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Application of acoustic emission testing in failure analysis – case studies

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ABSTRACT

The paper is primarily concerned with the detection of hydrogen embrittlement in Failure Analysis by employing acoustic emission (AE), monitoring techniques. This has been demonstrated on (1) a high carbon steel which failed by splitting during the drawing and handling operations, and (2) a pipeline steel which failed catastrophically while in service. The results show that the presence of hydrogen in a high carbon steel can be effectively determined by monitoring AE during delayed cracking tests. It has been observed that the AE counts rise slowly with increasing time in the initial stage of embrittlement, whereas they rise rapidly in the later stage prior to fracture. It has also been found that the initial embrittlement phase is characterized by low amplitude signals whereas the rapid crack growth is marked by high amplitude signals. The initial period of low amplitude signals is caused by the diffusion of hydrogen to the maximum triaxially stressed region causing microvoid to form. As the microvoid starts linking up giving rise to some critical crack size the amplitude of emitted signals increases. The results of the tensile tests that were conducted on pipe line steel indicates that the presence of notch in tensile test sample leads to a significant change in the AE activity. It shows that the counts per event in the notched specimen is higher than that in smooth wherever these is significant hydrogen pick up.

INTRODUCTION

Acoustic emission (AE) is the name given to the elastic waves that are generated within a solid as a consequence of deformation and fracture processes. Analysis of these signals can detect the deformation and fracture mechanism in a material very sensitively [1]. As hydrogen embrittlement (HE) is characterized by a materials tendency to crack leading to failure at reduced ductility, acoustic emission testing (AET) can be applied to detect hydrogen embrittlement failure. There exists several theories to describe the mechanism of HE in materials [2-4], but only a few methods exists to detect HE. Most of them detect changes of mechanical properties and correlate these to HE. The present paper is aimed to add a new method for identifying HE by means of monitoring AE during tensile and delayed failure experiments.

PRINCIPLE OF AE TESTING

AET relies on the detection of elastic waves generated by sudden deformation in stressed material (Fig. 1) These waves travel from the source to the sensors, where they are converted to electrical signal. The AE instrumentation measures these signals and produces data display from which the operator evaluates the condition and behaviour of the structure under stress. An AE test system therefore consists of (1) a sensor for picking of the signal (2) a preamplifier for amplifying the signal and (3) a processing unit for processing and analyzing the signal. Parameters used to analyze an AE signal is shown in Fig. 2.

