European Working Group on Acoustic Emission

EWGAE 2010
Vienna, 8th to 10th September

NDTnet

ONLINE MONITORING OF HOT DIE FORGING PROCESSES USING ACOUSTIC EMISSION (PART-II)

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Keywords: AE, online monitoring, hot die forging, high strain rate, light alloys, Mg alloys

Abstract

In part-I, the feasibility of using AE as an online monitoring technique for industrial forging processes has been investigated. The investigation considered monitoring the upsetting process of axis-symmetric specimens using a self-built data acquisition and analysis system up to 500 kHz. Two magnesium alloys and an aluminium alloy with three different geometries were used during these investigations. The experiments were performed under different thermomechanical loading conditions (temperatures, strains and strain rates). In addition, influences from machine noise, sensor positioning was also investigated and the achieved results were analysed.

In this second part, the investigation was performed in the range 400-1600 kHz using the high-end professional acoustic emission system AMSY-5 (Vallen Systeme, Germany). In this second series of experiments, specimens of the same geometries but of larger size have been used in order to allow more flexibility in the loading scheme, assure minimum temperature drop during the test, facilitate both macro and microstructure analysis and most important to deliver more AE energy to improve the signal to noise ratio.

The first part of this paper is devoted to describe the methodology used to reduce the hydraulic machine noise and discusses the different aspects considered during the choice of the front filters, adjusting the acquisition parameters and setting up signal-selection / rejection criteria. This will be followed by the main results achieved during the upsetting of the Al and Mg alloys specimens. Further, the methodology applied to correlate the obtained AE patterns to the test parameters is introduced.

Introduction

The feasibility of using acoustic emission as an online monitoring technique for industrial forging processes has been investigated in Part-I [1]. The aforementioned investigations considered AE monitoring of an upsetting process of axis-symmetric specimens made of AZ31 and AZ80 magnesium alloys as well as AW7075 aluminium alloy. Three different geometries were used during these investigations. The experiments were performed under different combinations of temperature, strain and strain rates. In addition, influences from machine noise as well as sensor positioning were also investigated and the achieved results were analysed. Based upon the promising results achieved in the first phase, a professional AE system has been employed for the investigations presented in this paper.

First section of this paper will focus on the methodology used to overcome the noise generated by the hydraulic test machine. In addition, different aspects considered during the choice of the front filters, adjusting the acquisition parameters and setting up signal rejection criteria will be discussed. In following sections, the main results achieved during the upsetting of Al and Mg alloys specimens will be summarized. Further, characteristic features from both time and frequency domains will be presented and the methodology applied to correlate the obtained AE patterns to the test parameters is introduced. Based on these results, a new pattern classification indicator will be introduced.

Instrumentation, Materials and Test Setup

In this second part, the investigation was performed using the high-end AE system AMSY-5 (Vallen Systeme, Germany). The system allows high sampling rates up to 10 MHz, the use of different types of resonant and broad band sensors (from 20 to 2400 kHz), variety of acquisition parameters and diverse digital filters. Within the scope of the work presented here, 5 MhZ sampling rate was applied on 3 channels with two resonant sensors (VS900-RIC, Vallen Systeme) and broadband sensor (2045-S, Fuji Sensors). Different front filters were used as it will be shown later. Parametric inputs representing ram displacement and forging force were acquired at 1.2 kHz and synchronized to the AE datasets. The upsetting tests were performed on the Instron (VHS-8800) testing machine. This servo-hydraulic machine provides the capability of performing controlled high strain rate tests on different materials at different levels of temperature. The machine features precision aligned punches, high stiffness load frames and high capacity actuators, and hence it is capable of simulating high strain rate forging processes. The VHS-8800 can be configured through a closed loop control to perform tests from quasi-static to impact speeds as well as cyclic testing.

In the experimental work presented here, three types of alloys were used. AZ31 and AZ80 specimens were manufactured from the same batch used in the preliminary experiments [1], while commercial AW6082 aluminium alloy has been employed as a widely used forging alloy. Same specimens' geometries were employed, but in a larger scale to allow for more flexibility in the loading scheme, assure minimum temperature drop during the test, facilitate both macro and microstructure analysis and most important to deliver more AE energy to improve the signal to noise ratio. The geometry and the dimensions of the used specimens are shown in Fig. **1**. The cylindrical specimens were used to evaluate the role of standard specimen geometries in characterising upsetting processes. The modification in the specimen geometry through the introduction of collar or through recessing and drilling was performed to develop stress concentration zones, which are more vulnerable to damage.

