Filtering of Acoustic Emission Signals for the Accurate Identification of Fracture Mechanisms in Bending Tests

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In this manuscript, acoustic emission (AE) analysis is used to identify the fracture mechanisms that take place during a three-point bending test of steel specimens. However, an important source of AE was detected and related to the deformation of the supports and the surface of the steel specimen in contact. This source creates AE signals that are very high in number and amplitude, and prevent determining accurately the onset stress for fracture mechanisms in specimens. A signal filtering is proposed based on the properties of the initial part of the recorded AE waveform, combined with a linear localization. The filtering successfully allows the AE signals to be classified according to their source as background noise, damage due to contact of the specimen surface to the supports and fracture mechanisms occurring in the specimen microstructure as a result of the bending test. The aforementioned filter has been successfully applied in case of a cold work tool steel DIN 1.2379 to determine accurately the stress level at which the first damaging mechanisms start to occur in the microstructure in situ during the three-point bending test. Filtered AE signal results indicating damage in the microstructure have been corroborated by inspection of the specimen’s surface in a Confocal Microscope. In default of using the proposed filter, unfiltered signals have been estimated to lead to an overestimation of critical stresses of about 20%, what is undesirable for most applications. [doi:10.2320/matertrans.M2013089]

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1. Introduction

Acoustic emission (AE) technique is a non-destructive testing (NDT) method useful in: (i) characterizing materials and (ii) monitoring the health of structures and machines.1–3 It is a powerful NDT method because self-generating flaws emit stress waves that can be detected with appropriate sensors, and the characteristics of the acquired signals are useful to evaluate the damage that is occurring within the material. This is the main advantage of the technique, but also its principal limitation due to the fact that the signal intensity cannot be controlled and the test is unrepeatable.4

In order to characterize the mechanical behavior of a material, monitoring the test with AE becomes a tool for understanding what is happening to the material throughout the whole test. However, acquired AE signals depend on several factors such as the type of mechanical test, the material under consideration and its types of damaging mechanisms, surface roughness, etc. Moreover, these signals are usually contaminated by background noise that can be classified according to its origin: the one inherent to the measurement chain (including both mechanical and electrical origin) and the one that appears as a consequence of the mechanical process being evaluated. Any noise, despite its origin, impairs the correlation between the failure mechanism and AE data. Therefore, the interpretation of the AE signals may produce an erroneous evaluation of the real damage. As a result, it is essential to apply some kind of filter in the acquisition and analysis of data, especially in the case of seeking the incipient origins of flaws.

Some methods have been proposed to extract the signals related to relevant sources of AE based on: (i) time domain features,5–6) (ii) frequency domain features6–7) or (iii) localization of the origin of the AE signal and relating this position with a possible real source of damage.8–9) In all cases, the filtering process used characteristics of the waveform (Fig. 1) as: duration (D), amplitude (A), energy (E), rise time (RT), frequency (f), etc., or a combination of them. It is accepted that damage signals are of higher amplitude and higher frequency than those relative to noise, which, in general, present lower amplitude, more duration, higher rise time and more absolute energy/signal strength than a crack or damage signal.9) As a result, most of the usual filtering processes are based on these general features of the signals.5–7) However, when AE is attempted on a laboratory scale, on small specimens, the waveform is overly deformed due to the reflections produced in the surfaces and the results of the filters are less effective than in big structures.

Many research studies on damage mechanisms for fragile materials use the bending test to identify the beginning of each damage mechanism10–14) (for example, in tool steels, cracking of carbides, decohesion between carbides and the
metallic matrix, plastic deformation, growth of cracks etc.). The bending test generates damage in a small area of the stressed specimen’s surface that can be controlled by microscopy, but it is difficult to detect the beginning of the damage mechanism with precision. The use of this test in a stepwise loading mode and comparing the AE signals with the observed damaged surface with a microscope facilitates the relating of the signal’s features with the mechanism that generates them. However, AE signals caused by the deformation of the specimen at the upper and lower supports (background noise due to the mechanical process) have the potential of masking the AE signals related to the damage mechanism; therefore preventing the detection of the applied stress at which the fracture mechanism takes place.

