surfaces. FEM modal analysis of the cracked specimen was performed to find out the resonant frequencies of the specimen. The specimen modeled and boundary conditions imposed to the specimen for performing FEM modal analysis are presented in Figure 4. The fixed boundary condition is applied at the support hole of the
specimen which was used to connect the shaker attachment to the specimen by arresting all degrees of freedom. From FEM analysis, the first five resonance frequencies of the specimen were recognized as 28.2, 37.8, 93.1, 112.3 and 188.4 Hz respectively. It was presumed and observed that this resonant frequencies and corresponding strong displacement causes strong crack faying surface motions which generated strong AE signal. We observed strong AE signal generation at 35 Hz and 180 Hz frequency of vibration of the specimen.

Vibration excitation was given to the specimen at 35 Hz by using a shaker, and the vibration induced the crack faying surface rubbing and clapping. The induced rubbing and clapping of the crack faying surfaces cause the excitation and propagation of AE signals in the specimen. The signals were sensed using PWAS sensors bonded 6-mm from the crack. The PWAS sensed AE signals were recorded using the Mistras AE system. A large number of AE signals were recorded during a short period of time. The signals collected were used to perform a correlation analysis by choosing a particular signal as the basis signal. The correlation analysis shows that the signals are similar. The correlation of AE signals and one typical AE signal collected is presented in Figure 5a and Figure 5b. The AE signal signature is observed to be wideband. Peaks in the frequency spectrum were observed at 100 kHz. At frequency spectrum between 300- 400 kHz, a peak in the frequency spectrum by gradual increment and decrement was also observed. The differences in signals are due to the uncertainty in AE source characteristic at the crack faying surfaces corresponding to various events. The minor difference in AE signal infers that, even though there is uncertainty in AE source characteristic which generates the AE signals, the source characteristics are within a tolerance limit.
To study the effect of the frequency of vibration of the specimen on the AE signal, another frequency of vibration of the specimen was also considered. AE signals received by PWAS when the plate is vibrated at 180 Hz frequency is presented in Figure 5c and Figure 5d. We observe that the frequency spectrum of the AE signals is wideband frequency spectra. At 180 Hz vibration of the specimen, a peak frequency of the AE signal spectra approximately at 100 kHz was observed similar to AE signal recorded at 35 Hz vibration. A gradual increase and decrease of frequency spectrum between 300-400 kHz were also observed. AE signals were observed to have a similar signature.

![Graphs](image)

Figure 5 AE signals generated due to vibration of specimen at various frequencies a) Correlation of AE signals generated due to the 35 Hz specimen vibration induced crack rubbing/clapping b) Sample AE signal at 35 Hz vibration c) Correlation of AE signals 180 Hz d) Sample AE signal at 180 Hz vibration
The crack faying surfaces formed during the fatigue experiment are very rough in texture with sharp peaks and valleys. The vibration of the specimen causes the sharp peaks and valleys of the crack faying surfaces to hit each other and generate AE signals. Hence the AE signal generation source can be considered as a point force excitation source or a point source. AE signals are generated by rubbing of crack faying surfaces at a point. Even at different frequencies the source characteristic or the mechanism of ultrasonic AE signal generation may remain the same since it is a point source excitation. Hence theoretically, it is not very likely that the AE signal signature may differ at different vibration exciter frequencies. A comparison of the AE signal signature at 35 Hz vibration and 180 Hz vibration can be observed from Figure 5b and Figure 5d. Clear similarities in AE signals and signal frequency spectrums are observed in the figure. The AE signal rise time, as well as the duration of the signal, are observed as approximately the same. Frequency spectrums of both signals were found to be very similar to broadband nature and to have very similar peaks and valleys.

To study the effect of external load on the rubbing/clapping AE signal signature, the specimen was mounted on the test cell, axially loaded and vibration excitation was applied. An axial load of 5kN is applied to the specimen by loading the specimen by turning the turnbuckle and applying the spring load. Four springs are arranged parallel to each other as presented in Figure 12. The effective spring constant of the springs is 437 N/mm. The spring loading is provided by turning the turnbuckle between the specimen and the spring. The turnbuckle was turned so that the spring deforms 11.5 mm, providing 5 kN load to the specimen. The extension of the spring monitors the effective load through a needle attached near the spring on the spring plate. After loading the specimen, the specimen was vibrated by the vibration exciter. A higher voltage of excitation was required to produce AE signals compared to specimen mounted in the test cell without any load. The AE signals were collected and the correlation of the AE signals is presented in Figure 14. The signals were found comparable to the AE signals obtained with the no-load case as well as the AE signal generated due to the unconstrained specimen vibration case. The signal is observed as wideband in frequency spectra with a higher amplitude at low-frequency range. Signals had a peak in the frequency spectrum at approximately 100 kHz. A peak in the frequency spectrum is observed between 300 kHz and 400 kHz. But the frequency response between 100 to 200 kHz has been reduced. The major frequency content is observed below 100 kHz, similar to the case of unloaded specimen rubbing and clapping AE signals. The signal correlation is found to be stronger compared to the case of no-load. The reason for such a strong correlation is hypothesized as follows. When the specimen is in a loaded condition, the crack will be in an open position. The vibration exciter causes relative motion of crack faying surfaces, but the rubbing between the two surfaces takes place only at the crack tips since all the other location of the crack is in open position. Hence the point source excitation will be happening only at the crack tips, and the excitation will be more consistent compared to the excitation when the crack is in the closed position.
Figure 6 AE signal generated due to the vibration of the specimen under axial tension a) Correlation of AE signals generated due to the vibration induced crack rubbing/clapping b) Sample AE signal at 35 Hz vibration

4 SUMMARY CONCLUSIONS AND FUTURE WORK

4.1 Summary

A fatigue crack in Al 2024-T3 specimen was generated by cyclic fatigue loading. Fatigue loading of 22 kN with an R ratio of 0.1 was applied for the generation of a fatigue crack. The fatigue loading was continued until the tip to tip crack length is 20 mm. FEM harmonic analysis was performed to analyze the resonant frequencies of the cracked specimen. A PWAS sensor was installed on the specimen at a distance of 5-mm from the crack. The specimen was attached to a shaker table, and vibration excitation was applied at the resonant frequencies of the specimen to generate AE signals due to crack rubbing/clapping. The AE signals generated were recorded using the PWAS and Mistras AE system. Correlation analysis was performed on the signals to identify the change in AE signals and variation in the asperity of the AE signal source. AE signals at 35 Hz and 180 Hz specimen vibrations were studied. AE signals in the specimen under load are also studied.

4.2 Conclusions

Resonant frequencies of the specimen are suitable for active rubbing and clapping of the crack faying surfaces. Specimen resonant frequencies do not affect the AE signal signature strongly. Correlation analysis can conveniently quantify the difference in a large number of AE signals. The difference in AE signal signature would correspond to the difference in the AE source characteristics. Close clustering of AE signals is obtained when the vibration AE was generated in an axially loaded specimen. When the crack is in a closed position the rubbing/clapping happens throughout the crack length. This will cause more change in the asperity of the AE signal source as well as AE signal generated from the source. When the crack is in open position, only the crack tips participate in the rubbing/clapping. This will cause less change in asperity of the AE
signal source as well as AE signals generated from the sources, resulting in a close correlation of AE signals.

5 REFERENCES