Mechanical Systems and Signal Processing 60-61 (2015) 198–207

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Wear detection by means of wavelet-based acoustic emission analysis

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A R T I C L E I N F O

Article history:
Received 7 December 2013
Received in revised form
8 February 2015
Accepted 16 February 2015
Available online 5 March 2015

Keywords:
Sliding wear
Signal-based wear detection
Acoustic emission
Automated wear classification
Continuous wavelet transform

A B S T R A C T

Wear detection and monitoring during operation are complex and difficult tasks especially for materials under sliding conditions. Due to the permanent contact and repetitive motion, the material surface remains during tests non-accessible for optical inspection so that attrition of the contact partners cannot be easily detected. This paper introduces the relevant scientific components of reliable and efficient condition monitoring system for online detection and automated classification of wear phenomena by means of acoustic emission (AE) and advanced signal processing approaches. The related experiments were performed using a tribological system consisting of two martensitic plates, sliding against each other. High sensitive piezoelectric transducer was used to provide the continuous measurement of AE signals. The recorded AE signals were analyzed mainly by time-frequency analysis. A feature extraction module using a novel combination of Short-Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT) were used for the first time. A detailed correlation analysis between complex signal characteristics and the surface damage resulting from contact fatigue was investigated. Three wear process stages were detected and could be distinguished. To obtain quantitative and detailed information about different wear phases, the AE energy was calculated using STFT and decomposed into a suitable number of frequency levels. The individual energy distribution and the cumulative AE energy of each frequency components were analyzed using CWT. Results show that the behavior of individual frequency component changes when the wear state changes. Here, specific frequency ranges are attributed to the different wear states. The study reveals that the application of the STFT-/CWT-based AE analysis is an appropriate approach to distinguish and to interpret the different damage states occurred during sliding contact. Based on this results a new generation of condition monitoring systems can be build, able to evaluate automatically the surface condition of machine components with sliding surfaces.

1. Introduction

Mechanical/material wear is a type of surface damage that occurs due to periodically repeating relative motion and contact between solid surfaces. Generally, it involves progressive loss of materials and depends on surface properties,

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http://dx.doi.org/10.1016/j.ymssp.2015.02.012
0888-3270/

material properties, operating conditions, stresses, lubricants, and geometry [1]. Depending on the mechanism responsible for material removal from the surface, three main mechanical wear mechanisms are identified, namely, adhesive wear, abrasive wear, and surface fatigue. Adhesive wear appears in form of wear elements generated by adhesion and tearing off of material from the sliding surface [2]. Abrasive wear arises when the sharp materials produce loose grains that have a higher hardness than the surface. Surface fatigue occurs as cracks and fractures caused by high plastic deformations [3]. Surface fatigue causes a noticeable decrease in functional properties of damaged structure and may lead to an unsafe operation of machines [4]. Wear phenomena also include asperity fraction, crack initiation, crack propagation, and plastic deformation [5]. Along with the different wear phenomena, materials emit energy in the form of high frequent mechanical vibrations. These emissions propagate throughout the surface of the material as Rayleigh waves within the frequency range from 100 kHz to 1 MHz [6]. The emission is defined as acoustic emission (AE). Also the American Society of Testing and Materials Terminology for Non-destructive Examinations defines AE as "the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material" [7]. Since the 1970s, AE is classified as non-destructive evaluation method and has been considered as the prime approach for the detection, microstructural characterization, and monitoring of damage processes. Compared to other Non-Destructive Testing (NDT) methods, the Acoustic Emission Technique (AET) is usually realized during loading, while most other methods are applied before or after the loading of structure. Acoustic Emission Technique is classified as passive NDT because it is performed by the energy released by the object and does not require an artificial excitation. Another advantage of AET is that the dynamic processes or changes in material can be continuously monitored in real-time using suitable hardware [8]. In [9], it was mentioned that AE is a suitable method to detect damage state allowing the evaluation of the quality of contact surface. Due to friction, AE is generated by impact of friction surfaces, surface damage and formation of adhesive junctions [9].

