A qualitatively new approach to acoustic emission measurements and its application to pure aluminium and Mg-Al alloys

R. Král[1]*, P. Dobroň[1], F. Chmelík[1], V. Koula[2], M. Rydlo[2], M. Janeček[1]

[1] *Charles University, Department of Physics of Materials, Ke Karlovu 5, CZ-121 16 Prague 2, Czech Republic*
[2] *ZD Rpety-Dakel, Ohrobecká 408, CZ-142 00 Prague 4, Czech Republic*

Abstract

A new method of acoustic emission measurements has been developed which allows a continuous sampling and storage of acoustic emission signal from up to four channels with a high sampling frequency. The approach differs qualitatively from the acoustic emission methods reported in the literature since it makes it possible to store the complete frequency spectra as measured by the detector and to make arbitrary analyses after the measurement including the analysis of effects that are below sensitivity threshold of the techniques used in the past. First applications of the method are presented for pure (99.99 %) aluminium, AZ31 magnesium and Al-4.8%Mg aluminium alloys deformed at room temperature.

K e y w o r d s: acoustic emission (AE), PLC effect, aluminium, magnesium, AZ31

1. Introduction

The effect of acoustic emission (AE) is a manifestation of transient elastic waves arising in a material from sudden localized irreversible structure changes. Since the pioneering work of Kaiser [1], AE has frequently been used to investigate plastic deformation of materials. The intensity of research in this area has varied over the time, re-gaining obviously more interest in the last several years. Generally, the AE methods that have been used in the past and reported in the literature both by other authors [2–7] and in our previous work [8–12], are based on evaluation of individual acoustic emission events which surpass some set threshold level. Various parameters of such events can be evaluated such as frequency of events for different thresholds, energy of events and waveforms of AE signal. Nevertheless, in many cases the effects remain hidden below the minimum threshold that is given by the noise level of the equipment. In such cases the AE methods were not able to detect any events and were thus not able to contribute to the understanding of the processes in the material.

In the present work we describe a qualitatively new approach to the AE measurements, which to consider-able extent eliminates the limitations described above. The main difference to the previously used methods is a continuous sampling and storage of acoustic emission signal from several channels as measured by the detector and performing consequently a statistical analysis on a complete stored spectrum. The fact that the spectrum is stored makes it possible to i) run various successive analyses, ii) evaluate individual time moments with respect to the properties of the whole spectrum, iii) use time consuming analyses that would not be possible to use in real time (during experiment).

2. Experimental procedure

A new generation DAKEL-CONTI-4 acoustic emission system, developed by the authors of this paper (V. Koula and M. Rydlo), was used which allows a continuous sampling and storage of AE signal from up to four channels with 2 MHz sampling frequency. The sampled AE signal is continuously stored on a dedicated hard disk connected to the measuring unit via a high speed interface, i.e. no processing of the data by the computer used to control the measur-

*Corresponding author: tel.: +420 221911615; e-mail address: rkral@met.mff.cuni.cz

ing unit takes place, which ensures high data transfer speeds. The software enables both i) evaluation of individual acoustic emission events in a standard way [2–12] (two-threshold-level detection recommended by an ASTM standard [13] was used with the thresholds set to 1.06 and 2.10 mV, respectively) and ii) analysis of the complete stored spectra based on statistical method. In the present work a method of averaged frequency spectra was used, as described in the following paragraph. A miniaturized MICRO-06 piezoelectric transducer with 3 mm diameter and a flat response in a frequency band from 100 to 600 kHz was used.

If we denote generally the registered AE signal in time t as $x(t)$ then the total energy E in some time interval can be written as

$$E = k \int x(t)^2 \mathrm{d}t, \tag{1}$$

where k is a constant. In the case of an electrical signal where $x(t)$ is voltage, the constant k is equal to $1/Z$, where Z is the impedance of the experimental set-up. In the case of discrete substitution the integral in (1) is replaced by a sum and $\mathrm{d}t$ is replaced by $1/f$, f being the sampling frequency, and we can write

$$E = \frac{1}{Z} \sum_i x_i^2 \frac{1}{f}. \tag{2}$$

If we confine us to the relative values of energy, the factors $1/Z$ and $1/f$ in (2) are not significant and it is only necessary to determine the value of the sum and relate it to some unit value (typically the maximum value registered during the experiment).

