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Acoustic Emission, A Non-Destructive Technique - An Overview

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Abstract: With increasing number of structures approaching their design life, it became very important for the designers and operators to develop innovative Structural Health Monitoring (SHM) techniques. Structural Health Monitoring (SHM) is the process of monitoring or assessing the condition of a structure in order to gather information on its current state by tracking variables like vibration, strain, stress and other physical phenomena, responses and conditions. It seeks to assist in non-destructive evaluations aimed to detect location and extent of damage, calculate the remaining life of an asset and predict upcoming accidents. Acoustic Emission technique is a passive monitoring approach based on the detection of elastic waves in structural components generated by damages, such as the initiation and propagation of cracks, the failure of steel wires, and the failure of bonds. Its primary goal is to detect, locate, and assess the intensity of damage in a non-invasive way, both when the structure is in-service and during load tests. Its application in SHM (Structural Health Monitoring) started much later compared to other fields, such as the aerospace industry. The interest has increased because elastic waves generated by damages propagate throughout the structure; therefore, it is possible to remotely detect damages in areas that are not easily accessible to visual inspections and direct measurements.
Keywords: Acoustic Emission (AE), Structural Health Monitoring (SHM)

I. INTRODUCTION

Acoustic Emission (AE) has been studied and used over the last seven decades and the science behind acoustic emissions is therefore well established. The technology has been applied to Non-destructive evaluation, material research and Structural Health Monitoring (SHM). Acoustic emission (AE) is applied to a variety of fields related to concrete engineering. With increasing need for maintenance, the non-destructive evaluation of in-service structures is being actively investigated all over the world. Acoustic emissions have become an important tool for instrumentation and monitoring due to the great advances in signal classification, instrumentation, and sensors. Kaiser was the first to use electronic instrumentation to detect audible sounds produced by metals during deformation. He observed that acoustic emission activity was irreversible. In other words, acoustic emissions do not generate during the reloading of a material until the stress level exceeded the previous high load. This irreversibility has become known as "Kaiser's Effect," and it has proved to be very useful in acoustic emission studies. Kaiser also proposed a distinction between burst and continuous emission, where the acoustic emissions are attributed to friction between grains. In recent years, acoustic emission sensors designed for the automated manufacturing environment have been very successful.

Acoustic emissions occur over a wide frequency range, but most often from 100 kHz to 1 MHz. The main benefit of using acoustic emission sensors in monitoring manufacturing processes is that the vibrations of the machine and ambient noises have a much narrower frequency range than does the acoustic emission signal. Thus, the received signal is mostly free of noise unrelated to the cutting process. However, interpretation of the acoustic emission data requires considerable testing experience and background knowledge.

A. Principle

The AE is a phenomenon in which transient elastic waves are generated by the rapid release of strain energy from a localized source due to microstructural changes in the material. Elastic waves travel into the material and move to the surface of a structural element where sensors can detect them. Therefore, an AE monitoring system requires two components: a source, such as crack propagation or a tendon failure; and a transducer, which receives and acquires the elastic wave. Figure 1 shows the working principle of an AE monitoring system [33].

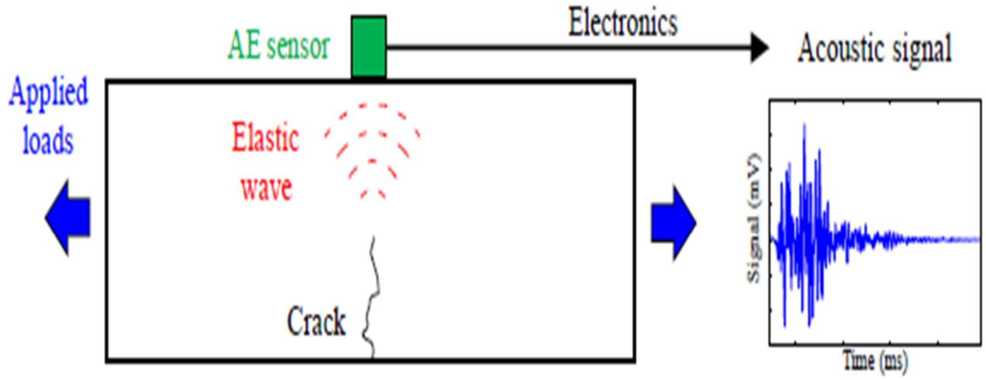

Figure 1. Working principle of an AE monitoring system.