The purpose of this investigation is to develop a signal filtering process capable to discriminate between AE signals emitted by natural damage mechanisms in specimens from others caused by the interaction of the specimen with the supports necessary to carry out the mechanical test. This enables to filter all AE signals not related to the damage mechanisms under investigation. The novelty of this type of filtering is that it extracts information only from the first cycles of the signals instead of from their whole length. In this work, the filtering process is applied to a three-point bending test of a cold work tool steel DIN 1.2379 in order to determine the onset stresses for the acting damaging mechanisms involved in the fracture process.

2. AE Sources in the Three-point Bending Test

In three-point bending tests the most stressed area and in which damage and final failure takes place is the centre of the specimen (Fig. 2). However, the AE signals emitted by natural damage generated in the microstructure as a result of the mechanical test are affected by both the background noise due to the measurement chain and the mechanical process.

The background noise related to the measurement chain in this kind of test can be reduced by using general measures conventionally employed in AE. These measures include the careful assembly of the acquisition system, which involves protecting the sensors, fixing the cables to avoid that they move and selecting the correct threshold to limit the quantity of signals reaching the sensors. Another common practice consists in applying a low frequency filter with the aim of cutting out vibration and machine noises.

Mechanical process background noise is mainly due to the high contact pressure at the specimen surface directly in contact with the supports of the bending fixture. These zones in the specimen can be severely damaged during the test, and they also generate AE signals. This spurious noise can be eliminated with a lineal location processor. In Fig. 2, the signals produced in zone II or III correspond mainly to this type of noise. The main problem occurs in the zone of interest (zone I), where the generated AE signals have two next damage origins: (i) the contact pressure between the upper central support and the specimen (noise signals) and (ii) the stress state induced in bending (signals of interest). The elimination of this kind of spurious signal has been attempted by different AE filtering processes, such as:

(a) To raise the threshold before or during the test. This procedure is not valid if the measurement deals with the nucleation of incipient cracks in the microstructure, because the energy released is very low and valid AE signals could be excluded.

(b) To study the relationship between the duration and amplitude of the signals. Swangson filters define some combinations of values to identify noise signals. It is a filter strongly dependent on the threshold and the waveform. In small specimens, the distorted waveforms make these filters unsuitable.

(c) The use of master-slave or guard technique. Master sensors are mounted near the source of interest and enclosed by others called slaves or guard sensors. If any signal arrives first to a guard sensor, it is rejected. This is useful only if the source of the signals is isolated.

(d) Some studies are based on frequency domain features in order to determine the damage severity or to identify different damage mechanisms, but they are not used to filter background noise (except low frequencies or noises with clear frequency predominance). In the case of small specimens, multiple reflections produce change of modes that distort the characteristics of the frequency domain.

3. De-noise Filtering Process

Although during the test, possible sources of background noise were identified and isolation mechanisms were applied (as detailed in Method section), the raw data acquired still
contain noise signals. The de-noise process developed in this work deals with the elimination of the AE signals which are emitted by (i) residual environmental noise (measurement chain noises) and (ii) AE signals related with the contact between supports and the specimen (mechanical process noise). As mentioned before, the waveforms in small laboratory specimens are quickly distorted, especially if they are made of a metallic material with low attenuation (Fig. 3). Therefore, the use of parameters related to AE wave shapes could be confusing to classify signals. Taking into account the small size of the specimens used in this study (as shown in section 4.2), only the very first cycles of the waveform carry information about the source (the rest of cycles must be discarded as they are affected by boundary reflections). This initial segment of waves is defined as $TS_1$ (Fig. 3) and its features were analyzed to identify the main characteristics of signals originated in zones II or III (Fig. 2), corresponding to damage due to supports and specimen surfaces. Then, the signals originated in the central area of the specimen (zone I) with similar characteristics to those of zones II and III were eliminated. This filter leaves AE signals exclusively related to microstructural damage generated as a result of the applied load during the bending test. Figure 4 presents a schematic diagram of the filtering applied in this work and the algorithm is summarized as follows:

- **Time segment definition:** Each signal is divided into three time segments (Fig. 3): (i) Signal segment 1, $TS_1$, (ii) signal segment 2, $TS_2$, with a length of three times $TS_1$, with the aim to include the peak amplitude of the signal, and (iii) signal segment 3, $TS_3$, including the full length of the signal excluding pre-trigger. $TS_2$ and $TS_3$ are used to clearly identify burst from continuous signal types. Continuous signal types are related to background noise and plasticity mechanism.20

- **Origin of hits:** Using linear location algorithms, the hits are classified according to their origin in the range of zones I, II and III (Fig. 2). The location in the x-zone is an event builder constructed with an x-sensor defined as normal and others defined as guard sensors. The velocity of propagation and the distances between sensors are detailed in Method section.

