Potentials and applications of the acoustic emission technology in mining and heavy machinery

Tobias Vraetz, M.Sc. [1)]
Dr.-Ing. Franz Domenic Boos [2)]
Dipl.-Wirt.-Ing. Dennis Röllinger [1)]
Dipl.-Wirt.-Ing. Christian Bernet [1)]
Christoph Büschgens, M.Sc. [1)]
Dr.-Ing. Ralph Baltes [1)]
Univ.-Prof. Dr.-Ing. Karl Nienhaus [1)]
[1)] Institut für Maschinentechnik der Rohstoffindustrie (IMR), RWTH Aachen University
[2)] thyssenkrupp Steel Europe AG

1 Introduction

The acoustic emission analysis is a technology-based methodology which has its origins in the non-destructive testing. Acoustic emission signals occur among others due to changes in the material structure as a result of external loads. The causes may be mechanisms like crack initiation, crack growth, cavitation, impacts, electrical discharges or friction. With the emergence of such signals in a short time small amounts of energy are released. The respective pulses are in the microsecond range, so that a sampling above the megahertz range is necessary to detect these signals. Based on the advances in digital data processing and the development of high-performance measurement systems, acoustic emission measurement technology has increasingly become the focus of scientific as well as industrial applications. Throughout the past years novel application scenarios on the applicability of acoustic emission technology have been discussed at the Institute for Mineral Resources Machine Technology. The focus of this publication is to summarize the potential of acoustic emission analysis for the following applications: [1]

- Bearing Diagnostics
- Fatigue Processes
- Rock Cutting Technologies
- Material Flow Characterization

One example for a successful application can be found in results of publicly funded project "MAEX" (**M**ulti-analysis **A**coustic **E**mission Data E**x**tractor). The results show that acoustic emission analysis supports proven methods of bearing diagnosis. The analysis and diagnosis of an oscillating bearing is thereby optimized and expanded. The second of the above mentioned research fields examines the origin of fatigue cracks in steel structures through fatigue tests. The focus is to reliably detect long fatigue cracks in order to determine the endurance fatigue strength. Investigating the application of acoustic emission analysis for rock cutting process different process parameters can be evaluated. This results in a better understanding of the process and is the basis of an automated system. In the final application, the acoustic emission technology is used in the treatment of minerals. By analyzing acoustic emissions originating in material impacts and friction during material transportation, the composition of a material stream can be identified.

2 Basics and Data Analysis

In order to understand the four applications it is necessary to summarize firstly the rudimentary principles of the acoustic emission technology and secondly the underlying data processing approaches. First of all, it is important to understand that all of the following methods are based on passive measurement principles. In contrast to other high-frequency based measurement systems and their ilk it is not necessary to actively induce signals into the structure/material. The measured signal derives from the process itself and does not need any additional equipment other than the acoustic emission sensor itself. The measured signals are based on elastic waves in solids which contain longitudinal, transversal and Rayleigh components. Therefore, acoustic emissions can be differentiated – based on this definition – from conventional structure-borne sound and airborne sound [e.g. 2] signals. A detailed derivation of the components of an acoustic emission signal can be found in [1].

The necessity for a deeper analysis is crucial for the understanding of signal propagation, damping and frequency behavior. Acoustic emission signals can be divided into continuous signals with no apparent beginning or end (for example, continuous noise of a process) and transient signals with recognizable beginning and end. The latter is also called "Acoustic Emission Bursts". The detection of these kind of bursts will be part of the data analysis approach.

In order to understand the acoustic emission data analysis approaches the second important aspect is based on a systematic evaluation and analysis of acoustic emission data. Regardless of the application, different methods of analysis need to be used and compared. The choice of method depends on the knowledge of each application and is of vital importance. Due to the high sampling rate of the signals and the associated large amount of data it is important to understand the complexity of the different analysis methods. The figure below schematically shows an overview of the three different approaches (statistical analysis in the time domain, frequency-based analysis methods and burst detection with subsequent signal shape-based analysis) for the evaluation and analysis of acoustic emission signals.

In some cases (e.g. when looking at a temperature curve) it is sufficient to analyze the time signal to identify differences or trends in the signal curve. In more complex problems several different characteristic features are necessary for the evaluation of waveforms. This procedure also applies to the analysis of acoustic emission signals. The literature provides several different features for trend and data analysis. These features can be applied to the acoustic emission concept.