The sum according to (2) is computed in time intervals $t_n = n \cdot 4096\ \mu$s for 8192 samples (which corresponds to 4096 μs at the sampling frequency 2 MHz). The 4096 μs interval was found to be optimal in the respect of minimization of noise while preserving sufficient sensitivity for detecting effects in AE signal. Thus the energy E_k of the k-th interval of 4096 μs is given by (k is going from 0):

$$E_k = K \sum_{i=k \times 8192}^{(k+1) \times 8192} x_i^2, \tag{3}$$

where K is a constant found from the condition that max $\{E_k\} = 1$. Histograms of relative energies of AE signal are then computed in 10 s time intervals, i.e. each histogram comprises 2441 energies.

Three different materials were used: i) 99.99 % pure aluminium, rolled to 2 mm and annealed 1 hour at 500 °C, ii) Al-4.8%Mg alloy, rolled to 1 mm and annealed 1 hour at 500 °C and iii) magnesium alloy AZ31

(3 wt.% Al, 0.8 wt.% Zn, 0.2 wt.% Mn) hot rolled at 300 °C to 1.3 mm thickness. The details of rolling are described elsewhere [14]. Flat samples with a 6 mm width were machined from the rolled sheets. Tensile tests were performed on a screw-driven Instron 5882 machine at the initial strain rate of 3.6×10^{-4} s^{-1} at room temperature (RT).

3. Experimental results

Averaged AE frequency spectra are showed in Fig. 1 for three different materials. The darkness of shading in the figures is proportional to the frequency density of energy of AE signal as obtained from the spectral analysis. The scale is relative, the unity being the maximum density in Fig. 1a. Count rates for two different threshold levels are also plotted in the figures with the scale on the right hand side, labelled "AE1" for the lower threshold level and "AE2" (only in Fig. 1a) for the higher threshold level. In Figs. 1b and 1c count rates for the higher threshold level are equal zero with the exception of the vicinity of yield point, therefore the label "AE2" is missing here. Notable is the fact, that a well structured spectra with a distinct time evolution was recorded also for pure aluminium in Fig. 1b where the AE count rate is negligible with exception of the vicinity of yield point. The stress-strain curve labelled "Stress" is presented only qualitatively, without any scale in y-direction, for the sake of legibility of the figures. The maxima of stresses are approximately 250 MPa, 230 MPa and 40 MPa for AZ31, Al-4.8%Mg and pure aluminium, respectively. The whole stress-strain curves are shown in case of AZ31 and Al-4.8%Mg, whereas only a part is shown in case of pure aluminium in order to be able to compare similar regions of deformation curve.