Since the late 1980s, many studies investigating the relationship between AE behavior and mechanical wear mechanisms have been carried out. A first group of authors [4,6,10–16] used the parameter-based method to analyze AE signals. This method is based on the extraction of relevant and important AE features from the AE raw signal measured in time domain. In general, AE counts, cumulative AE energy, cumulative AE hits, and AE energy distribution are generated and correlated with the damage evolution. Investigating those significant AE features, the different wear phases could be distinguished. Han et al. [10] examined the AE characteristics during fatigue crack propagation. The AE behavior exhibits the existence of three phases corresponding to fatigue crack initiation denoted by a rapid growth of AE counts, stable crack propagation specified by a decrease of AE counts, and unstable fatigue crack propagation identified by an increase of the AE counts until the end of the experiment. In [11] the sensitivity of AE to damage process during fatigue crack test is discussed and examined, it was concluded that the cumulated AE activities increases when damage increases. Zykova et al. [4] analyzed the measured AE activity with the counts rate method and the cumulative AE counts method. The authors identified three contact fatigue stages. At the beginning of the test, an increase of AE activity was observed. This was assigned to running-in phase (self-accommodation). The end of the Run-in phase is clearly indicated by a reduction of AE events that stayed constant. This stable phase ends when a strong pitting appears, and the AE activity begins to increase rapidly up to failure of the system. This correlation of the AE parameters with contact damage degradation was also recognized by [6,12–15]. In [15,16] a different position was pointed out. Here the process was subdivided into more than three phases.

A second group of authors [17–23] used the frequency-based AE method (also called the quantitative method). This method is mainly based on power spectral analysis. The frequency components of AE signal are examined by using of Fast Fourier Transform (FFT) and several time-frequency analysis methods like Short-Time Fourier Transform (STFT) and Wavelet Transform (WT). The peak amplitude of the spectrum and dominant frequencies were used as features to study the characteristics of acoustic emission signals. Hase et al. [18] examined AE signals during adhesive wear and abrasive wear by means of FFT. Here, adhesive wear which was physically correlated to transfer particles and quantities of wear elements, was characterized by a frequency peak at 1.1 MHz while abrasive wear such cutting and plastic deformation was denoted by frequency components in the range of 250 kHz–1 MHz. Similar results were observed in [19]. Asamene and Sundaresan [20] performed studies on two sliding flat steel surfaces to investigate the relationship between sliding friction and AE signals. Frequency components about 700 kHz were detected and assigned to friction. Kolubaev et al. [21] observed the presence of high-frequency components related to the formation of a damaged surface layer during sliding friction tests. Chang et al. [22] mentioned that emissions with frequency components in the range of 200–400 kHz are referred to friction of the surfaces and do not depend on the length of the crack. As stated in [23], AE signals occurring during sliding wear between a steel ball and a sapphire disc show frequency components in the range of 100–500 kHz. The results reveal that there is a "strong dependence on the lubrication conditions". This conclusion has also been noted in [17]; here the wavelet transform was used for early damage detection of highly stressed rotating components. The experimental results indicate that frequency components of 200–250 kHz correspond to crack initiation while crack propagation is characterized by AE signals with frequency components up to 400 kHz. Regarding the mentioned review, it is obvious that using only the parameter-based or the frequency-based AE method no agreement on the wear mechanism, resulting wear state, and the corresponding AE parameters and frequency components can be realized.

The main objective of this paper is to establish a direct correlation between state-of-wear and emitted AE. In detail, the effects of the damage progression process have to be described quantitatively and qualitatively. The related information can later be used to realize a lifetime prognosis. In Section 2, the test-rig and the developed measurement chain for AE detection are introduced. In addition, the new filtering techniques, combining the parameter-based AE method and the frequency-based AE method, based on STFT and Continuous Wavelet Transform (CWT) are discussed. Tests and examinations are performed for the whole lifetime of the sliding surfaces. In Section 3, the experimental results are presented. The AE energy

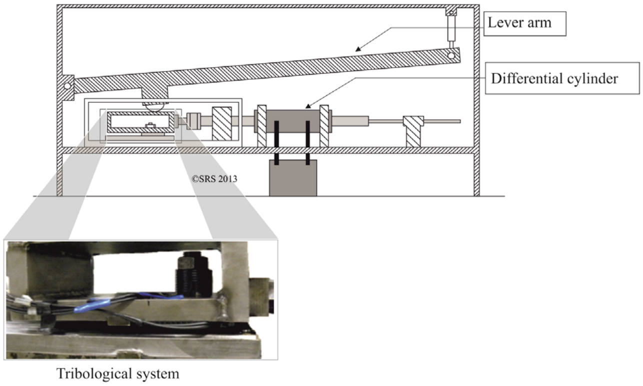

Fig. 1. Sketch of the test-rig, Chair SRS, University of Duisburg-Essen.