The upsetting tests were performed on the hydraulic testing machine VHS-8800 (Instron) at temperatures of T = 200°, 300° or 400°C and strain rates of $\dot{\varepsilon}$ = 1, 10 or 20 s^{-1}. To assure nearly constant temperature during the test, the specimens were heated and compressed within a hardened steel container. To study the influence of geometry and the sequence of deformation as well as the damage mechanism on the generated AE, the specimens were upset from 36 mm to different end heights of 28, 21, 14 or 10 mm depending upon specimen geometry, temperature and strain rate.

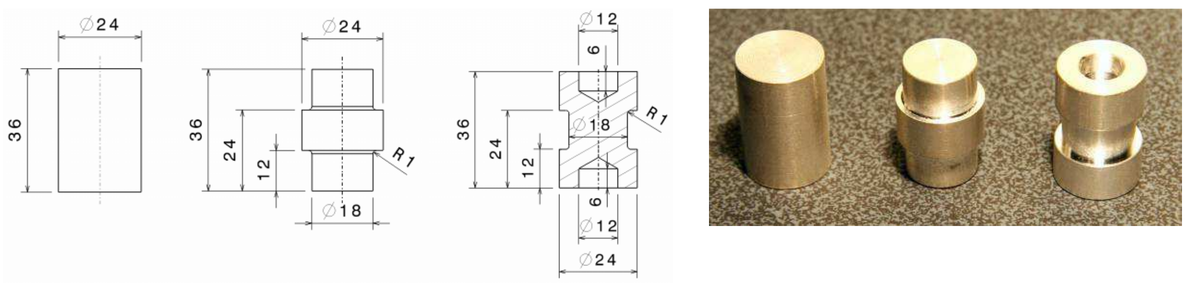


Fig. 1: Geometry and dimensions of the specimens employed in the upsetting test

Treatment of Noise and Optimisation of Acquisition Parameters

One of the major difficulties facing even AE experts is the presence of noise. Our aim was to provide guidelines, which can be applied by technicians or engineers, to perform the test with standard components and to extract the results with commercially available software. Two sets have been intended: a set for threshold-based acquisition and a set for continuous acquisition.

In the current investigations, the wideband background noise was caused mainly by the hydraulic machine drive. Moreover, an isolation of the generated noise due to the actuators actions or piston motion was not possible. As a result, the detected back ground noise on the machine punch was about 45-50 dB_{AE} during the free run of the machine, while a burst signal of 60-65 dB_{AE} is recorded during valve activities. Moreover, the circulation of the punch cooling water results in an additional noise of about 30 dB_{AE} in magnitude. Even if this back ground noise could be filtered out based on their energy level, a non-terminating AE signal that saturates the channel was always acquired as soon as a high-amplitude or high-energy event takes place (e.g. due to Hsu-Nielsen source). Even with the shortest available setting for DDT[i] and RAT[ii], it was not possible to realise hit termination. This resulted in a false estimation of the hits and hence all derived parameters (hits, counts, energy, duration, rise time, etc.). By applying a threshold of 50 dB_{AE}, it was possible to identify the start and end of bursts. These bursts featured some sort of systematic pattern similar to amplitude modulated sine waves. These bursts were generated by hydraulic pump or solenoid activation. By applying a front high-pass filter (300 kHz), the high peak/low frequency noisy portion of the signal could be cut off. The remaining machine noise could be filtered out through the use of additional subsequent filtering based on combination of signal duration and energy level. A band bass filter (400-1600 kHz) has been implemented for the rest of investigations, so that only signals of high frequency are acquired and stored.

Applying these threshold and filter settings, the sensitivity of identifying AE hits during upsetting of recessed aluminium samples was investigated based on various combinations of DDT and RAT values. Through the examination of waveforms and corresponding AE parameters (hits/cascaded hits) best possible combinations were realised by setting the RAT to values between 400 µs and 1 ms and the DDT to 50 µs shorter durations. A shorter RAT may result in better separation of the hits, but it diminishes the capability of identifying the overall AE pattern, and hence weakens the possibilities of correlation to physical events. With increasing the difference between the rearm and discrimination times (e.g. 200 µs), a huge amount of cascaded hits was registered unsystematically so that interpretability was negatively affected.