As expected, the (relative) energy of the AE signal represented by the shading in Figs. 1a,b,c, similarly as the AE count rates, is significantly higher in the case of AZ31 alloy than for pure aluminium and Al-4.8%Mg. There are clearly visible several frequency maxima (dark strips on the figures) in each figure that i) decrease after the yield point, ii) some of them obviously change their frequency with the time. The frequency position of the maxima decreases with time in some cases from which follows that i) they reflect the changes of the properties of the sample, i.e. are not associated with the parameters of the detector and electronics as resonance frequency, ii) the position of some of the maxima has very likely a relation to the length of the sample which increases with time. If we take into account the length of the sample between the grips ≈ 52 mm and the velocity of sound in magnesium ≈ 5000 m $\cdot$ s^{-1} and in aluminium ≈ 5500 m $\cdot$ s^{-1} we get the frequencies ≈ 96 kHz and ≈ 106 kHz for magnesium and aluminium, respectively. This is
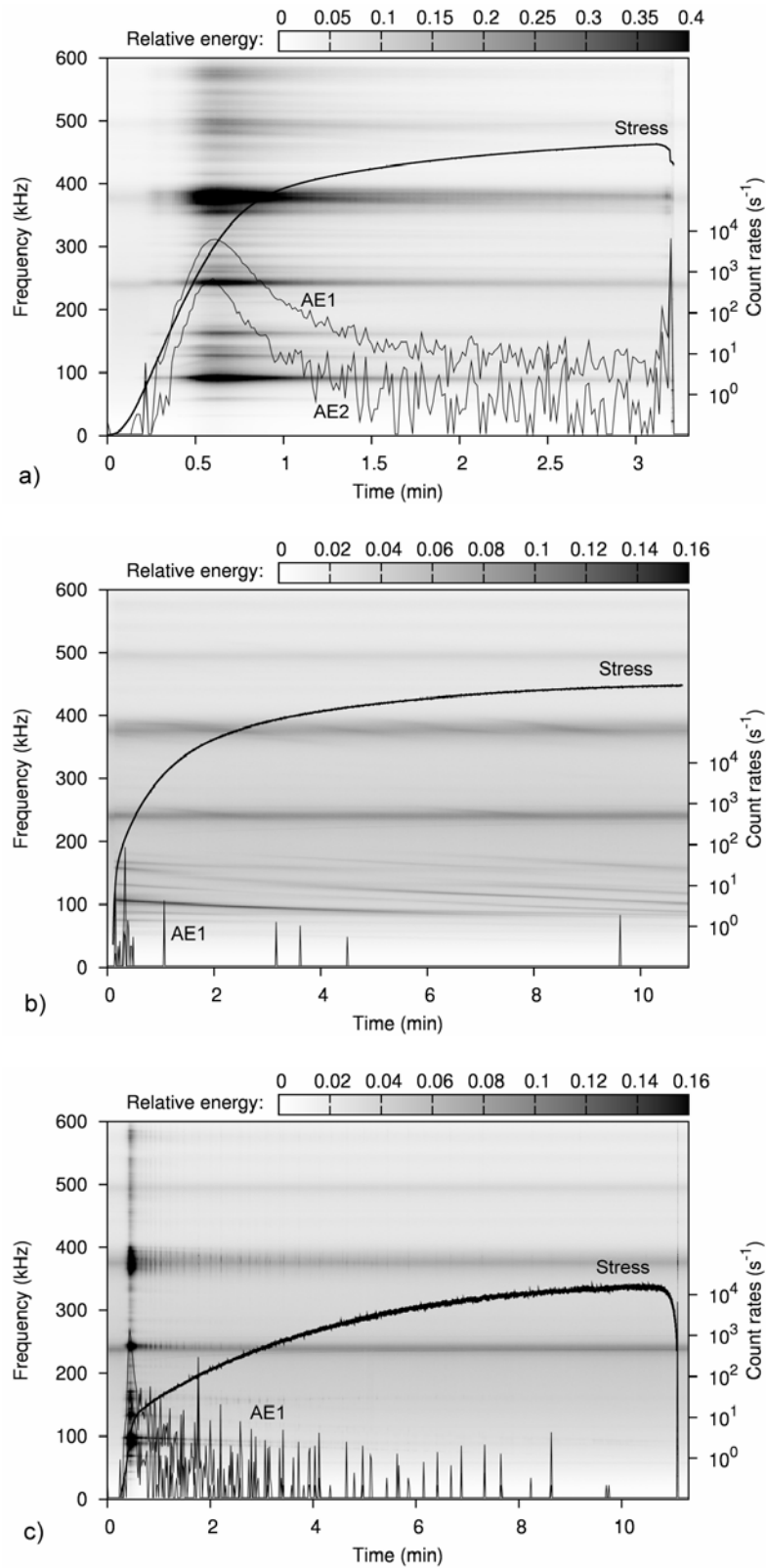
Fig. 1. Time evolution of acoustic emission energy spectra in three different materials deformed at the same crosshead speed (initial strain rate $\dot{\varepsilon}_0 = 3.6 \times 10^{-4}$ s^{-1}) at room temperature: a) AZ31 magnesium alloy, b) 99.99 % aluminium, c) Al-4.8%Mg alloy. The darkness of shading in the figures represents relative frequency density of the energy of AE signal, the unity being the maximum density in Fig. 1a. The scale is in the bar above the figures. Labels "AE1" and "AE2" stand for count rates, see text, the scale is on the right hand side. The stress-strain curve labelled "Stress" is presented only qualitatively, without any y-direction scale.
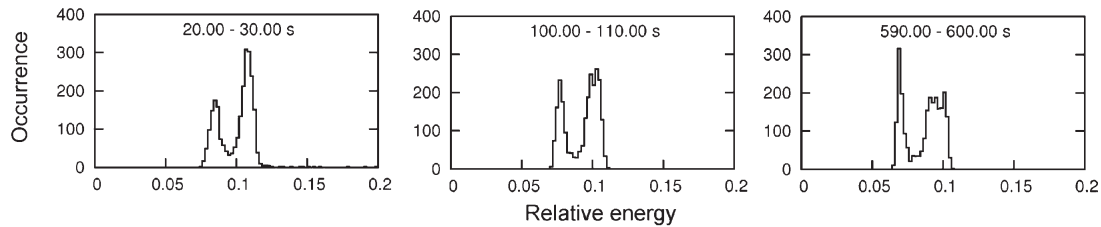
Fig. 2. Histograms of relative energies of acoustic emission signal integrated over 4 ms time interval for 99.99 % aluminium.
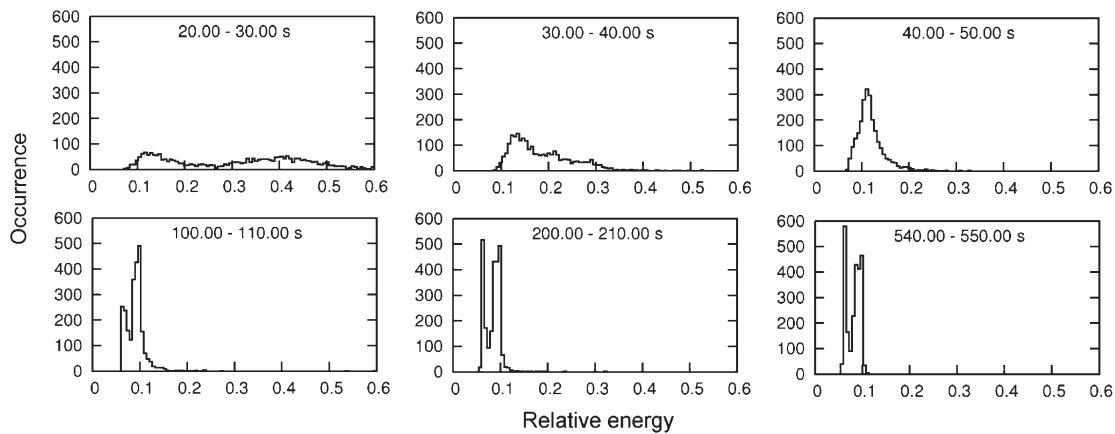