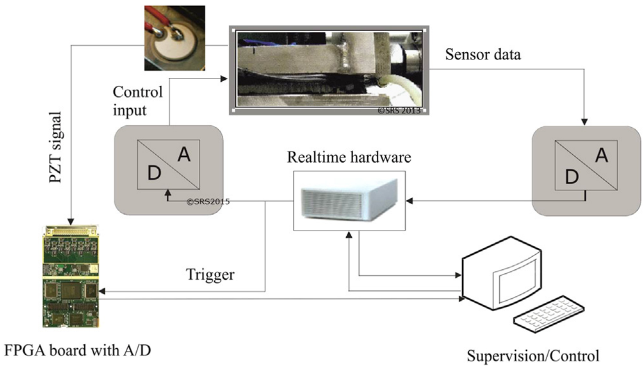

Fig. 2. Sketch of FPGA-based measurement chain used for acoustic emission detection.

distribution and the cumulative AE energy are calculated and decomposed into different frequency levels using STFT. Frequency components are extracted at different scales extracted to investigate a correlation between AE characteristics and the surface damage resulting from contact fatigue. The CWT is applied to the decomposed AE energy distribution. Each frequency level is attributed to a specific wear phase. The results reveal a distinction between different wear-related effects during different states of the system's life.

2. Experimental tests

2.1. Test rig and measurement chain

The analyzed tribological system consists of two "wear resistant" plates with a martensitic microstructure. The plates are of different sizes sliding against each other. The horizontal movement is generated and realized by a differential hydraulic cylinder. To accelerate the wear process, the system is stressed by an adjustable normal load performed by a controlled lever arm. In Fig. 1, the "wear resistant" plates and the related test rig construction is shown.

Long duration tests with constant operating conditions (force, pressure, temperature) and variable parameters (lubrication type, lubrication interval, and plate hardness) were performed. Specific piezoelectric sensors were used to measure the emitted elastic waves of small amplitudes and very high frequencies propagating through the material. To minimize the attenuation of the emitted AE signals, the sensor was glued as close as possible to the wear zone. The coupling between the sensor and the surface of the plate was permanent and very stiff. A suitable coupling material with an appropriate acoustic impedance and attenuation was chosen. The geometry of the applied sensor is those of a small disc with a thickness of 0.55 mm and a diameter of 10 mm, resulting in a resonance frequency of 3.6 MHz. The measured voltage is amplified with an impedance converter and fed to a Field Programmable Gate Array (FPGA)-board. The board is equipped with AD-converters with a resolution of 16 bits and a maximum sampling frequency of 25 MHz. Subsequently, the measured signal is analyzed by various signal processing methods. The FPGA-based measurement chain is depicted in Fig. 2. According to [24], special attention is paid to higher frequencies (>300 kHz). An appropriate sampling rate of 4 MHz was chosen to assure a high resolution of the discretized piezoelectric voltage of particular interest. For identifying AE properties, specific filtering and analysis functions including STFT and CWT are developed.

2.2. Signal processing

The recorded AE signals are non-stationary and appear as transient signals with undefined waveform. Signal processing in time-domain is not efficient to extract frequency information of interest. A frequency-based analysis such as Fast Fourier Transform (FFT) is limited to stationary and periodic signals and cannot retrieve the time related information [25]. According to [26], the meaningful AE characteristics occurring due to instantaneously physical character vary in time and frequency. Hence, time-frequency analysis is a suitable method to reveal the AE specifications undetectable in the original signal. Time-frequency analysis provides the possibility to evaluate the time-variant character of the frequency components.

The typical time-frequency analysis method to study AE signals is STFT. Within STFT algorithms, a signal is multiplied by a window function. The FFT of the product is performed. Afterward, the sliding window moves along the time axis, so the calculation is repeated until the end of the signal. Short-Time Fourier Transform provides information about the specific frequency characteristics of the occurring events and allows a representation in the time-frequency domain [27]. This information is, therefore, limited in precision. The time and frequency precision are determined mainly by the width of the window that is constant for all frequencies. The accuracy of the solution is limited by the time-frequency resolution tradeoff [28]. In addition to STFT, the WT has been successfully used and became the most informative approach for analysis of transient AE signals. Wavelet transform provides suitable time-frequency localized information, which is analyzed simultaneously with high resolution at different frequency ranges [25]. The superiority of the wavelets is more tangible in the case of non-stationary measurements, sudden changes in time direction, discontinuities in higher derivatives, and breakdown points [29]. Wavelet transform is also applied to compress or denoise a signal without noticeable attenuation. In the last years, WT was widely used for fault detection, identification, and location [26,31–35]. In [30], WT was successfully applied for fault diagnosis of induction machines. Li et al. [31] affiliated that WT is an efficient signal processing method for AE-based tool wear monitoring during turning. Khamedi et al. [32] analyzed AE signals generated during tensile test loading of dual phase steel by means of WT. Gaul et al. [35] used WT to identify the location of synthetic AE source generated on the surface of a fatigue specimen by a local thermal expansion. The results proved the efficiency of WT in the analysis of AE signals detecting micro mechanisms identifying failure.