In addition to the analysis in the time domain acoustic emission data can be processed and analyzed in the frequency domain. The derivation of the frequency-based methods can be found in many publications, including [3] and [4]. The frequency based analysis of the following applications are based on Fourier analysis and/or short-time Fourier spectrum.

The last presented approach is the so-called burst recognition. Different burst recognition methods have been developed at the Institute for Mineral Resources Machine Technology. Each method has its own advantages and disadvantages. Based on the individual methods burst-specific parameters can be derived, which can be used to evaluate acoustic emission signals. Burst recognition itself is a crucial, if not the decisive, approach to the analysis and evaluation of burst parameters. Depending on the application, it may be necessary to identify and evaluate all bursts. In other applications, it is not necessary to record all the bursts in detail, but it is enough to consider a trend over time.

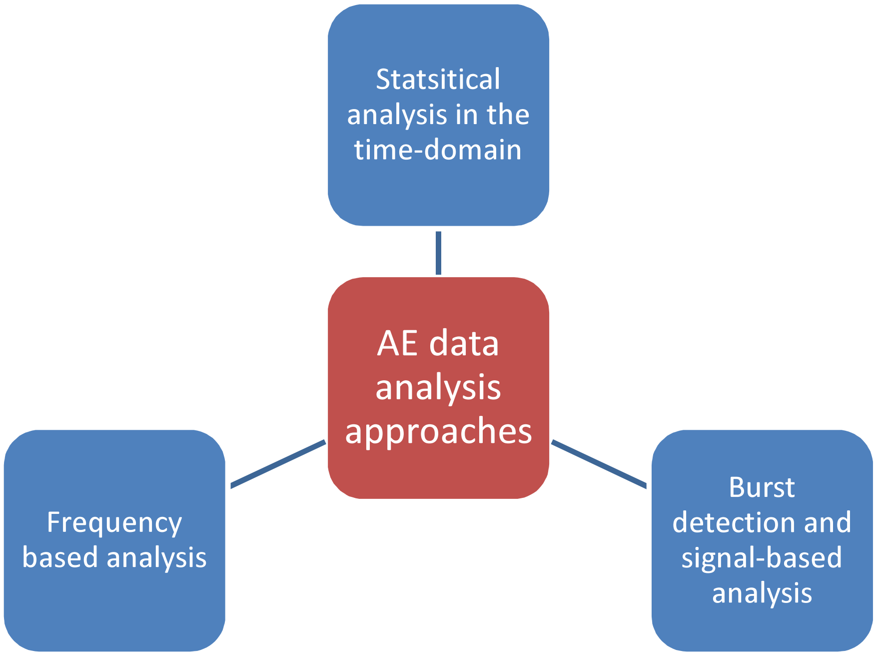

Figure 1: Acoustic emission data analysis approaches

3 Bearing Diagnostics

Condition monitoring of roller bearings has played an important role in engineering for decades. Not only are roller bearings part of most of the complex machines but what is more, their failure is often critical causing the machine to break down. The most common tool for bearing monitoring are acceleration signals. For most of the conventional application cases vibration signal analysis is sufficient. There are, however, still some applications that pose a challenge to vibration analysis, namely slow rotating and oscillating bearings.

The operational experience of bearings in these applications revealed some major problems. If a bearing rotates with a low frequency, the vibration velocity is low. This can in turn make it difficult to detect a detriment in the frequency domain [5]. Acoustic Emission, however, is - other than vibrations - linked to other physical sources and has, therefore, a high potential to indicate damages in the bearing at a very early stage, even if traditional methods using vibration measurement fail.

Miettinen et al. [5] showed that fault frequencies could be identified from AE time signal even at very low rotational frequency. In addition, the burst count method was identified as a reliable method for monitoring. Research by Elforjani [6] also indicated that analysis of traditional AE Burst counts also provided a simple, rapid and robust technique for inspecting bearings defects and failure. The problems of condition monitoring on oscillating bearings are even more challenging because the oscillating movement cannot be described through a sequence of pulses.