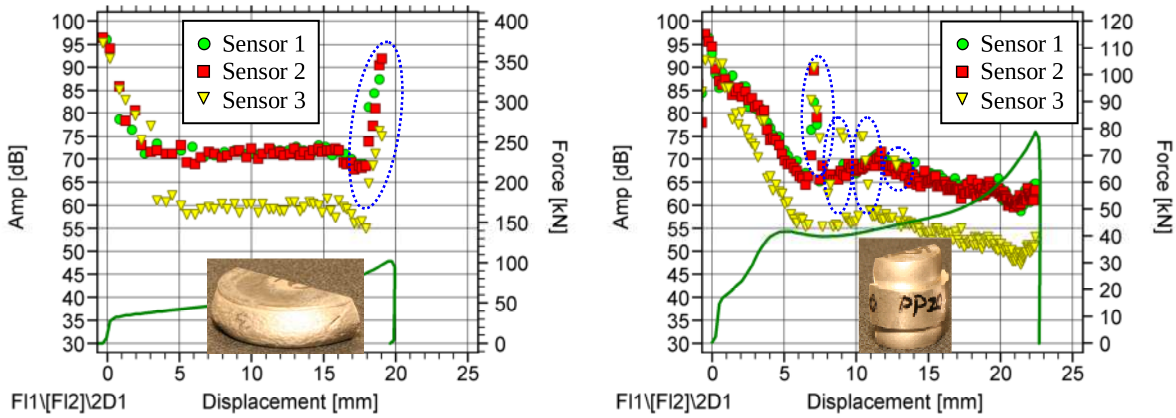
In case of continuous acquisition, various sets of parameters were tested while applying the same threshold and band-pass filter. Appropriate results could be achieved using 4096 samples at sampling rate of 5 MS/s (page length of 819.2 µs) or 10 MS/s (page length of 409.6 µs), RAT of one page of 409.6 µs and an automatically set DDT of 409.4 µs. The page length has been chosen, so that the physical meaning of the activities generating the AE can be correlated and interpreted. A very short page length would result in abstraction to single hits, while a very long one will reduce the resolution of displayed signal and hence the ability to describe the patterns. Contrarily, it will give a better recognisability to the relation between AE and the progress of the forming process. The latter influence can be compensated for by correlating the calculated AE parameters (amplitude, energy, counts, etc.) to the history of parametric quantities like the force or displacement. During test performed in continuous acquisition mode. It is clear that the high acquired energies, hit rates and short temporal separation among hits encountered in this investigation is directly related to process configuration (e.g. the high upsetting velocity / existence of stress concentrations). This presents a new challenge for AE specialists as well as for AE system manufacturer to develop a method and system that is capable of coping with these demands in order to bring AE onto the metal forming manufacturing lines.

Acoustic Emission Detected for Specimens with Peculiar Behaviour

In order to infer about the type of AE pattern accompanying internal or external changes in material or process (yielding, deformation, friction, etc.) or damage (crack initiation, crack propagation, complete failure), AE parameters alone were not sufficient in all cases. More detailed examination of the AE waveform was besides required. Even with wave analysis in the time domain, it was not possible to distinguish between some particular events. A spectral analysis has been performed in addition in order to incorporate more information from the frequency domain. Although many of the available TFR analysis methods are suitable for detailed analysis and correlation purposes, they do not suit quality control applications which normally require a discrimination index for the purposes of fast/online classification and decision making. By the end of investigations, it has been possible to define a set of analysis parameter or signal characteristics, which can be combined to detect different events and to correlate them to the corresponding phenomena or mechanisms. Some of the applied methods may be directly applied for failure detection in a “Go/No Go” quality control system. However, a systematic and simplified diagnostic method was needed in order to bring AE to the manufacturing lines.