An elastic wave is a combination of longitudinal, transverse, and reflected waves, with a broadband frequency range from kHz to MHz. Even though they are called acoustic emissions, elastic waves are neither acoustic (from 2 kHz to 20 kHz) nor ultrasonic (over 20 kHz).

AE sensors are typically piezoelectric or PZT devices that transform the motion produced by the transient elastic wave into an electrical signal, which is digitized and stored.

The selection of the transducer's sensitivity and frequency response is critical for the effectiveness of the AE technique and depends on the characteristics of the monitored structure.

When an elastic wave reaches the sensor, it is transduced into an electrical signal, recorded, amplified, and typically represented in a diagram with the time expressed in seconds (s) on the horizontal axis and the signal amplitude expressed in volts (V) on the vertical axis.

The signal is usually affected by background and environmental noise due to the wind and passers-by; therefore, the reduction of such noises requires a band-pass filter [33].

B. AE Signal Parameters

The electrical signal identifies an acoustic event, also called a hit, when it crosses a certain threshold, expressed in volts (V) or similarly in decibels (dB). This threshold is defined as the minimum amplitude that the signal must have to be considered in the analysis: typical values for reinforced concrete structures are around 40–45 dB, but sometimes it can be up to 60 dB. Moreover, the signal must cross the threshold at least three times consecutively to be one hit.

A hit can be described by characteristic parameters, which are defined in the time-domain, as represented in Figure 2, or in the frequency-domain, as represented in Figure 3. Here is a summary of the parameters we considered in our analysis.

1) *Amplitude:* It is the maximum amplitude of the signal in the time-domain after its amplification. It is expressed in decibels and V_{ref} = 1 μV from the sensor corresponds to 0 dB.
2) *Duration:* it is the time interval between the first and the last threshold-crossing of a hit.
3) *Count:* it is the number of times that the signal exceeds the threshold within the duration: it strongly depends on the threshold and the sampling frequency.
4) *Signal Strength (Energy):* it is the measured area of the rectified signal envelope (MARSE). Typically, it includes the absolute value of areas of both the positive and negative envelopes. Its unit of measure is Volts × second [V·s], and it is a function of both the amplitude and the duration. It ispreferred over count to interpret the magnitude of the event.
5) *Peak Frequency:* it is the frequency corresponding to the peak observed in the power spectrum resulting from an FFT (Fast Fourier Transformation) of the signal.

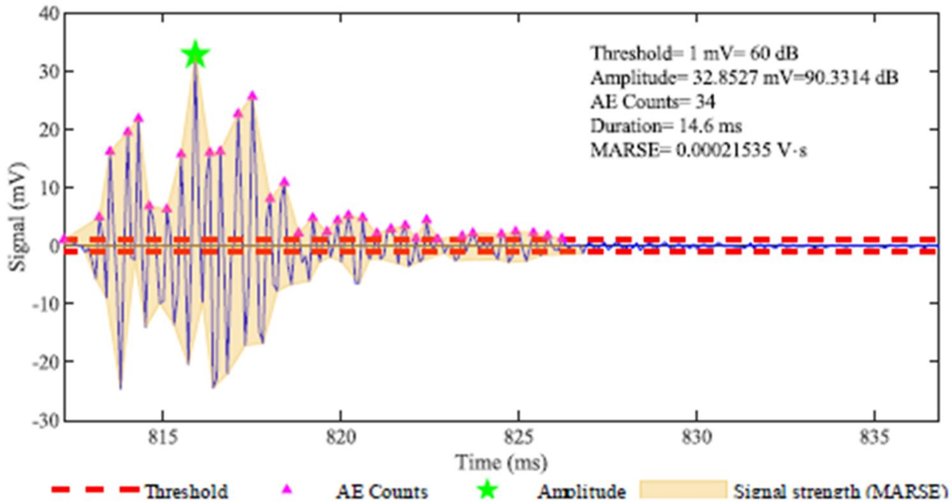

Figure 2. AE signal and parameters expressed in the time-domain.