2.3. Continuous wavelet transform

The continuous wavelet transform is defined as “the sum over all time of the signal multiplied by scaled, shifted versions of the wavelet function” [36]. The application of CWT allows the detection of hidden transients and short-time events, pattern recognition, multi-resolution features extraction, and data compression.

To implement CWT, a mother wavelet $\psi(t) \in L^2(\mathbb{R})$ with an effectively limited duration and zero average is required. According to [36–38], the mother wavelet $\psi(t)$ must satisfy the following properties:

The function integrates to zero as

$$\int_{-\infty}^{\infty} \psi(t)dt = 0, \tag{1}$$

its Fourier Transform $\psi(\omega)$ satisfies the admissibility condition as

$$\int_{-\infty}^{\infty} \frac{|\psi(\omega)|^2}{\omega} d\omega < \infty. \tag{2}$$

Once the mother wavelet is chosen, the CWT of the function $f(t) \in L^2(\mathbb{R})$ is defined by the equation

$$CWT(a,b) = (f\ ,\ \psi_{a,b}) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)dt,$$
$$a \neq 0 \in \mathbb{R} \quad \text{and} \quad b \in \mathbb{R}. \tag{3}$$

here, the variable a represents the scale and determines the stretching and compressing of the wavelet while b is referred to the translation. Eqs. (1) and (2) assure the perfect reconstruction of the signal $f(t)$ from the coefficients $CWT(a,b)$ by means of the inverse CWT, which is described in [36–38], as

$$f(t) = \frac{1}{C} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{|a^2|} CWT(a,b)\psi(t)da\, db, \tag{4}$$

$$C = \int_0^{\infty} \frac{|\psi(\omega)^2|}{\omega} d\omega. \tag{5}$$

In this paper, the Morlet wavelet is chosen as mother wavelet to analyze the AE data measured during the wear process. According to [37], Morlet wavelet achieves as the best compromise between time resolution and frequency resolution. It is widely used for detection and identification of transient events with hidden information. The Morlet wavelet is defined in [37] as

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} e^{2\pi j f_c t} e^{t^2/f_b}. \tag{6}$$

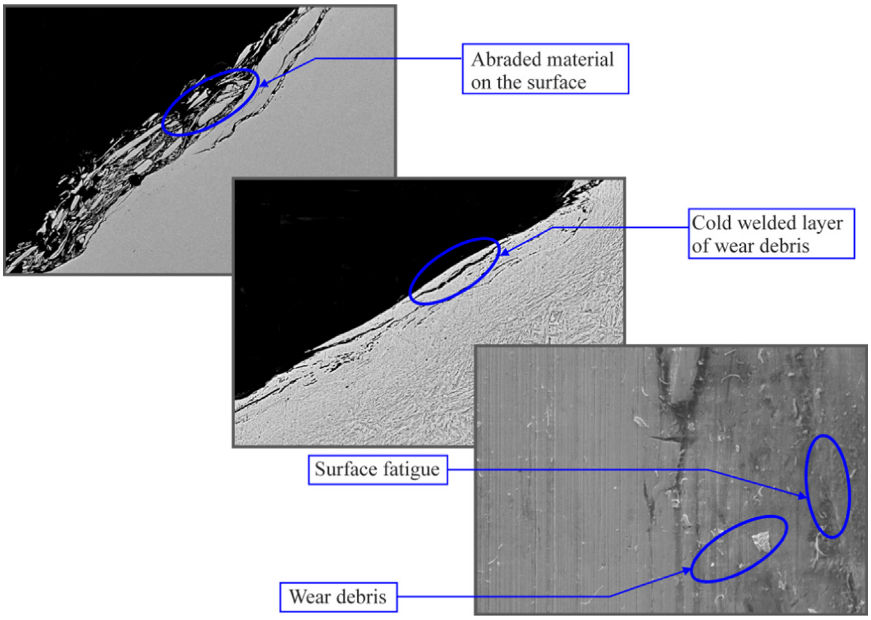

Fig. 3. SEM analysis of plate surface after 20 days endurance test, results from tests realized at Chair SRS, University of Duisburg-Essen.

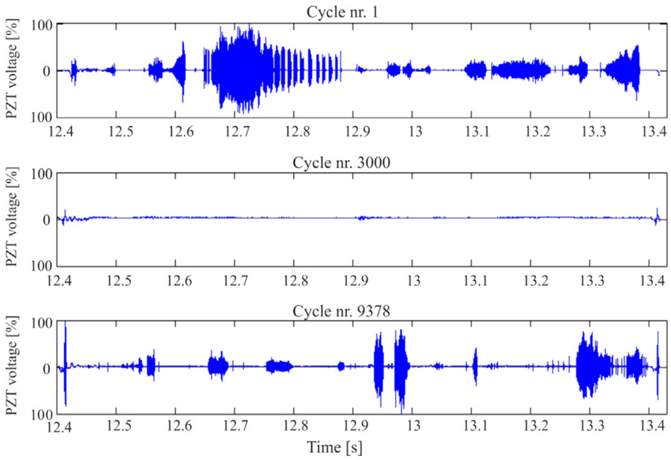

Fig. 4. Raw AE signals measured during three different test cycles.

