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

D. Baccar, D. Söffker *

Chair of Dynamics and Control, Department of Mechanical and Process Engineering, University of Duisburg-Essen, 47048 Duisburg, Germany

ARTICLE INFO

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

ABSTRACT

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,

* Corresponding author. Tel.: +492033793429; fax: +492033793027.
E-mail address: soeffker@uni-due.de (D. Söffker).

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