This problem is especially relevant for the highly stressed bearings in oscillating pitch systems in wind turbines [7-9]. Vibration analysis in this case proved insufficient because most analysis methods are based on the sequence of pulses. Here, acoustic emission offers an alternative for these application because it offers some additional features that can be used to monitor the bearing. Early works by Messner [10] and also Nienhaus [11] showed that using the acoustic emission signal it is possible to monitor bearings even with burst count and statistical coefficients. Nienhaus further showed that the acoustic emission signal is more sensitive than the vibration signal for oscillating and rotating conditions.

This work has been intensified by Boos, Röllinger and Vraetz [12-14] in a publicly funded research project (MAEX). The results of the tests conducted have been consistently good and delineate a high potential for condition monitoring of oscillating and slow rotating bearings with a number of different burst count methods. The burst count allows for the monitoring of a trend over the lifetime of a bearing. For a reliable condition monitoring using a burst count a constant measurement is necessary. A distinction between good and bad condition of a bearing was suggested by Boos [1] using a feature space. Final findings of the research project, acquired out of long-term tests will be published later this year.

4 Fatigue Processes

Acoustic emission testing has already been proven in the fatigue analysis of steel in experiments with cyclic load [15-16]. Figure 2 shows the results of [15] generated on welded and base metal specimens (all specimens are notched centrically) of Q345 steel in four point bending experiments. The measured acoustic emission counts are plotted normalized against the normalized cycles for two different load stages (1.6 kN up to 16 kN and 2.0 kN up to 20 kN). The acoustic emission counts are the number of exceedings of a threshold defined for the acoustic emission signal. After the counts increase steeply in stage 1, their gain is almost constant in stage 2. Finally, the counts increase against steeply in stage 3.

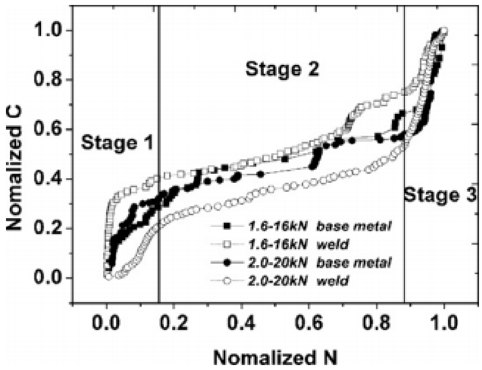

Figure 2: Acoustic Emission counts against cycles [15]

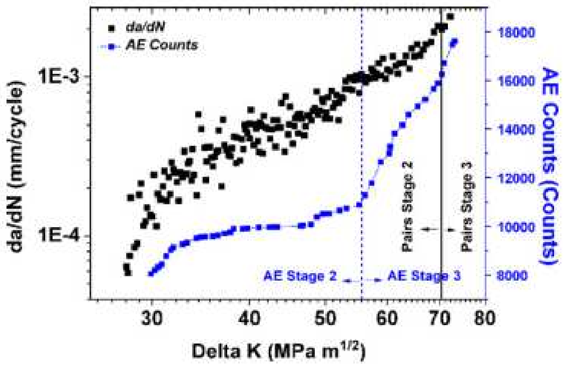

Figure 3: Crack growth rate and Acoustic Emission counts against stress intensity factor [15]

In figure 3 the acoustic emission counts are compared to the crack growth rate for a base metal specimen and the load stage 1.6 up to 16 kN. The change from acoustic emission stage 2 to stage 3 happens about 15 MPa $m^{1/2}$ earlier than the change of the crack growth rate from the linear sub-critical stage 2 and the stage 3.

In order to determine the crack initiation, tests with increasing loads were performed together with the Department of Ferrous Metallurgy of RWTH Aachen University. A load increasing test is a test with cyclic load where the stress amplitude is increased intervallic until the specimen breaks. The test with a round steel specimen showed a good correlation between the conventional method for determining of crack initiation – temperature measurement – and acoustic emission. While the whole test lasted 270 minutes, the temperature begins to increase significantly just at about 180 minutes into the test. This indicates the beginning of the growth of long fatigue cracks. Simultaneously, the count of detected bursts increases significantly. [1]

Therefore, acoustic emission testing in the analysis of fatigue of steel components is an effective tool in order to characterize the crack initiation and growth. It also has a big potential to evaluate the cyclic damage condition on the inside of components.

