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BRIEF TECHNICAL NOTE

The Use of Acoustic Emission Monitoring to Rank Paper Materials with Respect to Their Fracture Toughness

P.A. Gradin · D. Graham · P. Nygård · H. Vallen

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Abstract In this study, a simplified Acoustic Emission (AE) equipment, in essence an AE signal conditioner and a USB (Universal Serial Bus) data acquisition system, is used to study what happens in paper structures during mechanical loading. By the use of such equipment, some parameters that can be extracted are e.g. the stress and strain at onset of AE, the stress and strain at the onset of rapid AE defined as some numerical factor (larger then one) times the initial emission rate, the emission rate at the first stage of loading and the stress and strain at final failure i.e. when the specimen loses its load carrying ability.In this study however, the interest is focused on one particular parameter i.e. the elastic strain energy density W_c at onset of AE. This is a parameter with a clear physical meaning and in this study, the correlation between this parameter and a fracture toughness measure, is investigated.The conclusion is that when nine different paper materials (with a large span regarding properties) are considered, there is a correlation (however not linear) between these two parameters.

P.A. Gradin (✉)
Mid Sweden University, S-851 70 Sundsvall, Sweden
e-mail: per.gradin@miun.se

D. Graham
School of Computing and Mathematical Sciences,
University of Greenwich, 30 Park Row, London SE10 9LS, UK

P. Nygård
Paper and Fibre Research Institute,
NO-7491 Trondheim, Norway

H. Vallen
Vallen-Systeme GmbH, Schaeftlarner Weg 26A,
D-82057 Icking, Germany

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Introduction

In the paper industry, standard tensile tests are being performed on a routine basis a number of times every 24 h and the tensile index (tensile strength in essence) and the strain at break are being recorded. In addition to this, fracture toughness tests are also often performed using a different device. The use of Acoustic Emission (AE) monitoring of paper has been described in e.g. [1–6] and in this study, the possibility of using AE to extract more data from a simple tensile test and in particular if it is possible to extract some parameter which could serve as a fracture toughness measure, is being investigated. The tests were carried out on standard specimens with a given (1%/min) strain rate while the total (summed) number of acoustic events were being recorded using a simple device i.e. a signal conditioner. It has been shown in a previous publication [2] that there is a direct coupling between a damage parameter D and the total number of acoustic events for a paper material in situations where it can be assumed that the dominant damage mechanism is fibre/fibre bond failure. This means that the damage evolution for such a material can in principle be monitored by recording the total number of acoustic events.

It is shown also in [2] that when it is assumed that one (scalar) damage parameter D is sufficient to describe the damage state then the elastic energy density is the generalised force conjugate to the damage rate dD/dt. Also, it is shown that damage starts when the elastic strain energy density reaches a critical value W_c. Performing a tensile test on paper while recording the Acoustic Emission (AE) and plotting stress and total (summed) number of events versus the strain in the same figure, one would get something as shown in Fig. 1 where σ and ε denotes stress and strain, respectively.

If the onset of AE is taken to be equivalent to the onset of damage, then the elastic strain energy density at onset of AE; W_c can easily be determined (since it is a uni-axial loading situation) from the stress σ_c as:

$$W_c = \sigma_c^2/(2E) \quad (1)$$

where E is the E-modulus which is obtained from the stress–strain curve.

Now, since the growth of an existing defect e.g. a crack in paper structure, by necessity involves the initiation of a critical damage state in points ahead of the crack tip, it seemed natural to investigate whether there existed some kind of correlation between the critical strain energy density W_c and some measure of the fracture toughness. It is however not at all obvious that such a correlation should exist, since W_c determines the initiation of damage and the fracture toughness determines the propagation of an existing crack.

It has been suggested that the *J*-integral used in fracture mechanics should be used to assess the fracture toughness of a paper material [7] and it can be shown that, under certain assumptions, the *J*-integral represents an energy flow to the process zone at the crack tip. However, to determine the fracture toughness from e.g. the *J*-integral, an additional test has to be performed i.e. a specimen with an existing crack has to be tested.

The parameter suggested here i.e. W_c is trivial to calculate if one has got the stress–strain and AE-curves for the material and W_c has also a clear physical meaning i.e. it is the elastic strain energy (recoverable energy) per unit volume when the paper starts to deteriorate by fibre/fibre bond breaks due to mechanical loading. W_c might well be a "stand -alone" parameter for characterising the fibre/fibre bond properties of paper materials.