- **Initial classification of the signals:** according to the time segment definition and signal origin, the signals are defined as $H_{ij}$ where $i = 1...3$ refers to the time segment and $j = 1...3$ refers to the origin of the signal.

  - **Time domain features:** the average amplitude of each time segment ($AT_{ij}$) for all signals is obtained by the Root Mean Square (RMS) method.

  - **FFT features:**
    - (i) Two frequency segments ($k$) were defined between 95–450 kHz ($k = 1$) and 450–850 kHz ($k = 2$); in accordance with the sensor response.
    - (ii) $AF_{ij}(k)$: average amplitude in the frequency domain of the signal.

  - **Definition of decision variables:**
    - (i) Amplitude Ratio ($AR_i$) defined as the ratio of $AT_{2,j}$ to $AT_{3,j}$; to identify burst type signals from continuous ones.
    - (ii) Spectral Bands Ratio ($SBR_{ij}$): is the ratio of $AF_{ij}(1)$ to $AF_{ij}(2)$ for $i = 1$. This indicator allows the clustering of signals according to the energy distribution in the frequency segments previously defined.

  - **Criteria for discrimination of the measurement chain for background noise:** to reject signals which present a continuous waveform. In this particular case, after observation, the threshold of $AR_i > 6$ dB gives good results.

  - **Classifying damage mechanism:** Identify appropriate features capable of clustering signals. For this study: the correlation between $SBR_i$ and $AT_{1,i}$.

### 4. Method

The filtering process is applied to the acquisition data obtained in a monotonic three-point bending test. To correlate
and identify AE signals with specimen damage a Confocal Microscope (CM) is used to inspect the microstructure of the samples.

4.1 Experimental procedure

The three-point bending test is carried out in a universal testing machine with a constant span length of 40 mm using an articulated fixture to minimize torsion effects. The displacement rate applied was 0.1 mm/min and the test took place at room temperature. The set-up is schematized in Fig. 2.

4.2 Specimens

Cold work tool steel DIN 1.2379 specimens were used in this investigation. They had a prismatic shape (length = 50 mm, width = 8 mm and thickness = 6 mm) with the forging direction oriented parallel to the long axis of specimens. Samples were mechanically ground and their corners were rounded to avoid stress concentration and remove any defect introduced during sample preparation. The face subject to tensile stress during the bending test was carefully polished to a mirror finish using colloidal silica particles measuring approximately 40 nm.

The goal of the three-point bending test coupled to AE analysis in this tool steel is to obtain accurate data regarding damaging mechanisms at the initial stage of fracture. Picas et al.\textsuperscript{21} reported that breakage of primary carbides determines the onset for crack nucleation and propagation in tool steels under monotonic conditions. Thus, AE signals emitted by carbide failures were sought in this work. In order to verify that the breakage of carbides generates different signals with respect to those caused by contact pressure at upper and lower supports, the three-point bending test was also performed with a spring steel DIN 55Cr3. This is a martensitic steel with no large primary carbides embedded as in 1.2379, that is why no AE activity was expected related to their breakage. The chemical composition and hardness of 1.2379 and 55Cr3 are summarized in Table 1.