3. Results and discussion

Previous works [39,40] of the authors focusing on the same tribological system, show that due to the heat development during the shaping process, a thin coating with a very brittle microstructure on the surface of the wear plates occurs. Some tensile cracks can be observed in the coating before applying load. During the first hours of the application of the load this coating is eroded, particles scratch the surface leading to abrasive wear. After that, fatigue cracks appear and may continue to grow and reach the material subsurface. Additionally some small cracks appear near the surface. In Fig. 3 Scanning Microscope Electron analysis (SEM) of a plate sample after 20 days endurance test is shown. The identified main wear effects are related to abrasive wear and surface fatigue. Surface fatigue initiates and propagates cracks after a certain number of cyclic events and leads to system failure.

To investigate a correlation between these physical effects and the occurring acoustic emissions, transient events and characteristic frequencies for these stochastically appearing effects were analyzed. The severity of the wear process change should be indicated by characteristics of transient events, amplitudes, and specific frequencies appearing in time and/or frequency domain.

In Fig. 4, as illustration examples, segments of the raw AE signal measured during three different process cycles are shown. Burst and continuous AE signals are detected. The type of AE signal depends on the nature of the energy release. Burst type AE signals correspond to a discrete micromechanical event well separated in time, characterized by short duration and high amplitude [41].

Acoustic Emission bursts are principally caused by phase transformations, crack initiation and propagation in a brittle material [42]. Continuous AE signals are closely spaced in time, characterized by small amplitude and caused by plastic deformation, diffusion-controlled phase transformations [41]. The detected AE signals show dissimilarities in amplitude, frequency, severity, and waveform. This proves that AE changes when the wear mechanism changes.

To extract relevant characteristics distinguishing different wear stages from related AE signals, the analysis is focused on the AE energy generated during the wear process. To calculate the AE energy, the STFT $X(\omega)$ of the AE signal of each cycle was generated and the Root Mean Square (RMS) of the power spectrum was calculated so that each cycle was assigned by the energy value

$$E(\omega) = |X(\omega)|^2. \tag{7}$$

Referring to [4,42–44], the AE behavior over the system usage allows the distinction of three main characteristic states. The three major phases to be distinguished are the

(a) Run-in phase,
(b) Permanent-wear phase (stable phase) and,
(c) Wear-out phase.

Within the Run-in phase, AE energy increases rapidly and systems have a high probability to fail. The Permanent-wear phase is indicated by a decrease in AE energy, which still constant until the Wear-out phase begins. During the Wear-out phase, AE energy increases continuously until system fails.

To illustrate the mentioned phenomena, the emitted AE energy is shown as a function of the number of cycles in Fig. 5. Significant regions of the process and irregularities of the energy events related to wear effects are detected. During the first 40 cycles, the AE energy appears with high amplitude. Next the amplitude decreases strongly and reaches a stable value. After approximately 3200 cycles, a sudden grew of AE energy, detectable by discontinuous impulses, appears. The AE energy

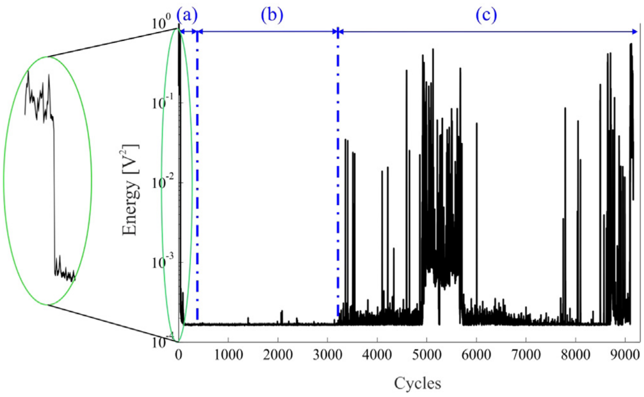

Fig. 5. AE energy as a function of cycles. (a) Run-in phase, (b) Permanent-wear phase, and (c) Wear-out phase.