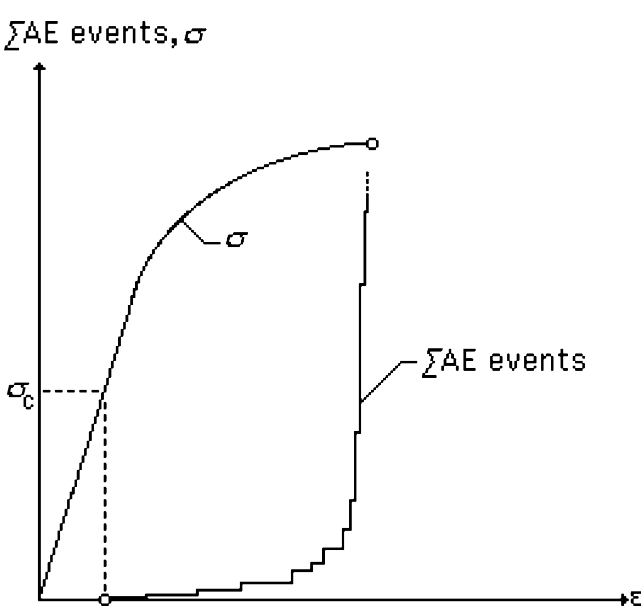

Fig. 1 Schematic AE curve for a paper material

Table 1 Ten samples considered

Material	Surface weight [10^{-3} kg/m^2]	Thickness [10^{-6} m]	Type of paper
1	46.0±0.3	72.2±0.8	Newsprint
2	51.2±0.2	82.6±0.7	Improved newsprint
3	53.0±0.3	84.3±1.4	Improved newsprint
4	143.0±1.0	186.0±4.0	Linerboard
5	476.1±1.0	563.0±15.0	Coreboard
6	50.7±0.5	75.5±2.5	Sack paper
7	76.5±0.6	106.0±3.5	Sack paper
8	83.1±0.6	116.0±1.2	Abrasive raw paper
9	179.0±0.8	224.0±2.8	Office board

Experimental

Nine different commercial paper grades were tested in this study. The loading was in the Machine Direction (MD). MD is the direction in which the paper web travels through the paper machine during production. A detailed specification of the properties of the nine paper grades is given in Tables 1 and 2 where the stiffness, tensile strength etc all refer to the MD. Note that each property is given as the average value ± one standard deviation.

The surface weight and thickness were determined according to [9] and [10] respectively.

The specimens (ten for each material) had a gauge length of 100 mm and a width of 15 mm. This information together with the information in Tables 1 and 2 is sufficient to calculate W_c according to equation (1) from a known value of σ_c. For example if the tensile stiffness for a certain sample is k (taken from Table 2) then the elasticity modulus E is given by: $E=kL/(wt)$ where L is the gauge length, w the

Table 2 Ten samples considered

Material	Tensile strength/unit width [10^3 N/m]	Tensile stiffness [10^3 N/m]	Strain at break [%]
1	2.72±0.14	399±7	1.02±0.08
2	3.46±0.17	458±26	1.13±0.08
3	3.05±0.12	402±15	1.20±0.05
4	16.80±0.62	1608±34	1.92±0.14
5	27.70±1.66	3129±52	1.88±0.18
6	4.33±0.26	499±21	2.34±0.17
7	6.37±0.35	749±30	2.41±0.15
8	8.85±0.21	941±17	2.25±0.11
9	10.60±0.23	1233±32	2.53±0.09