AE Maximum Amplitudes during Cracking

Crack initiation and propagation events emit a lot of free energy in form of AE. Cracking is a complex process which combines simultaneous different deformation levels and events that extend from elastic to sever plastic deformation and failure. Due to the concentration of crack sources locally, depending on the geometry of examined object, many AE signals/hits may superpose resulting in high amplitude AE signal. The examples presented here do not show the entire results of all performed experiments, but are intended for a guided presentation of situations at which AE method excels as a promising online monitoring tool for metal forming applications. For example, aluminium specimen, shown in **Fig. 2**-a, has reached its forming limit after upsetting stroke of nearly 18 mm. The crack on the surface of the middle section (collar) was visible to the naked eye. The change in AE peak amplitudes is so large to discriminate from the background level and the load case is favourable for cracking. Moreover, the events have been located by all sensors: an easy-to-detect case. Such cases represented the major portion of all failures encountered during the upsetting of cylindrical specimens which mainly failed at their forming limit with shear cracks on their surface.



a) Single surface crack developed in AW6082 specimen upset at T = 300 °C and $\dot{\varepsilon}$ = 10 s^{-1}

b) Cracks at transition radius developed in AZ31 specimen upset at T = 400 °C and $\dot{\varepsilon}$ = 10 s^{-1}

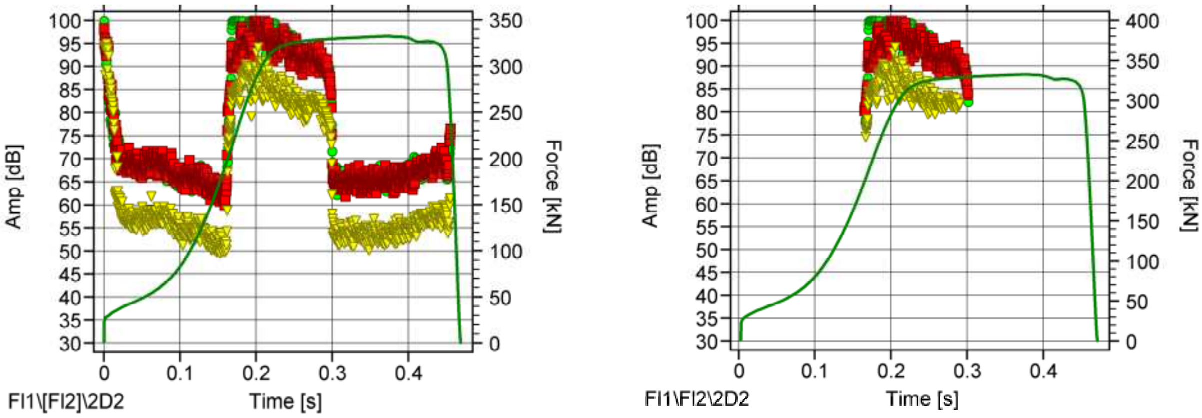
Fig. 2: Examples of high amplitude crack signal emitted during upsetting of collar specimens made of AW6082 and AZ31 alloys

In case of AZ31 specimen, Fig. **2**-b, higher activity levels have been recorded from the beginning of deformation. At onset of cracking, a number of higher hits (64 ~ 90 dB) could be distinguished from the background level (≈ 54 ~ 60 dB). A number of hair cracks could be visually detected on the surfaces of both upper and lower cylinders. The fine shear cracks were mainly directed along the ±45° to the upsetting direction. The detection of the latter crack events was only possible with aid of the 2 MHz broad band sensor, while the same events were detected by the VS900-RIC sensor at amplitudes comparable to the level of normal deformation signals. This means that it is possible and practically more advantageous to detect crack events at very high frequency bands over 1 MHz. In other words, it is more beneficial in case of forming industry, where very high levels of noise and interruptions from hydraulic machines are present, to acquire AE cracking signals with broadband sensors in the range above 1MHz.

AE Peak Amplitudes during Friction

Friction is considered as one of the most important aspects which should be considered during the study of metal forging processes. The AE emitted during forging operations can vary widely based on the process condition. Based on forging temperature, velocity as well as the quality of lubrication, friction related AE may vary from a continuous and low amplitude signal to relatively short/intermittent signals of higher intensity. **Fig. 3**-a represents the AE peak amplitudes encountered during the lubrication-free upsetting of a cylindrical AW6082 specimen at 400 °C and $\dot{\varepsilon}$ = 10 s^{-1}. This sudden and large increase in the AE level, which is comparable to those signals at yielding, was not accompanied by any remarkable failure in the specimen. Further criteria are required to infer about the cause of the high AE amplitudes and energy levels.