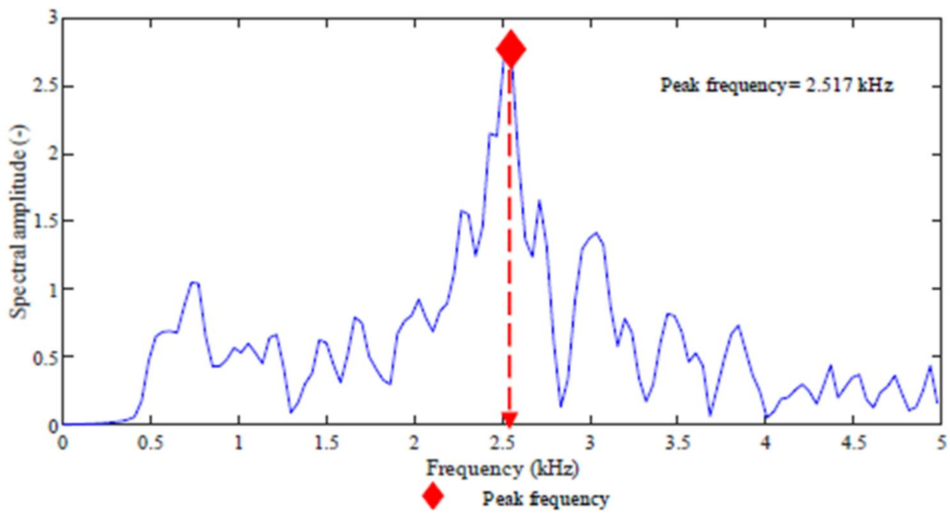

Figure 3. AE signal and parameters expressed in the frequency-domain.

To discriminate different acoustic events, we must select three time-parameters, PDT, HDT, and HLT, represented in Figure 4. Their choice is critical for the correct identification of hits.

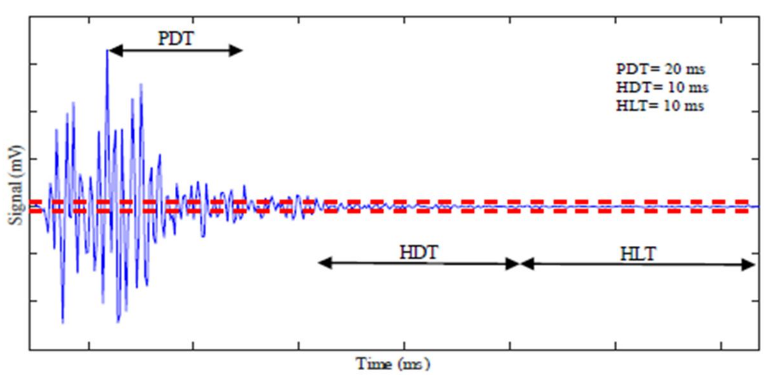

Figure 4. Peak definition time (PDT), hit definition time (HDT), and hit lockout time (HLT). They discriminate one hit from another.

6) *Peak definition time (PDT):* It is the time after the peak amplitude in which a new greater peak amplitude can replace the original one; after the PDT has expired, the original peak-amplitude isnot replaced.
7) *Hit definition time (HDT):* It is the time after the last threshold-crossing that defines the end of the hit.
8) *Hit lockout time (HLT):* It is the time after the HDT during which a threshold-crossing will not trig a new hit. A new hit can start only after the HLT has expired.

C. AE Analysis for Load Tests

A structural element subjected to loading and unloading cycles experiences a propagation of damages and emits acoustic waves only when the previous maximum load level is exceeded. The absence of AE during a loading phase is called the Kaiser effect and happens only with an elastic behavior of the material. In the case of plastic deformations, the Kaiser effect is violated, and acoustic waves are emitted during all the loading phase; this phenomenon is called the Felicity Effect. The Kaiser and the Felicity effects identified during load tests can highlight the presence of flaws or other structural damages and help to assess the integrity of the structural element [33].

II. LITERATURE REVIEW

Non-destructive testing methods and applications have become of increasing interest due to the worldwide aging and deteriorating infrastructure network (Colombo et al. 2003a; Glaser 2004; Grosse et al. 2006; Lovejoy 2006; Ohtsu 1996; Uomoto 1987). In the field of Civil Engineering, bridges and bridge components as well as non-structural elements such as roadway pavements for example, are affected. In particular, the Acoustic Emission (AE) technique offers the unique opportunity to monitor infrastructure components in real-time and detect sudden changes in the integrity of the monitored element (Grosse and Ohtsu 2008).

Commonly, analysis methods of purely qualitative nature are used to estimate the current condition or make predictions on the future state of a monitored component. Using quantitative analysis methods, source locations and characteristics can be deduced, similarly to the case for earthquake sources. If properly configured, crack formation and propagation can hence be quantified with this technique. A detailed review of literature on Acoustic Emission (AE) technique is presented in the detail. In this section we have elaborated the different works being carried out in different countries by the researchers on different materials and structures.