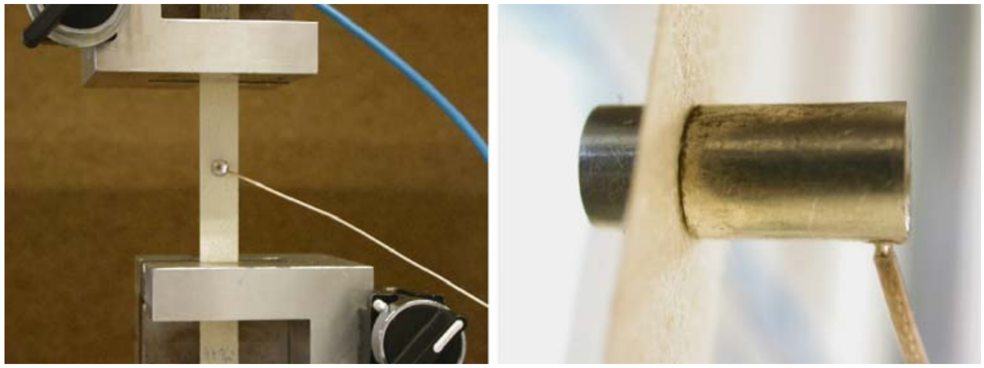

Fig. 2 Experimental setup and close up of the acoustic sensor

width and t the thickness of the paper specimen. Knowing σ_c, W_c will follow directly from equation (1).

Since there is a habit in the paper industry to use the surface weight ([kg/m^2]) instead of the thickness, σ_c is the force per unit width at onset of AE, divided by the surface weight and instead of t in the expression for E, is also used the surface weight.

The specimens used for the AE-monitoring had the same length and width as those used to determine the tensile strength etc. In Fig. 2 is shown the experimental setup together with a close up of the sensor showing that it is attached to the paper by means of a permanent magnet:

The specimens were equipped with one specially developed piezoelectric frequency resonance sensor (resonance frequency 300 kHz) and the data acquisition was taken care of with a simple signal conditioner (Model Vallen-Systeme ASCO-PH5 [8]) shown in Fig. 3 together with a sensor attached to a 100 Euro bill.

This signal conditioner delivers the analogue outputs APK and ASL. APK is a logarithmic representation of the highest amplitude of the AE signal within a time window of about 400 µs. ASL was not used in this application. APK load and elongation were measured in 200 µs intervals and stored. This concept makes it possible to vary the event detection threshold after the data acquisition. The event threshold is by definition the maximum amplitude that an acoustic event has to exceed in order to be registered as an event. A threshold value of 41.0 dB was found suitable.

It is a general observation that when performing AE monitoring on paper, there is a very large scatter in e.g. the stress value when the first event occurs. To decrease this scatter one has to define in some way what is meant by significant acoustic emission. The critical stress σ_c was therefore and quite arbitrarily defined as the stress at which the total number of acoustic events was equal to 10% of the total number of events at final failure i.e. when the specimen loses its load carrying ability. In Table 3 is shown (as average ± one standard deviation) the total number of acoustic events N_f at total failure for the nine materials considered.

It can be observed that there is a large scatter in N_f.

The deformation rate (strain rate) was 1%/min for all specimens and the tests were performed in a standard paper testing environment.

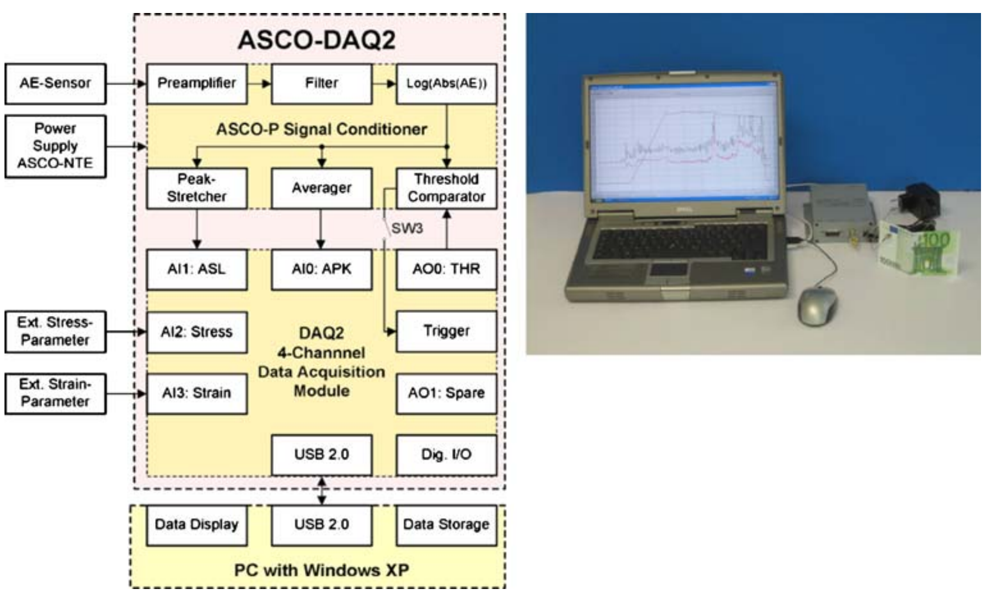

Fig. 3 The data acquisition system used

Table 3 Acoustic events at total failure

Material	N_f
1	47±6
2	39±5
3	42±6
4	338±39
5	320±62
6	54±11
7	64±8
8	330±36
9	177±13

For the J-integral testing which was performed as described in [7], ten specimens for each material, were used. The J-integral testing was performed with the loading in the MD (see above for definition) and with the crack being orthogonal to this direction.