Although the discrimination among some types of patterns could be achieved with the aid of a combined energy and count filter, the difference among friction, deformation (yield) and cracking signals could not be realised based on these simple criteria. It is well known that many AE parameters are dependant on acquisition parameter, especially the threshold and RAT settings in correlation with strain rate. For example, all friction hits described in the previous case could be discriminated from the events encountered at the elastic plastic zone as well as from the deformation hits by rejecting the hits counts less than 50 and energies below 500E+03 energy unit, as shown in **Fig. 3**-b. However, waveforms should be examined to verify the assumed filtering criteria. Moreover, detailed analysis of the AE patterns is necessary in order to provide a correct and accurate correlation between the acquired AE and the encountered events.



(a) non filtered (b) filtered

Fig. 3: AE peak amplitude acquired during lubrication-free upsetting of cylindrical AW6082 specimens at T = 400 °C and $\dot{\varepsilon}$ = 10 s^{-1}

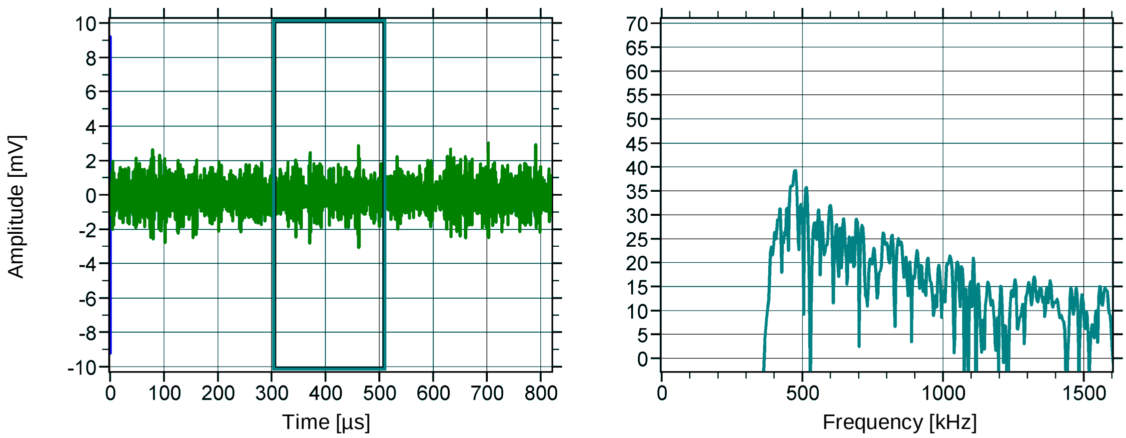
AE Waveforms and Spectrums in Correlation with Physical Events

In this section, some examples of the waveforms recorded by the transient recorder during some of the previously presented cases will be used to show how it is possible to differentiate between different events based on their characteristic patterns. The next examples are mainly related to the forging process and can be divided into three main groups. The first group includes AE patterns usually obtained during deformation. Within this group, the patterns acquired at the elasto-plastic transition differ from those encountered during fully plastic deformation.

Depending on the material family, there exists some deviation in the form acquired in the time domain, too. The second group is comprised of typical AE patterns encountered during cracking. The patterns within this group can be classified according to the stages of cracking process. Some similarities/discrepancies to deformation-related patterns encountered at high strain rate test will be discussed. In the third group, waveforms and frequency spectrums related to friction events will be focused on. Features that can be used to discriminate friction-related AE patterns from cracking and deformation-related patterns will be discussed. Other patterns, which mainly represent systematic low energy machine-related activities discussed previously.

Group 1: AE waveforms/patterns encountered during deformation

AE patterns emitted by deformation events possess two main characteristics. In time domain, the signals seem – at first look – similar to friction signals overlapped with some noise signals or similar to machine noise signals. Because of application of the high-pass filter, machine signal have been completely filtered out, so that no signal is acquired during free-run status. In frequency domain, the spectrum is characterised by wide band excitation of low energy content. Because the start and the end point of hits could not be distinguished in the time domain, the frequency spectrum represents an overlap of different signals resulting in a non-smooth FFT profile due to the moving windowing effect (**Fig. 4**).