Fig. 3. Histograms of relative energies of acoustic emission signal integrated over 4 ms time interval for the Al-4.8%Mg alloy.

in a good accordance with the frequencies of the first maxima (the dark stripes closest to the bottom of the figure) in the Figs. 1a,b.

Histograms of relative energies of AE signal integrated over 4 ms interval are shown in Figs. 2 and 3 for pure aluminium at three different time intervals and for Al-4.8%Mg alloy at six different time intervals, respectively. The unity for computing relative energies is the maximum energy observed in AZ31. Again, it is notable in Figs. 2 and 3, that even if the AE signal is below the minimum threshold level for AE events (i.e. the count rates are zero i) almost all the time after the yield point in the case of pure aluminium and ii) at later stages of deformation in the case of Al-4.8%Mg, see curves labelled "AE1" in Figs. 1b,c) we can obtain clear and unambiguous data from the analysis of the stored complete spectrum. We can exclude that the shape of the histograms in Figs. 2 and 3 is only some effect of the method (e.g. noise or resonance of the detector) by a comparison of histograms for same time intervals (i.e. 20–30 s and 100–110 s) in Figs. 2 and 3 where we can see a distinct difference, although the energy of the AE signal is similar as can be seen from the comparison of Figs. 1b,c.

4. Discussion

In the following, we will concentrate on Al-4.8%Mg alloy and 99.99 % pure aluminium since in AZ31 the

AE count rates are high during the whole deformation. If we look at the histograms in Figs. 2 and 3 in time we can see that in pure aluminium the character of the histograms is very similar in all time intervals with two narrow maxima of occurrence that i) together only slightly shift to lower energies and that ii) interchange their relative occurrence, the occurrence of the lower energy maximum increasing and occurrence of higher energy maximum decreasing. In contrast to this, in Al-4.8%Mg the character of histograms changes substantially in time. At the early stages the histograms are widespread with two indistinct maxima, see interval 20–30 s in Fig. 2. Later, one single maximum evolves at lower energies and in final stages the character of the histogram becomes very similar to that of pure aluminium.

We suppose that the difference of the character of histograms in different time intervals in the case of Al-4.8%Mg is caused by different deformation mechanisms that are dominant at various phases of deformation. As we have demonstrated in one of our previous works [15] for an Al-3.5%Mg alloy the intense AE signal at the early stages is caused by massive multiplication of dislocations near yield point and collective break-away of dislocations during the PLC effect. The subsequent decrease of AE count rate is caused by an increasing density of forest dislocation during the deformation. This reduces both flight distance and the free length of moving dislocations. If the AE count rate eventually reaches zero as in the present case in

pure aluminium or in later stages in Al-4.8%Mg, no information can be gained from the threshold-based AE measurements as used in [15] for an Al-3.5%Mg.