4.3 AE Measurements

Figure 2(b) shows the AE acquisition set-up. The equipment was an AMSY-5 (Vallen System, GmbH) equipped with four channels and connected to a computer with VisualAE software (Vallen System, GmbH). The test was monitored using three small resonant-type sensors firmly attached to the specimen. One sensor (S1) was mounted in the center of the tensile face, and the other two (S2 and S3) were on the opposite side. All of them were aligned with the three supports of the bending fixture. The sensors present a resonant frequency centered on 700 kHz, but their response is relatively flat until 450 kHz and between 550 to 800 kHz. To guarantee enough acoustic transmission, silicone grease was introduced between the plate of the sensor and the surface of specimen. The three (central and roller) supports were covered with a PVC film with a thickness of 0.15 mm, to minimize the frictional noises with the specimen during the test.

Some preliminary measurements of the background noise were conducted in order to determine the threshold level. In this case, four sensors were attached to the specimen and the upper anvil assembly. As AE activity was detected with amplitudes below 30 dB, the threshold level was fixed at 34 dB.

The propagation velocity through the specimen was determined using two simulated AE events: a Hsu-Nielsen source (pencil lead break) and digital signals sent through the sensors. Acquisition parameters and event builder parameters are summarized in Table 2.

5. Results and Discussion

Figure 5 shows the cross-plot correlation of $SBR_j$ versus $AT_{1,j}$ for the two steels during the three-point bending test. Figure 5(a) plots the results of 1.2379 and it shows a clear common area for hits in zones I, II and III (superimposed on the graph). Hits located in zones II and III can only occur due to contacts with the rolling supports. Hence, hits located in zone I with similar characteristics of $SBR_j$ versus $AT_{1,j}$ to those of zones II and II are assumed to be generated by the contact of the specimen with the upper central support. The signals with a different relationship between $SBR_j$ and $AT_{1,j}$ are only located in zone I and correspond to the relevant signals for the test (natural damage in the microstructure as a result of the applied stress). The sources of these hits are carbide breakage and crack nucleation and propagation from them. The events located in zone II and III with higher amplitude (80–85 dB) correspond to the movement of the supports due to the displacement of the load device when the test was finished (encircled in Fig. 5(a)).

The spring steel specimens were employed to check the results of the clustering process, as shown in Fig. 5(b). The located hits in each zone of the specimen have similar characteristics in reference to the relationship between $SBR_j$ and $AT_{1,j}$. In this case, the predominant source of AE was that generated by contact pressure between supports and specimen surface. Nevertheless, a larger quantity of hits was located in zone I (Fig. 5(b))—central support was double force that the rolling supports—and some damage occurred in the center of the specimen that was related to plastic

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Mn</th>
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<tr>
<td>1.2379</td>
<td>1.5–1.6</td>
<td>11.0–12.0</td>
<td>0.6–0.8</td>
<td>0.9–1.0</td>
<td>—</td>
<td>60–62</td>
</tr>
<tr>
<td>55Cr3</td>
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<td>0.85</td>
<td>—</td>
<td>—</td>
<td>0.85</td>
<td>43–45</td>
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<table>
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<td>Sample rate</td>
<td>10 MHz</td>
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<tr>
<td>Threshold, Thr.</td>
<td>34 dB</td>
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<tr>
<td>Ream Time, RT</td>
<td>0.0512 ms</td>
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<tr>
<td>Duration Discrimination Time, DDT</td>
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<td>1st Hit Discrimination Time, FHCDT</td>
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<tr>
<td>Time segment 1, $TS_1$</td>
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</tr>
<tr>
<td>Time segment 2, $TS_2$</td>
<td>10 µs</td>
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<tr>
<td>Time segment 3, $TS_3$</td>
<td>50 µs</td>
</tr>
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</table>
deformation taking place in the microstructure. The similar results for both steels, with one common mechanism of damage, permit the identification of the characteristics of the contact pressure damage signals. So, the relationship \( SBR_j \cdot AT_j \) becomes an indicator of damage in the supports during the bending test.

Having identified the characteristics of the signals corresponding to damage generated at contacting points of the surface, signals measured in 1.2379 steel with identical features of 55Cr3 steel were removed (Fig. 6(a)) from the raw data. Figure 6(b) presents cumulative hits that first arrived to S1 during the test and compares results for unfiltered (■-line) and filtered data (○-line) of a 1.2379 specimen. The filtering process eliminates an important quantity of undesirable hits, in this case around of the 60% of the signals.