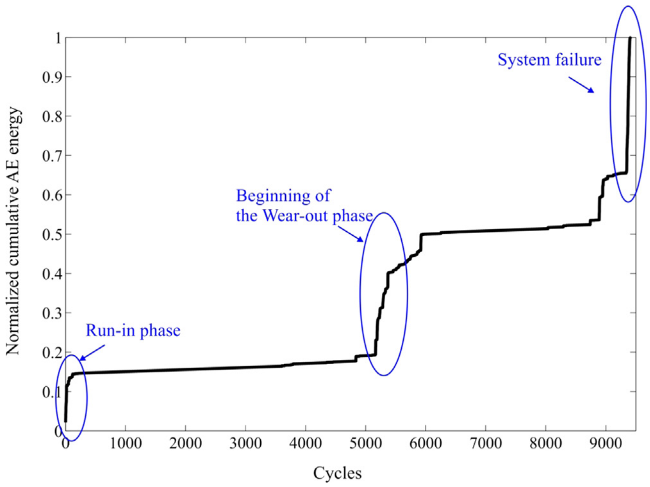

Fig. 6. Damage progression based on cumulated AE as a function of cycles.

increases until the end of the experiment. It is also noticed that the amplitude of the individual AE energy measured during the Run-in phase and the Wear-out phase are similar. A distinction between the different wear mechanisms based on the signals amplitude seems not be possible.

To extract more relevant information corresponding to specific wear-states, the cumulative energy over number of cycles was carried out. The cumulative energy is equal to the integral of the AE energy distribution $\int E(\omega)dt$. In Fig. 6, the integrated AE energy as a function of cycles is shown. Following [43], it can be assumed, that continuously with the ongoing integrated AE, the system's damage progress develops showing the different wear stages. The Run-in phase is represented

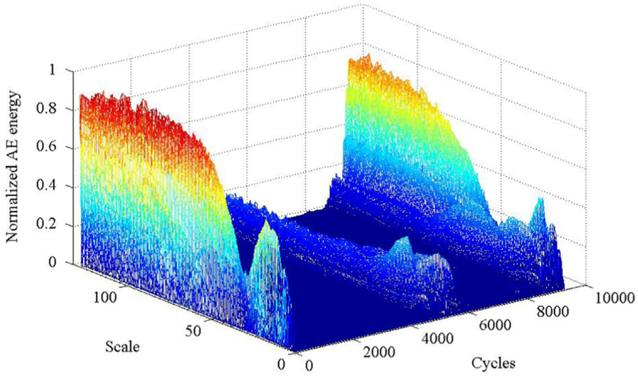

Fig. 7. Continuous wavelet transform of the generated AE energy.