On contrary to this, using the method presented in this paper we can gain information from AE signal even if the AE count rate is zero. One of the possibilities is an analysis of the histograms of relative energies of acoustic emission signal as presented in Figs. 2 and 3. We assume that, in the histograms for later stages of deformation in Figs. 2 and 3, the shift of the two maxima to lower energies corresponds to a decrease of flight distance and free length of dislocations [15]. The change in the character of the peaks, i.e.: i) gradual evolution of a single maximum peak to double maximum peak in Al-4.8%Mg at the time interval 40–110 s in Fig. 3 and the ii) interchange of relative occurrence in the double maxima peaks at later stages (lower energy peak increasing and vice versa) in both Figs. 2 and 3, we ascribe to the change in significance of different dislocation mechanisms that are in operation at various stages of deformation. In Al-Mg alloys the cross-slip of dislocations is the main softening mechanism at room temperature, becoming more pronounced at later stages of deformation, see e.g. [16, 17]. We suppose that the gradual increase of occurrence of the lower maxima in double peaks in Figs. 2 and 3 is due to the relative increase of cross-slip events compared to other mechanisms, which at these stages is mainly glide of dislocations in the array of forest dislocations.

5. Conclusions

It has been demonstrated that the described augmentation of acoustic emission experimental technique presents a qualitatively new approach to the phenomenon. Basis of the method is an ex-post statistical analysis of the stored complete frequency spectra which makes it possible to reveal effects "hidden in the noise" not observable by the methods based on analysis of signals surpassing the same threshold which is constrained by noise level. The method was applied to three different aluminium/magnesium based materials – pure aluminium and commercial AZ31 and Al-4.8%Mg alloys – delivering clear and unambiguous data even in the cases when AE signal is below the minimum threshold level for AE events.

Acknowledgements

References

[1] KAISER, J.: Arch. Eisenhuttenwes., *24*, 1953, p. 43.
[2] BOTTEN, R.—WU, X.—HU, D.—LORETTO, M. H.: Acta Mater., *49*, 2001, p. 1687.
[3] INOUE, H.—TSUZUKI, R.—NOHARA, S.—IWAKURA, C.: J. Alloys Compd., 2007, in press, doi:10.1016/j.jallcom.2006.12.079.
[4] VINOGRADOV, A.—MERSON, D. L.—PATLAN, V.—HASHIMOTO, S.: Mater. Sci. and Eng., *A341*, 2003, p. 57.
[5] LOU, X. Y.—LI, M.—BOGER, R. K.—AGNEW, S. R.—WAGONER, R. H.: Int. J. Plast., *23*, 2007, p. 44.
[6] BROTHERS, A. H.—PRINE, D. W.—DUNAND, D. C.: Intermetallics, *14*, 2006, p. 857.
[7] TROJANOVA, Z.—CACERES, C. H.: Scripta Mater., *56*, 2007, p. 793.
[8] RICHETON, T.—DOBRON, P.—CHMELIK, F.—WEISS, J.—LOUCHET, F.: Mater. Sci. Eng., *A 424*, 2006, p. 190.
[9] DOBROŇ, P.—CHMELÍK, F.—BOHLEN, J.—LETZIG, D.—KAINER, K. U.: Kovove Mater., *43*, 2005, p. 193.
[10] JANECEK, M.—KRAL, R.—DOBRON, P.—CHMELIK, F.—SUPIK, V.—HOLLANDER, F.: Mater. Sci. Eng., *A462*, 2007, p. 311.
[11] MATHIS, K.—CHMELIK, F.—JANECEK, M.—HADZIMA, B.—TROJANOVA, Z.—LUKAC, P.: Acta Mater., *54*, 2006, p. 5361.
[12] TROJANOVA, Z.—LUKAC, P.—CHMELIK, F.—RIEHEMANN, W.: Journal of Alloys Compd., *355*, 2003, p. 113.
[13] ASTM B 557-94, Test Methods of Tension Testing Wrought and Cast Aluminium-and Magnesium-Alloy Products. Annual Book of ASTM Standards. West Conshohocken, PA, ASTM International 1994, vol. 02.02.
[14] JANEČEK, M.—ŠUPÍK, V.—HOLLÄNDER, F.—WENDT, J.: Kovove Mater., *43*, 2005, p. 218.
[15] CHMELIK, F.—KLOSE, F. B.—DIERKE, H.—SACHL, J.—NEUHAUSER, H.—LUKAC, P.: Mater. Sci. Eng., *A462*, 2007, p. 53.
[16] KRAL, R.: Phys. Stat. Sol. (a), *157*, 1996, p. 255.
[17] KRAL, R.—LUKAC, P.: Mater. Sci. Eng., *234*, 1997, p. 786.