A. Acoustic Emission Applications in Civil Engineering

1) *Bouja, G. Ballivy, B. Benmokrane, Z. Piasta & amp; N. Feknous (1991)* An acoustic emission (AE) technique has been applied as a diagnostic method for grouted rock anchors subjected to uplift loads, in order to characterize their major failure mechanisms. The laboratory tests with limestone consisted of three AE generating mechanisms that included debonding, crack propagation and non-elastic deformation. Signals resulted from extraction of model bars grouted in limestone NX core samples were employed to classify AE time histories. These observations were then extended to bar extraction from 300 x 300 x 100 mm blocks of the same rock. Debonding dominated behaviour and there was an almost complete lack of crack propagation [12].
2) *U. GROSSE, Markus KRÜGER, Steven D. GLASER (2006)* Acoustic emission techniques are an additional monitoring method to investigate the status of a bridge or some of its components. It has the potential to detect defects in terms of cracks propagating during the routine use of structures [10].
3) *Grosse, Christian U.; Ohtsu, Masayasu (Eds.) Nagataki, Fujiwara (2008)* AE techniques draw a great attention to diagnostic applications and in material testing. It can be applied to real large-scale structures as well as the observation of the cracking process in laboratory specimen to study fracture processes [8].
4) *Schumacher,Thomas et al. (2009)* AE sensors were employed to identify vehicles equipped with studded tires passing over bridges. AE systems offer the opportunity for more reliable data on the number of studded tires in operation and the time periods of use on a particular highway. That can be utilized primarily to improve design and maintenance of road surfaces. It was found that this analysis method may assist in estimating the operating load conditions of in-service bridges [7].
5) *Dr. Boris Muravin, Prof. Gregory Muravin, Dr. Ludmila Lezvinsky (2010)* Acoustic emission method uniquely fits to the concept of SHM due to its capabilities to examine, monitor structures and assess structural integrity during their normal operation [11].
6) *Tonelli, D.; Luchetta, M.; Rossi, F.; Migliorino, P.; Zonta, D. (2020)* AE can be used successfully in permanent monitoring of pre-stressed concrete bridges to provide information on the cracking state and maximum load withstand. They can also be used as a non-destructive technique in short-term monitoring to discriminate whether a structural member has pre-existent cracks or not [33].

7) *T.J. Chotard, A. Smith, D. Rotureau, D. Fargeot and C. Gault (2003)* AE technique can be considered as a potentially interesting tool to characterise the early hydration of a cement paste (0–24 h). This ‘‘passive technique’’ allows a continuous and an in-situ monitoring of cement paste setting [45].
8) *M. Seto, M. Utagawa, K. Katsuyama (2002)* In this study the possibilities of acoustic emission (AE) technique was investigated to measure in situ rock stress. At first, they conducted the fundamental works to know how accurately the previous stress can be estimated from AE technique. Next, the technique was applied to the rock cores obtained from drilled boreholes in underground opening. The AE method was suggested to determine in situ rock stress with reasonable accuracy using AE signatures in repeated loadings of a rock core specimen [46].
9) *TOMOKI SHIOTANI and DIMITRIOS G. AGGELIS (2007)* Deteriorated concrete structures are repaired by means of grouting. In order to evaluate the repair effectiveness two NDT techniques namely seismic tomography and acoustic emission are applied. Using traveling time of elastic waves, structural velocity is estimated. AE activity is monitored along with water pressurization of the permeability test. As a result, contrary to the common expectation that the velocity increase after filling with grouting agent, enormous amount of velocity drop was obtained after repair due to the incomplete developing process of grout material, whereas AE activity showed dramatic decrease after repair. Furthermore after comparison of those results to the quantity of grouting material, it became clear that damage indices based on AE activity exhibited well the actual damage of concrete structures [47].
10) *Anastasopoulos, A., Bousias, S., Tsimogiannis, A. and Toutountzakis, T. (2006)* Acoustic Emission (AE) monitoring was performed during Pseudo-Dynamic Testing of a torsionally unbalanced, two-storey, one-by-one bay reinforced concrete frame structure. Real time monitoring of AE activity versus the complex applied load resulted in semi quantitative damage characterization as well as comparative evaluation of the damage evolution of the different size columns. Evolution of the AE energy rate per channel, as revealed from zonal location, and the energy rate of linearly located sources enabled the identification of damage areas and the forecast of crack locations before cracks were visible with naked eye. In addition to that, the results of post processing evaluation allowed for the verification of the witnessed damaged areas and formed the basis for quantitative assessment of damage criticality [48].
11) *Elizarov, S. V., Alyakritsky, A. L. and Sagaidak, A.I. (2006)* Appearance and growth of cracks in the concrete structures are estimated by occurrence of AE events. Frequency characteristics of AE events can depend on the cracks size and deformation volume. The cracks growth affects AE frequency spectra features, shifting them toward the lower values. The obtained effect is of some importance for justified selection of frequency interval to register AE caused by any defects of definite size in the concrete members and structures [49].