Figure 7(a) shows in more detail data plotted in Fig. 6(b) and it can be observed that the hits located in zone I according to the filtered data (○-line) begin later than with unfiltered data (■-line). Results of microstructural inspection of 1.2379 at zone I at a stress level below 800 MPa show no damage (see Fig. 8(a)), while above 800 MPa carbides have already broken (Fig. 8(b)). Note that if the data is not filtered, the conclusion could be that carbide cracking begins at around 650 MPa, while in reality it occurs at more than 800 MPa in this specimen. This result points out the importance of extracting relevant signals to evaluate the onset stresses for damage in the microstructure of a specimen. Comparable results were obtained by Fukaura and Ono\(^{22}\) testing a JIS SKD11, equivalent to a 1.2379, in a tensile test without the problem of pressure contacts.
The signals located in zones II and III were also correlated with the micrographic images, as shown in Fig. 9 in case of 1.2379. It can be seen that damage generated due to contacts with the rolling supports can be very different from specimen to specimen, and even in one single specimen if applied stresses are similar. In Fig. 9(a) there is virtually no damage, in Fig. 9(b) the damage is visible and in Fig. 9(c) the damage is severe (presenting scratches, cracks and even some broken carbides). Such differences may probably be explained due to relative movements of specimens and lower rolling supports during the test.

Figure 10 shows the cumulative unfiltered hits that reach S2 and S3 first for two different specimens. In both cases the cumulative number of hits increases exponentially during linear load increase. At the beginning of the tests, with low loads, there is no damage to the specimen and practically no hits are getting to sensors S2 or S3. When damage is generated in the surface of the specimen in contact with...
rolling supports, some hits appear and grow continually until the load is removed. Moreover, the total number of hits in these sensors is related to the severity of the damage induced in the specimen. Specimen P3 presented low damage on the contact surface (Fig. 9(a)) and similar results were observed in both contact surfaces in zone II and III. The number of hits related to contact damage is presented in cumulative form in Fig. 10(a). S1 and S2 present equal behavior and a similar total number of hits. Instead, specimen P2 presents two different behaviors at the contact area; at one area (in zone II) severe contact damage were observed (Fig. 9(c)), while at the other roller support contact area there is almost no damage (Fig. 9(d)). The sensor mounted at the closest position to this damaged surface was S2 with more than 400 hits (Fig. 10(b)), while signals with first arrival to S3, mounted near the non-damaged surface, only presented 60 hits. It allows stating that there is a strong relationship between this cluster of signals and the observed contact damage.

6. Conclusions

The technique of acoustic emission measurements has been successfully applied to detect and identify the fracture mechanisms in steels with high hardness levels (higher than 44 HRC, as a tool steel and a spring steel) by means of three-point bending test. The main difficulty from the AE measurements point of view is the coexistence of useful AE signals generated during the fracture events with spurious signals related to damage in the contact surfaces of the specimen with upper central and lower supports that do not account for the specimen fracture process. Specifically, it is found that the signal caused by the damage induced by the supports is stronger at the beginning than that caused by the cracking of carbides and crack propagation, which is the real fracture mechanism in the studied steels. The coexistence of both signals seriously hampers the proper identification and evaluation of the fracture mechanisms.

Aimed at overcoming such uncertainty, a filtering protocol is proposed based on the first segment of the waveform, which detects and filters the AE signal distortions caused by reflections. Taking advantage of the characteristics of frequency features, the proposed filtering analysis provides the main parameters only for the first segment of time. The analysis permits to successfully identify the different origins of AE signals generated during the bending test that are: background noises, damage at the contact area between the specimen and the supports and the fracture process leading to specimen failure. The filtering process is applied to the analysis of fracture mechanisms in a tool steel. It allows for an accurate determination of the stress level that triggers carbide cracking, that is 800 MPa for the studied DIN 1.2379 steel. Such value was experimentally confirmed by surface inspection of tested samples. The use of unfiltered signals would erroneously set this carbide fracture stress level at 650 MPa, which represents an error of close to 20%. It would give bad data to tool steel makers for the microstructural design of tool steels and induce to misunderstandings to the tool user when trying to correlate the micromechanical properties of the tool steel to the macroscopic behavior of industrial tools.

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