Results

In Table 4 are given the J-integral or, using the same notation as in [7] the J_{Ic}^{w}-values together with the corresponding W_c-values. The unit for J_{Ic}^{w} i.e. [Nm m/kg] also comes from using the surface weight [kg/m^2] as a measure of the thickness. Again, the values are given as an average ± one standard deviation and every average value is based on the testing of ten specimens.

Note that the ratio between the standard deviations and the average values are given in percent inside parentheses in Table 4. From this one might get the impression that the scatter in W_c is in general less or even much less than the scatter in J_{Ic}^{w}. However, this is not necessarily the case since the testing of the thickness and stiffness (and also J_{Ic}^{w}) was performed in another laboratory and reported as the average and standard deviation only. Hence, the standard deviation for W_c refers to the standard deviation of σ_c^2 only.

The data in Table 4 is also plotted in Fig. 4 where the standard deviation for J_{Ic}^{w} has been indicated. Quite

Table 4 Ten samples considered

Material	W_c [J/kg]	J_{Ic}^{w} [J m/kg]
1	14.3±0.5 (3.3%)	8.0±1.3 (16.3%)
2	17.5±0.8 (4.6%)	8.5±1.0 (11.8%)
3	16.7±0.8 (4.8%)	8.4±1.3 (15.5%)
4	47.3±0.8 (1.6%)	16.4±1.6 (9.8%)
5	23.1±1.2 (5.1%)	11.2±0.8 (7.1%)
6	26.8±1.8 (6.7%)	14.0±3.0 (21.4%)
7	26.7±1.1 (4.2%)	14.1±2.4 (17.0%)
8	35.7±0.8 (2.3%)	14.5±1.8 (12.4%)
9	18.6±0.2 (1.3%)	12.9±1.2 (9.3%)

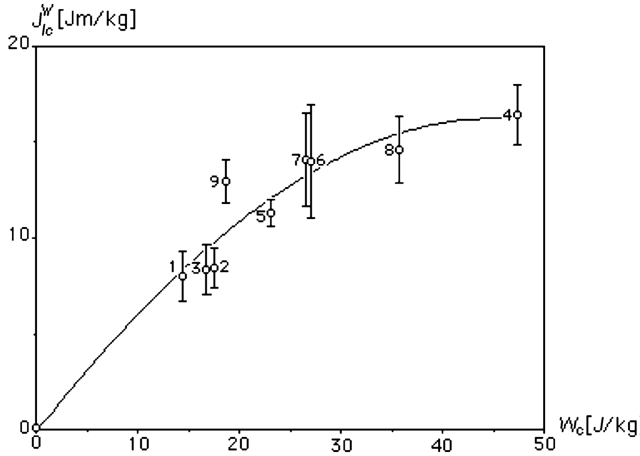

Fig. 4 J_{Ic}^{w} versus W_c. The numbers refer to the different materials

arbitrarily, a third order polynomial has been fitted to the average values and it should be noted that an extra point has been added since it is, for physical reasons, assumed that W_c=0 when $J_{Ic}^{w} = 0$.

Referring to [7] the J_{Ic}^{w}-values in Fig. 4 represents a range of values representative for mechanical printing grades (to the left) over fine paper and to kraft liner to the right. There seems to be a correlation between J_{Ic}^{w} and W_c even if it is not a linear correlation. However, performing a best fit of a linear relation through the origin and through the first five data points will give the relation shown in Fig. 5:

J_{Ic}^{w} values up to around 10.0 Jm/kg are representative for mechanical printing grades ([7]) with papers 1, 2 and 3 in that region. Mechanical printing grades are manufactured out of mechanical pulp with a presumably low fibre/fibre bond strength compared to for example liner. That the dominating damage mechanism in mechanical printing grades i.e. papers 1, 2 and 3, is fibre/fibre bond failure has been shown experimentally in [2]. From Fig. 5 it is concluded that it might be worthwhile to investigate in more detail if there exists a linear correlation between J_{Ic}^{w}