B. *Acoustic Emission Applications in Automobile Industries*

1) *Peyman KABIRI Hamid GHADERI (2011)* Uses AE signal analysis to identify faulty combustion of an automobile engine regardless of the type of automobile. The analyzed AE signals are recorded in the workshop with a considerable amount of environmental noise, yet the proposed methodology can still operate. As the signals are recorded from four different types of automobile engines, one can claim that the methodology used in this paper has this potential to be used for different types of automobile engines. Therefore, it is possible to say that the proposed method is automobile independent. Considering the reported result, suitability of wavelet based features as well as CFS algorithm for feature selection is proved [13].
2) *Sameh M. Metwalley, Nabil Hammad and Shawki A. Abouel-seoud (2014)* The Fast Fourier Transform (FFT) technique and the high order statistic of RMS (the root mean square value (efficient value) of the signal) averages reflect in the Sound Pressure Level (SPL) responses of the gearbox. This can be an effective way to carry out the predictive maintenance regime and consequently to save money and look promising. The identification of gearbox noise in terms of SPL is introduced. When applied to the gearbox, the method resulted in an accurate account of the state of the gear, even, when applied to real data taken from the gear test. The results look promising. Moreover, the proposed noise in terms of sound pressure level (SPL) signature methodology has to be tested on the other test rig also. RMS average value could be a good indicator for early detection and characterization of faults [14].

C. *Acoustic Emission Applications in Non-Destructive Testing*

The application of acoustic emission to non-destructive testing of materials in the ultrasonic regime, typically takes place between 100 kHz and 1 MHz’s.

Unlike conventional ultrasonic testing, AE tools are designed for monitoring acoustic emissions produced within the material during failure or stress, rather than actively transmitting waves, then collecting them after they have traveled through the material. Part failure can be documented during unattended monitoring. The monitoring of the level of AE activity during multiple load cycles forms the basis for many AE safety inspection methods that allow the parts undergoing inspection to remain in service.

1) *Blitz, Jack; G. Simpson (1991)* The technique is used, for example, to study the formation of cracks during the welding process, as opposed to locating them after the weld has been formed with the more familiar ultrasonic testing technique. In a material under active stress, such as some components of an airplane during flight, transducers mounted in an area can detect the formation of a crack at the moment it begins propagating. A group of transducers can be used to record signals, then locate the precise area of their origin by measuring the time for the sound to reach different transducers [15].
2) *Stuart Hewerdine, ed Rugby (1993)* The technique is also valuable for detecting cracks forming in pressure vessels [14][15] and pipelines transporting liquids under high pressures. Also, this technique is used for estimation of corrosion in reinforced concrete structures [16].
3) *Blitz, Jack; G. Simpson (1991) and A.K. (2005)* In addition to non-destructive testing, acoustic emission monitoring has applications in process monitoring. Applications where acoustic emission monitoring has successfully been used include detecting anomalies in fluidized beds, and end points in batch granulation [15] [18].
4) *Veerachai Leelalerkiet, Toshimitsu Shimizu, Yuichi Tomoda and Masayasu Ohtsu (2005)* According to AE results, it is found that onset of corrosion initiates after chloride concentration becomes above the critical level of 0.3 ~ 0.6 kg/m3. Nucleation of corrosion cracking starts actively, when the chloride con- tent exceeds 1.2 kg/m3. AE technique can identify onset of corrosion and give warning of corrosion earlier than the half- cell potential measurement [19].
5) *A. Anastasopoulos, D. A. Kourousis, P.T. Cole (2008)* During AE testing, flaws in the structure are detected at early stages, before they may become critical, allowing an early action to be taken and, thus, significantly enhancing the plant's safety, since pressure spheres occasionally contain hazardous materials. The results of AE testing and analysis with appropriate procedures enable the characterization of the detected flaws, from insignificant to severe, thus, further inspection is targeted to the areas of the structure that actually require it, reducing drastically the inspection time, while no time is wasted in parts of the sphere that are in good condition. In Europe alone thousands of spheres have been tested using AE technology. The method has also been applied to pressure vessels, bullets, reactors, columns, pipelines, steam drums and other machinery and equipment. The results have been advantageous and industries report reductions in catastrophic failures of equipment and considerable resource gains. The non-intrusive, in-service, global structural assessment nature of the technique is accepted world-wide as an important addition to traditional NDT techniques [17].