5 Rock Cutting Technology

Continuous mechanical cutting is an increasingly applied mining method. In literature mechanical cutting is often described as the key for the automation of extraction machinery. In order for autonomous work of a machine without human supervision the machine needs to sense its environment. Given the fact that machines themselves unlike humans are not able sense their surroundings, sensors are needed to provide the data. It is necessary for the machine to make decisions based on these sensor data. [17-18]

Acoustic Emission technology is capable of providing additional information about a cutting process and therefore useful for machine automation. The Institute for Advanced Mining Technology of RWTH Aachen University has been applying acoustic emission technology in the field of rock cutting for more than five years. In the following selected research topics will be presented briefly.

During the extraction process the machine naturally has to follow the mineral body in the course of the deposit. Hence an automated machine needs to be able to detect whether it is currently cutting host rock or the desired ore. Sensors based on acoustic emission data can enable this detection process. Taking a closer look at an acoustic emission raw signal there are two possibilities for signal processing as described in chapter 2. First the signal can be processes in frequency domain. Second a processing in the time domain is possible.

In the first approach the frequency domain analysis is used to differentiate between two materials. It could be shown, that the frequency domain signal between gypsum, oil shale, coal and waste rock can be used to clearly differentiate between these materials [19]. All materials possess their characteristic frequencies in the acoustic emission spectrum. This can be seen in diverging heights of amplitudes compared to other materials. Therefore this fact can be used to identify materials being cut. Unfortunately the frequency resolution is not sufficient enough for a real time distinction. The necessary processes are to resource intensive at the moment. The same result was accomplished when trying to detect different process parameter like cutting depth as well as grain size of the material being cut. In both cases some features appear that can be used to distinguish materials. Both of these features are not adequate for online measurement during extraction due to a limitation of current hardware. Hence a different approach was necessary to enable boundary layer or material detection. [20]

In the time domain two approaches were investigated in the past. The first approach was to count the number of bursts occurring in a predefined time window. Using this method enabled to distinguish between cutting host rock and valuable minerals. The second method used was to create characteristic values of the sensor signal. With these characteristic values it is now possible, to identify the materials being cut as well [1]. The results were reproduced with different materials and in different hardness. As a result it was found that acoustic emission is an adequate method for boundary layer detection.

Furthermore, also based on these results, the question was raised if it is possible to use acoustic emission data for condition monitoring purposes during an extraction process. Therefore, tests with various cutting pick geometries were conducted as well as tests with different cutting speed and cutting depth. The results of the measurement were compared to the results of cutting force measurements.

It was found that the acoustic emissions generated during the cutting process of rock, change with the pick geometry. Both the back clearance angle as well as the rake angle have a direct influence [21]. Not only the geometrical dimensions, but also the wear status of the cutting tool have an influence on the acoustic emissions generated. It appeared that the more a cutting tool is worn out the more acoustic emission are generated. This is because of the greater surface of the picks tip which needs more pressure to force its way into the rock material. Due to this increased pressure more cracks arise in the surrounding rock material which are one of the main sources of acoustic emission. The larger tip surface also induces a larger crushing zone at the tip. The friction between the crushed particles is increased and so is the acoustic emission. From this follows that acoustic emission is suitable to be used as condition monitoring device for cutting tools. To use acoustic emission in the underground cutting process the sensors has to be attached to every cutting pick or at least the cutting drum.

The influence of rotational cutting on the acoustic emission signal was researched as well. As a matter of fact, no negative influence of the cutting track could be observed. The acoustic emission data were measured at three different positions: One sensor was attached to the rock sample. The second sensor was mounted on to the first bearing connected to the cutting wheel. The third sensor was installed on the gear. The sensors located at the sample and the bearing proved to provide sufficient signal strength. The measurement at the gear however was dampened strongly by the coupling installed on the test rig and was of no use.

6 Material Flow Characterization

With a focus on material flow characterization, laboratory tests on artificial mixtures in [22] already showed the potential of the Acoustic Emission Technology in this field of application. The presented tests show the ability to characterize material flows via AE sensors. AE Signals recorded during transport and impact processes were scrutinized to establish characteristic values and parameters based on particle density, particle hardness or the fracture behavior.

In order to employ the acoustic emission technology for material characterization, laboratory, pilot and field tests were conducted. Tests in dry environment and also under wet conditions within a pipe were performed to evaluate the applicability of this technology in different fields. Distinct characteristics based on differences in density, hardness and/or fracture either for the desired ore (mineral/ore/coal) or the host rock were identified. Based on the development of characteristic parameters and algorithms within these tests, a better control of the production processes inside concentrating units will be possible in the future. The developed algorithms will be further validated in future field tests to ensure that they are also reliable for large scale operations. The main approach is to use statistical values to analyze the acoustic emission signal online. The evaluation will focus on different material contents and different material grain sizes.