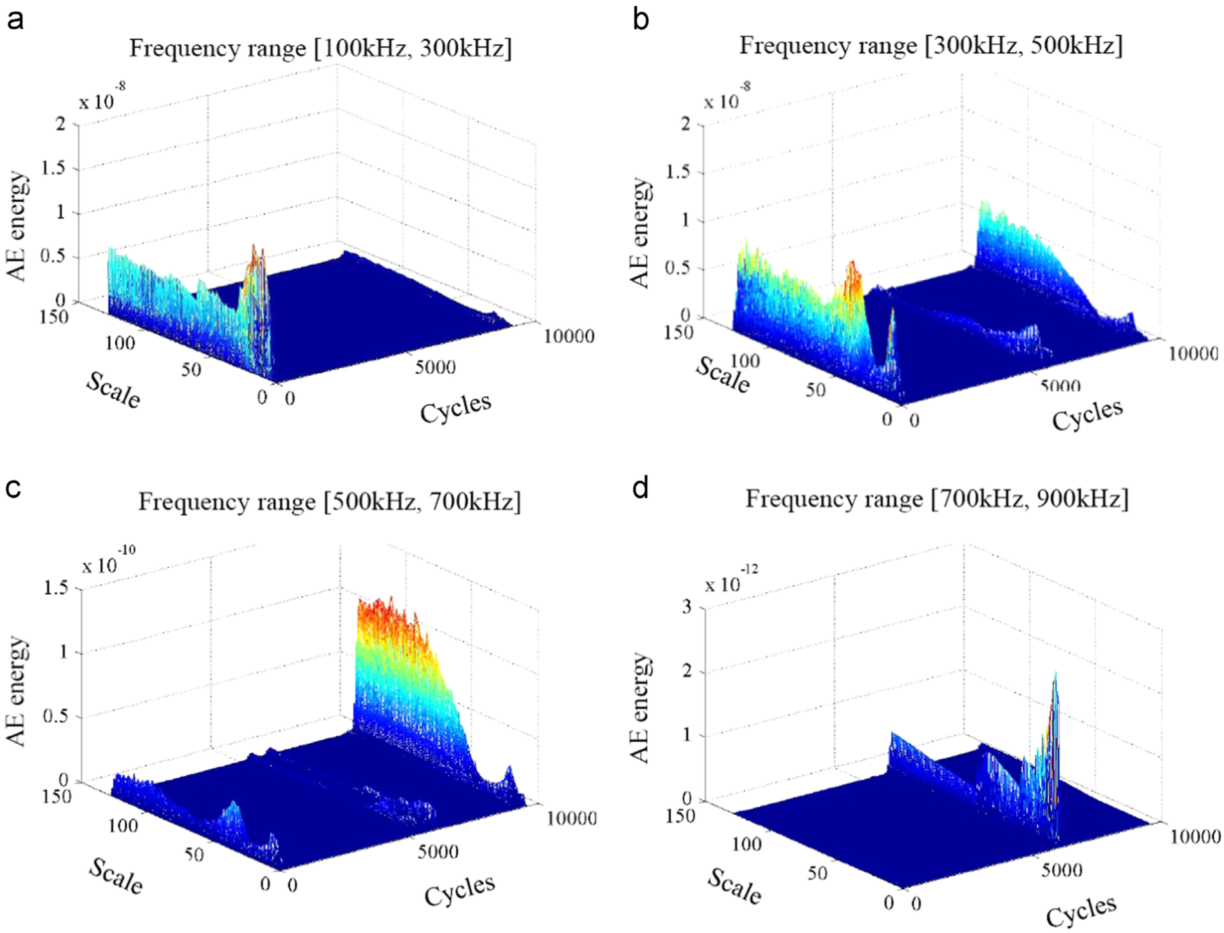

Fig. 8. Result of CWT in different frequency ranges [100 kHz 300 kHz], [300 kHz 500 kHz], [500 kHz 700 kHz], and [700 kHz 900 kHz].

by the first gradient. The Permanent-wear phase begins when the gradient attains approximate the normalized value of 0.15 and remains constant until the next gradient indicating the beginning of the Wear-out phase. Based on the experimental results, it becomes clear, that investigating the AE energy distribution and cumulative energy qualitative information about the wear state as well as the level of deterioration of the system can be established.

From [39] it cannot be deduced that the Run-in phase and the Wear-out phase can be identified based on the information connected to the individual transient events. This leads to the conclusion that this lack should be solved. Therefore, in this paper, the frequency components are examined using CWT with respect to learning about options to distinguish wear phases with the aim to use it for automation, control, and supervision/monitoring purposes.

The CWT results of the AE energy are exhibited in Fig. 7. It can be seen that during phases, the Run-in phase, and the Wear-out phase, frequency components within the range of [40 kHz, 1000 kHz] with nearly similar energy content occur. Using a decomposition of the AE signal into frequency ranges of equal length, hidden information connected to the occurred damage can be detected.

In Fig. 8, the obtained CWT of the decomposed signals is shown. It can be observed that each phase is characterized by specific frequency components. This knowledge allows a correlation between the wear state and the corresponding frequency range. In the sequel detailed frequency-band-wise explanations are given.

In the first frequency band, only the Run-in phase shows AE, which means that AE signal with frequencies between [100 kHz, 300 kHz] are mainly related to wear mechanism affected during the Run-in phase. Frequency components in the range of [300 kHz, 500 kHz] occur in each phase and dominate over the complete process because of their high energy

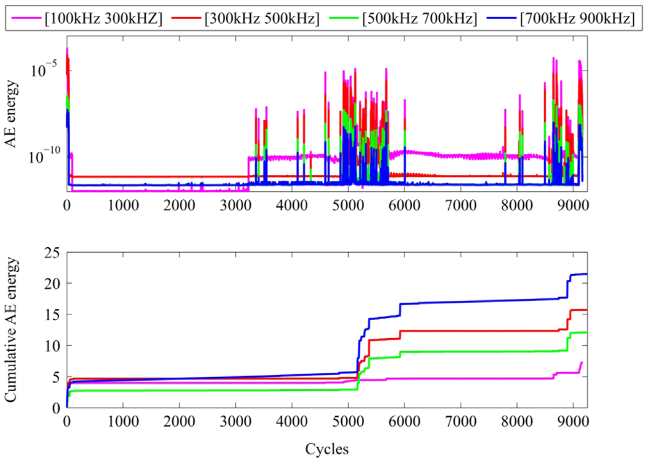

Fig. 9. Reconstructed signals and their corresponding cumulative AE energy.