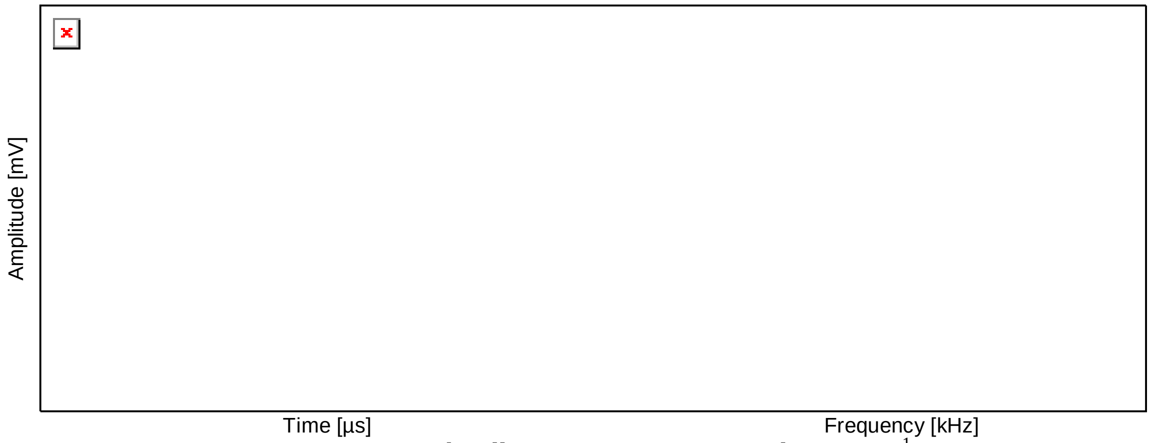


Recessed AZ31 specimens upset at T = 300 °C and $\dot{\varepsilon}$ = 1 s^{-1}

Fig. 4: Examples of yielding signals in time and frequency domains at low velocities

With increased test temperature at low strain rate ($\dot{\varepsilon}$ = 1 s^{-1}) no significant change could be determined in the AE level during plastic deformation of the tested aluminium and magnesium alloys. Contrarily, the AE level at yield featured significant increase with increasing strain rate in case of magnesium alloys. Moreover, an increase in the overall AE activity level and amplitudes has been recorded during upsetting of all recessed specimens tested at temperatures above 300 °C and strain rates above 10 s^{-1}, even if the specimens were not cracked. Upsetting the specimen with collar under the latter conditions exhibited only high AE at the yield zone but not during the plastic deformation. Detailed microstructural examination of those recessed specimens showed a clear dynamic recovery (DRV) and dynamic recrystallisation (DRX) along developed shear zones. A phenomenon described by other authors in AW6xxx and AZxx alloys [2].

With increasing the upsetting velocity, a significant change can be observed not only in amplitude but also in the recorded AE pattern as shown in **Fig. 5**. A sequence of equispaced hits that lasts over the elasto-plastic deformation zone. In addition, the calculated FFT spectrums exhibit mutual features, which are completely different from those described before in case of low strain rates. For a single hit, the main energy content extends over the range 400 - 800 kHz. Thereafter, a nearly linear decay is observed, because the high amplitude signals emitted at the higher strain rates imply lower frequencies.



AZ31 specimen with collar upset at T = 300 °C and $\dot{\varepsilon}$ = 10 s^{-1}

Fig. 5: Examples of yielding signals in time and frequency domains at high velocities

Group 2: AE waveforms/patterns encountered during cracking

Signals related to cracking events are characterised by a number of features in both time and frequency domains. In time domain, a number of transient impulses, whose rate is proportional to the crack propagation rate, can be detected.

The example shown in Fig. **6** represents a typical crack-related pattern in dependence on the tested material and the applied strain rate. Very high amplitude signals can be directly observed. This is usually followed by instable crack propagation phase, in which many parallel cracking events of different peak amplitudes can be encountered, especially under severe deformation conditions at higher strain rates. This leads to the formation of complicated patterns composed of hit-packets arising from different consecutive activities. The number of hits, counts as well as the amplitudes is proportional to the amount of emitted energy, which is consequently related to the severity of damage. Observation of hits' progress for a longer duration (zooming out on the time scale) can be used to infer about the stages of the forming process as described in previous paper.