Besides artificial mixtures of wood pellets and steel nuts in dry environments and different types of spheres – steel, glass, plastic, rubber and wood – within a water stream inside a pipe [22], some realistic mixtures of minerals were already investigated on the test rigs at RWTH Aachen University. These tests showed a particularly good outcome for the analysis of gypsum/anhydrite [1] and coal/host rock [23]. Current tests on sand-gravel mixtures and flint/limestone have delivered promising results so far, too.

In the future, the IMR will develop a complete measurement concept in order to identify the composition of material streams based on high frequency acoustic emission waves. The sensor system detects the impact of the rock on a metallic structure e.g. a chute at a transfer point, a vibratory feeder conveyor or an installed bypass, to detect the characteristics of the material stream. Based on differences in density, hardness and fracture behavior of the analyzed materials, the new designed measurement system should discriminate between the desired product (mineral/ore/coal), dead rock and mixtures of those.

Besides the mass flow and the volume of product per time, the particle size distribution on the conveyor belt or bypass will also be measured. With the additional information of the material stream in real time it will be possible to optimize the efficiency and the performance of the whole transport and the following concentration process with regard to an increase in output and probable cost reduction. The focus also lies on the development of a low cost hardware acoustic emission measuring unit cased in a ruggedized housing which is at the same time easy to apply in operation. Accordingly, to tackle high sampling rates the development of an intelligent data pre-processing method is inevitable to abolish the necessity for storing large amounts of unusable data.

The system itself will need to be mounted at different measurement sections within the process to identify the optimal spot for the generation of additional composition information. Besides that, the hardware module will be evaluated in terms of usability and reliability in open pit as well as underground operations and wet mining processes, where raw material extraction is done under water, e.g. manganese nodule extraction. The implementation of this system will allow the operator to track relevant process parameters online and use this information to optimize the process control and the following processing.

7 Conclusion

Further development of acoustic emission testing is decisively dependent on the use of new methods for collecting and processing data as well as the exploitation of new fields of application. In this paper different use cases were described which have not yet been established as industrial applications:

- Monitoring of slow rotating or oscillating roller bearings
- Detection of the growth of long fatigue cracks in order to determine the endurance fatigue strength
- Differentiation of materials and pick monitoring in support of rock cutting technology
- Material flow characterization under dry and wet conditions

The results of these use cases need to be verified through further field testing. The wireless recording of acoustic emission signals e.g. would enable the application of the technology on rotating machine parts and at locations which are difficult to access. Through miniaturization measuring will be possible in areas with limited amount of space and limitation of radio contact. An increased precision in the detection of bursts will enhance the significance of extracted parameters. The intensified use of up-to-date methods for data processing such as pattern recognition, support vector machines and wavelet analysis could improve the quality of information decisively. Online preprocessing of data, real-time determination of characteristic values, and the use of self-learning systems can concentrate the gained data and accelerate the generation of information in order to reach the goal to enable process control.

8 Literature

[1] F. D. Boos: "Acoustic Emission bei der Maschienen- und Prozessüberwachung - Neue Analysemethoden und Anwendungsgebiete", Aachen, Zillekens, 2015

[2] DIN-EN-1330-9:2009-09: Zerstörungsfreie Prüfung - Terminologie - Teil 9: Begriffe der Schallemissionsprüfung, Deutsche Industrie Norm, 2009

[3] M. Meyer: "Signalverarbeitung Analoge und digitale Signale, Systeme und Filter", 7. verb. Aufl. 2014, Springer Fachmedien Wiesbaden, Wiesbaden, ISBN: 978-3-658-02612-7, 2014

[4] R. Hoffmann and M. Wolff: "Intelligente Signalverarbeitung", 2. Aufl. 2014, Springer, 2014

[5] J. Miettinen and P. Pataniitty: "Acoustic emission in monitoring extremely slowly rotating rolling bearing", in Proceedings of COMADEM, Oxford, 1999, pp. 289-297

[6] M. A. Elforjani: "Condition Monitoring of Slow Speed Rotating Machinery Using Acoustic Emission Technology", Dissertation, Cranfield, 2010