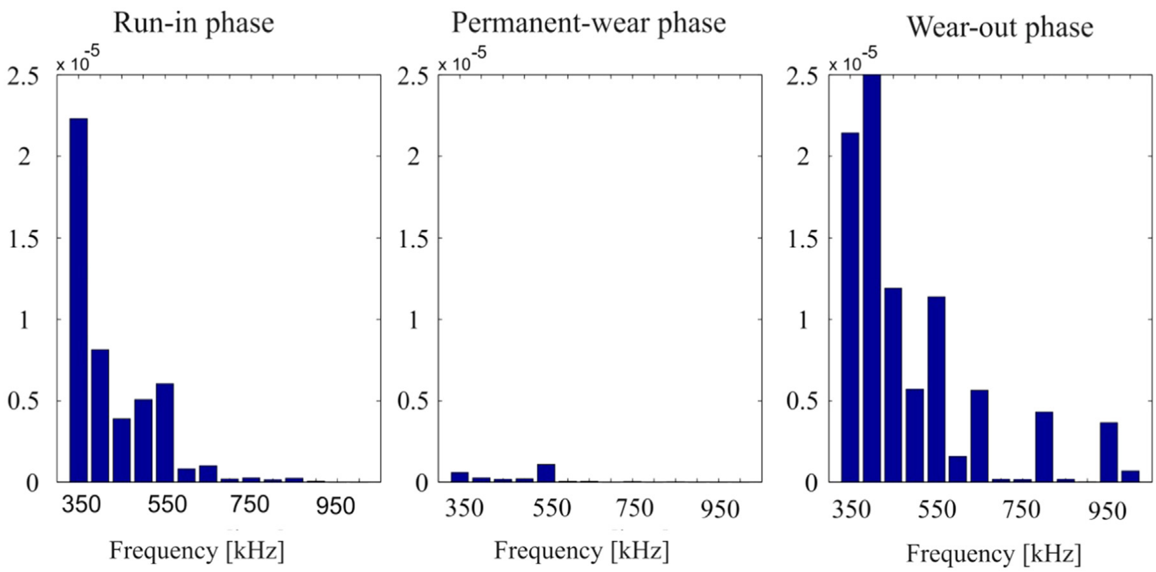

Fig. 10. Histogram of specific frequency contents in the three wear phases

content. The beginning of the Wear-out phase is characterized by AE signals with frequencies between [700 kHz, 900 kHz]. Right before system failure, frequency components located in the range of [500 kHz, 700 kHz] can be shown. These results can be used, based on the introduced filtering technique, to build a wear-related behavior model.

This frequency repartition is also observed in the individual cumulative AE energy. The signals reconstructed from the CWT coefficients and their correspondent cumulative AE energy are shown in Fig. 9. Here the beginning of the Wear-out phase is obviously characterized by a steep and great gradient related to the signal with frequency components between 700 kHz and 900 kHz. The distribution of frequency components during the three process phases can be summarized as illustrated in Fig. 10. Comparing this result with the SEM results, it can be deduced that frequency components up to 500 kHz can be associated with tensile cracks detected in the thin coating developed during the shaping process. Frequency components in the range of [300 kHz, 900 kHz] can be related to abrasive wear and fatigue cracks which grow into and below the ground material. It can be concluded that the combination of the parameter-based AE method and the frequency-based AE method is appropriate to describe the incremental damage and therefore also to distinguish the introduced three different phases.

Based on the accumulated process data, the actual process state with respect to absolute emitted AE can be evaluated and possibly related to similar combinations of applications combining specific materials and operations. Based on the known behavior, wear-related monitoring and diagnostic maintenance approaches can be applied. Additionally, these results prove the ability of the introduced FPGA-based measurement chain for online damage state detection.

The introduced approach can be used to judge the actual wear state based on related individual measurements. It should be noted that this approach does not use any model beside the information about (material-specific) frequencies as learned from the experiments. The information related to the damage accumulation and the damage assigned frequencies can be applied to obtain asset management or lifetime control of the system.

4. Summary and conclusion

To establish the fundamentals of a new generation of condition monitoring systems for automated evaluation of sliding wear states during operation, a tribological system affected by sliding wear was studied. Acoustic emission and advanced signal processing techniques were applied and a measurement chain based on FPGA was developed and tested. To reveal the occurring time and the energy content of the transient event, several analysis functions have been developed. By applying the STFT to the AE raw signals, AE energy was calculated. The energy distribution and the cumulated AE energy allow the identification of three wear phases. It can be shown by experiments that the initial, as well as the final wear stages, were accompanied by AE events of high energy contents. In order to automatically distinguish the different wear mechanism occurring during the sliding process, the AE energy was decomposed into four frequency levels and the CWT was applied to each frequency band. From the related experiment, it was concluded that each wear phase is associated with a typical and specific set of frequency components providing the logical base for a clear connection between the physical surface condition and the related evaluation. Here AE signals and material changes like abrasive wear, small cracks close to the surface, and surface fatigue can be determined and therefore, also be used for evaluation. It can be concluded that the examination of the wear process using the cumulative AE energy and CWT analysis allows the detection and quantification of the state-of-damage and the damage progression.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ymssp.2015.02.012.

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