In frequency domain, the crack related hits are characterised by high energy content at very high frequencies up to 2 MHz, as shown in Fig. **6**. For tests carried out at higher strain rates, one should be careful not to mingle the detected AE patterns due to cracking with those resulting from deformation at the yield zone, and which has been shown in group 1.

Recessed AZ80 specimen upset at T = 400 °C and $\dot{\varepsilon}$ = 20 s^{-1}

Fig. 6: Example of crack related signals in time and frequency domains

Group 3: AE waveforms/patterns encountered during friction

Friction signals possess relatively longer patterns, which take the form of constant sine wave or a sum of a few harmonic sinusoidal waves of different amplitudes. This can be observed in the frequency spectrum by the existence of a number of peaks at few harmonic related frequencies as shown. These examples show that the whole friction pattern may run constantly between two bounds or may be modulated by lower frequency wave as shown in Fig. **7**. The encountered amplitudes may reach very high levels as shown here. These amplitudes can be high enough to be comparable with those emitted by complete failure events.

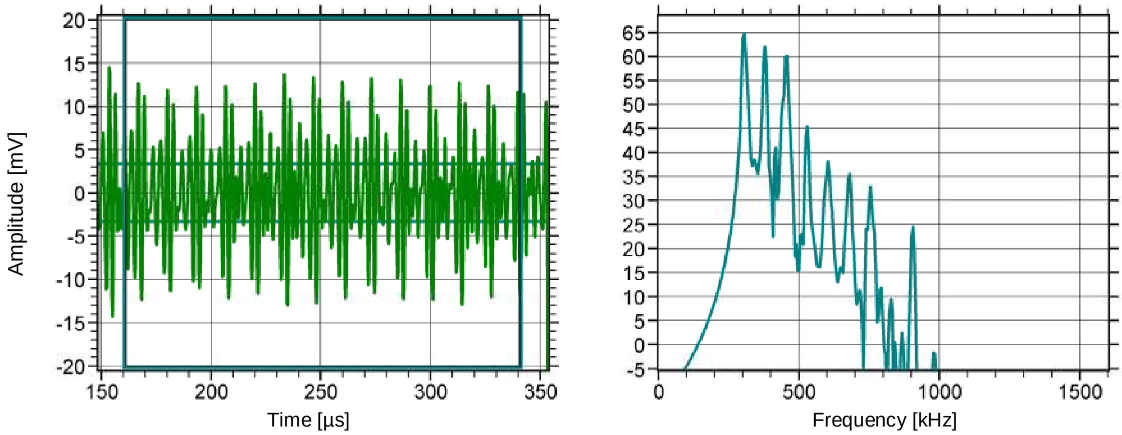


Fig. 7: Examples of frcition-related AE patterns showing harmonic wave components (AW6082 cylindrical specimen upset without lubrication at T = 400 °C and $\dot{\varepsilon}$ = 10 s^{-1})

AE Patterns Indicator for Forging (AE-PIFF)

Through the previously presented examples, it can be shown that AE amplitude can not be used alone to infer about the encountered events. Although a combination of AE parameters may be helpful in identifying process instabilities / interruptions or to infer about its severity based on comparison with some reference values, it is neither possible to identify its origin accurately nor to perform this correlation / evaluation online. Moreover, the analysis of AE wave forms and the corresponding frequency spectrums is an experience-dependent task, which is completely associated with a lot of tedious and interminable work that does not fit to industrial applications. A method for AE analysis that can be applied to infer about the type of signal and correlation of patterns to definite events without comparing to a reference signal or patterns is being currently under development. A simplified pattern/event classification indicator which is based on combination of some basic AE signal parameters, derived spectral components along with weighing parameters based on timing is being verified. The AE pattern indicator for forging is tested not only capable of distinguishing different types of events but also to categorise them.

Acknowledgement

The authors would like to thank the German Research Foundation DFG for the financial support of the current work within the frame work of the Project BE-1691/78

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[i] **Rearm Time (RAT):** The duration after which a new hit (or a set of hit cascades) should be registered. Rearm Time starts when the signal falls below threshold and expires when no threshold crossing has been detected during its duration.

[ii] **Duration Discrimination Time (DDT)** defines the detection of the end of a hit. The DDT timer starts with reset of RAT. If no threshold crossings are detected for the length of the DDT, the end of the hit is determined and the hit duration is calculated.