[7] K. Nienhaus, D. Röllinger, D. Boos, T. Vraetz, and R. Baltes: "Condition Monitoring of Oscillating Bearings with Acoustic Emission Technology", Progress in Acoustic Emission XVII, pp. 55-60, 2014

[8] M. R. Stammler: "Blade bearings in wind turbines: Damage modes and test strategies", 2nd Conference for Wind Power Drives, CWD 2015, Eurogress Aachen, 3rd - 4th March, 2015

[9] Abschlussbericht für das Verbundprojekt „Erhöhung der Verfügbarkeit von Windkraftanlagen", IZP Dresden, Fraunhofer-Institut IWES (vormals ISET Kassel), SAG Erwin Peters GmbH, ENERTRAG AG

[10] A. Messner, P. Burgwinkel, and R. Baltes: "Zuverlässige Überwacung von langsam oszillierenden Lagern mittels Acoustic Emission", presented at the 7. Aachener Kolloquium für Instandhaltung, Diagnose und Anlagenüberwachung (AKIDA), Aachen, 2008

[11] C. Klein, C. Emmerich, and K. Nienhaus: "Acoustic Emission und Körperschall in der Wälzlagerdiagnose als Konkurrenten und Partner", VDI Berichte 2191, 2013

[12] D. Röllinger, D. Boos, T. Vraetz, and K. Nienhaus: "Acoustic Emission as a Tool for Condition Monitoring of Oscillating Bearings", 31st Conference

of the European Working Group on Acoustic Emission (EWGAE): September 3 - 5, 2014 in Dresden, Germany / DGZfP, vol. BB 149, 2014

[13] T. Vraetz, D. Boos, D. Röllinger, and K. Nienhaus: "Condition Monitoring of Pitch Bearings with Acoustic Emission Technology," presented at the 2nd Conference for Wind Power Drives 2015, Aachen, Germany, 2015

[14] F. D. Boos, D. Röllinger, T. Vraetz, K. Nienhaus and M. Hessing: "Analyse von Acoustic Emission Signalen mit neuartigen Analysemethoden und fortschrittlicher Hardware" presented at the 10. Aachener Kolloquium für Instandhaltung, Diagnose und Anlagenüberwachung (AKIDA), Aachen, 2014

[15] Z. Han, H. Luo, J. Cao and H. Wang: "Acoustic emission during fatigue crack propagation in a micro-alloyed steel and welds", Mat. Science and Engineering A, 2011

[16] M.N. Babu, C.K. Mukhopadhyay, G. Sasikala, B. Shashank Dutt, S. Venugopal, Shaju K Albert, A.K. Bhaduri and T. Jayakumar: "Fatigue Crack Growth Characterization of RAFM Steel using Acoustic Emission Technique", Procedia Engineering 55, 2013, pp. 722-726

[17] G. Bäckblom, E. Forssberg, S. Haugen, J. Johzannson, and T. Naartrijärvi: "Smart mine of the future", Lulea: Rock Tech Center, 2010

[18] P. Hopwood: "Tracking the trends 2016", Deloitte, 2015

[19] K. Nienhaus, C. Klein, F. D. Boos and R. Baltes: "Acoustic Emission and pick forces in rock cutting", Aachen International Mining Symposium 2012, Aachen, 2012

[20] S. Flach: "Experimentelle Untersuchung zum Einfluss der Spantiefe und Korngröße auf die Acoustic Emission", Aachen, 2016, unpublished

[21] C. Büschgens and T. Bartnizki: "Changes in acoustic emission during linear cutting", MPES 2015, Johannesburg: SAIMM, 2015

[22] T. Vraetz, F. D. Boos, R. Baltes, K. Nienhaus, C. Schropp, K. Neubert, H. Knapp and H. Wotruba: "Material Stream Characterization with Acoustic Emission Technology", 7th Sensor-Based Sorting & Control 2016, February 23-24, 2016 in Aachen, Germany, pp. 259-269, Shaker Verlag, ISBN: 978-3-8440-4323-5

[23] K. Nienhaus, H. Wotruba, F. D. Boos, T. Vraetz, S. Klösges, and K. Neubert: "Combining Acoustic Emission and Vibration Technologies Harbors Huge Potential for Material Characterization", in Chemical Engineering and Technology, 2016, 39, Wiley