D. Acoustic Emission Applications in Machining

Application of acoustic emission technique for on-line monitoring of various manufacturing processes such as punch stretching, drawing, blanking, forging, machining and grinding has been reviewed and discussed. During the past several years has established the effectiveness of acoustic emission sensing methodologies for machine condition analysis and process monitoring. AE has been proposed and evaluated for a variety of sensing tasks as well as for use as a technique for quantitative studies of manufacturing processes.

1) *Tim Toutountzakis, David Mba (2003)* The authors demonstrated the applicability of AE to gear health diagnosis. The behavior of AE to changes in speed or process in real time has been presented [20].
2) *Drago¸s A. Axinte, Nabil Gindy (2003)* The authors correlate the condition of broaching tools to the output signals obtained from multiple sensors, namely, acoustic emission (AE), vibration, cutting forces and hydraulic pressure, connected to a hydraulic broaching machine. The results show that AE, vibration and cutting force signals are all sensitive to tool condition and a correlation can be made between the broaching tool condition and sensory signals using a variety of signal analysis techniques. Time and frequency domain analysis of the output signals showed that there is a wide choice of sensors and signal processing techniques that can be utilized for tool condition monitoring in broaching [21].
3) *A. Velayudham R. Krishnamurthy T. Soundarapandian (2005)* The wavelet packet transform is used as a tool, to characterize the acoustic emission signals released from glass/phenolic polymeric composite during drilling. The results show that the selected monitoring indices from the wavelet packet coefficients are capable of detecting the drill condition effectively [22].

4) *J. Francis Xavier and S. Sampathkumar (2005)* It is possible to observe tool wear level related features both in AE time series and their RMS values. Particularly interesting are the statistical properties of the AE time series, in which power law characteristics have been identified. This behaviour has already been observed in the properties of acoustic emission signals in numerous other fields. The frequency distributions of the RMS values have also been studied as a function of wear, showing that even in this case it is possible to identify discriminating features [27].
5) *M T Mathew, P Srinivasa Pai, L A Rocha (2008)* AE signal analysis was applied for sensing tool wear in face milling operations. Cutting tests were carried out on a vertical milling machine. The results of this investigation indicate that AE can be effectively used for Monitoring tool wear in face milling operations. Ring down count (RDC) and RMS voltage can be effectively used as indicators for tool wear monitoring in face milling.RMS voltage is very clear in distinguishing the normal state from the abnormal state [24].
6) *Karali Patra (2011)* the author describes the development of a tool wear monitoring system using AE signals acquired during drilling on mild steel work-piece. AE energy of the signal has shown increasing trend with increasing drill wear [23].
7) *Emission O.A. Olufayo, K. Abou-El-Hossein, T. van Nieker (2011)* The work highlights the effects of acoustic emission (AE) signals emitted during the milling of H13 tool steel as an important parameter in the identification of tool wear. These generated AE signals provide information on the chip formation, wear, fracture and general deformation. Furthermore, it is aimed at implementing an online monitoring system for machine tools, using a sensor fusion approach to adequately determine process parameters necessary for creating an adequate tool change timing schedule for machining operations [25].
8) *P. Kulandaivelu P. Senthil Kumar (2011)* Crater wear stages can be monitored by observing cumulative mean values of AE parameters like Area, RMS value and average value. The limiting values of AE parameters obtained to monitor tool condition for a given cutting conditions is found to be applicable to monitor tool condition, even when the cutting speed is varied within ± 12% by keeping all other cutting conditions constant [26].

III. CONCLUSION

AE signal technique is use in many industries. AE is not limited to a particular field; huge amount of research is going to find out its feasibility in different application. It is an easy and effective tool for health monitoring of machines, products, buildings, gears etc. more and more application of AE in different field will come up in future.

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