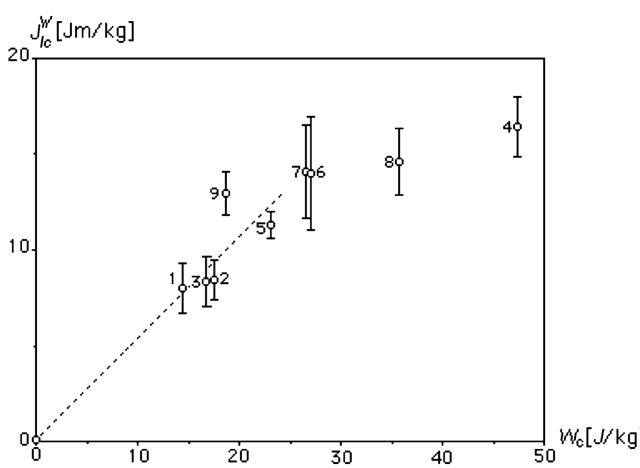

Fig. 5 A linear relation fitted to the first five data points

and W_c for this class of paper materials i.e. paper materials with a low fibre/fibre bond strength.

Discussion

Some of the papers involved in this study are made of mechanical pulp and some of chemical pulp beaten to different degrees. Further on, since also some of the materials are filled with starch, it can be assumed that the bond strength for the materials considered, varies in a large interval.

It can be argued that taking e.g. σ_f^2/E where σ_f is the failure stress and E the elasticity modulus, will give an as good a correlation with the J-integral as does W_c and hence there is no need for using AE monitoring. This is not true since a standard tensile test will not give any information about the micro structural events occurring in the paper. For instance, it is possible to derive a material parameter from the AE curve, which determines the damage evolution rate (the subject of a coming paper). Also, by considering the strain interval from the onset of damage up to final failure, it might be possible to get an indication of the narrowness of the bond strength distribution.

The results presented in this paper is just a first attempt to show that AE-monitoring might be a versatile tool in the testing of materials by showing that one parameter derived from the AE results correlates with some parameter believed to say something about one aspect of the quality of paper.

To conclude, more investigations have to be performed in order to be certain of the correlation between J_{Ic}^b and W_c. If the correlation can be confirmed for certain classes of paper materials, then by simply attaching an acoustic sensor to a tensile specimen (which has to be tested anyway) it should be possible to rank paper materials with respect to their fracture toughness. Another thing worth mentioning is that a tensile test performed in an industrial environment is run at a strain rate of 100%/min while in this study a deformation rate of 1%/min was used. The influence of the deformation rate on the correlation between J_{Ic}^b and W_c must hence be investigated. Finally, it might well be that there is a linear relation between J_{Ic}^b and W_c for paper materials with a low fibre/fibre bond strength.

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References

1. Gradin PA, Nyström S, Flink P, Forsberg S, Stollmaier F (1997) Acoustic emission monitoring of light weight coated paper. J Pulp Pap Sci 23:3, March.
2. Isaksson P, Gradin PA, Kulachenko A (2006) The onset and progression of damage in isotropic paper sheets. Int J Solids Struct 43:713–726.
3. Yamauchi T, Okumura S, Noguchi M (1990) J Pulp Pap Sci 16:2, Jan.
4. Yamauchi T, Okumura S, Murakami K (1989) J Pulp Pap Sci 15:1, Jan.
5. Yamauchi T, Okumura S, Noguchi M (1990) J Pulp Pap Sci 16:2, Jan.
6. Salminen LI, Tolvanen AI, Alava MJ (2003) Acoustic emission from paper fracture. Phys Rev Lett 89:185503.
7. Wellmar P, Fellers C, Delhage L (1997) Fracture toughness of paper-development of a test method. Nordic Pulp Pap Research J 12(3):189–195.
8. Vallen Systeme GmbH, Product Description ASCO-P, ASCO-DAQ2 at http://www.vallen.de.
9. ISO 536, Paper and board-determination of grammage, 1988.
10. ISO 534, Paper and board-determination of thickness and apparent bulk density or apparent sheet density, 1988.