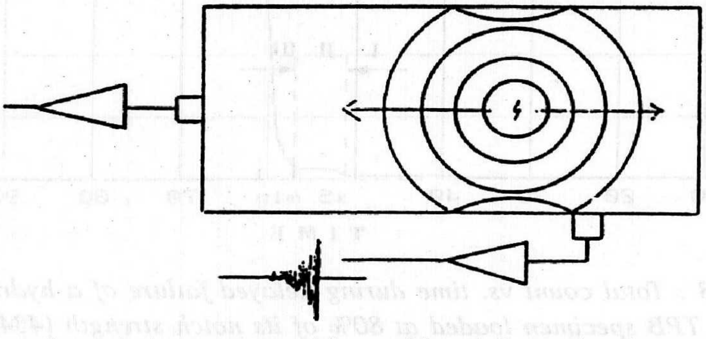

Fig. 1 : Acoustic emission generated by sudden deformation in stressed material

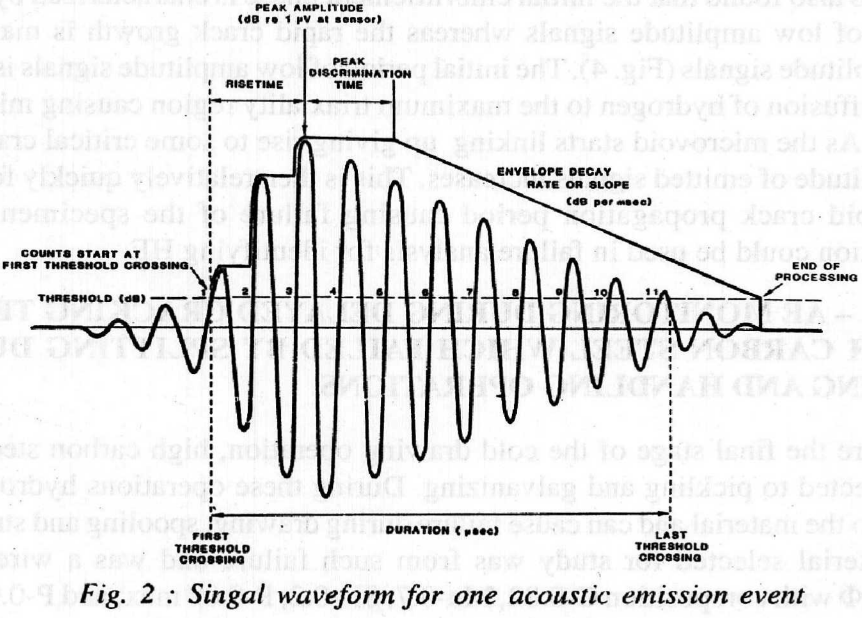

Fig. 2 : Singal waveform for one acoustic emission event

AE MONITORING DURING DELAYED FAILURE EXPERIMENTS

A high strength material containing hydrogen and susceptible to hydrogen embrittlement can fail at a constant load because of hydrogen induced cracking by diffusion of hydrogen to maximum triaxially stressed region. This is called delayed failure. AE monitoring at NML[5] during delayed failure test of a hydrogen charged TPB specimen of 4340 steel show that the AE counts rose slowly with increasing time in the initial stage of embrittlement, whereas it rose rapidly in the later stage prior to fracture (Fig. 3).

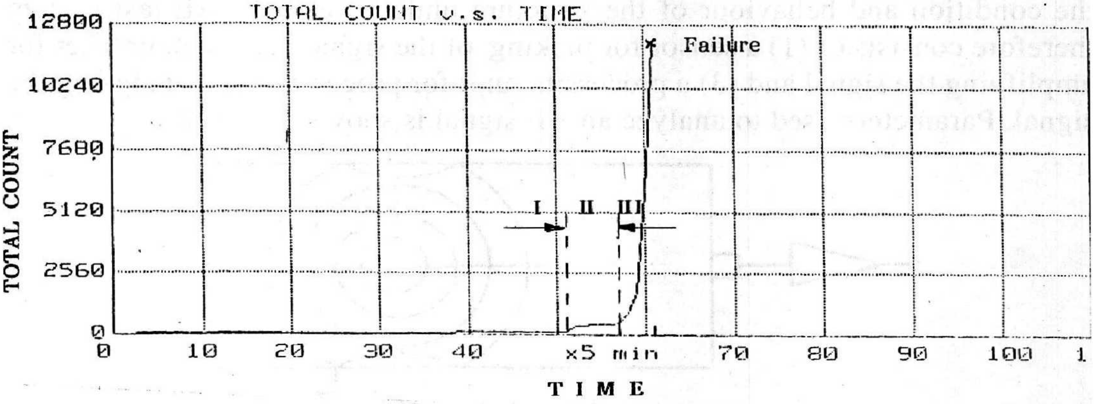

Fig. 3 : Total count vs. time during delayed failure of a hydrogen charged TPB specimen loaded at 80% of its notch strength (4340 steel)

It was also found that the initial embrittlement phase is characterized by a large number of low amplitude signals whereas the rapid crack growth is marked by high amplitude signals (Fig. 4). The initial period of low amplitude signals is caused by the diffusion of hydrogen to the maximum triaxiality region causing microvoid to form. As the microvoid starts linking up giving rise to some critical crack size the amplitude of emitted signals increases. This is then relatively quickly followed by a rapid crack propagation period causing failure of the specimen. These information could be used in failure analysis for identifying HE

CASE 1 – AE MONITORING DURING DELAYED CRACKING TEST OF A HIGH CARBON STEEL WHICH FAILED BY SPLITTING DURING DRAWING AND HANDLING OPERATIONS.

Before the final stage of the cold drawing operation, high carbon steel wires are subjected to pickling and galvanizing. During these operations hydrogen can enter into the material and can cause failure during drawing, spooling and stranding. The material selected for study was from such failure and was a wire rod of 4.16mmΦ with composition C-0.82, Mn-0.7, Si - 0.2, P-0.02 max, and P-0.02 max.

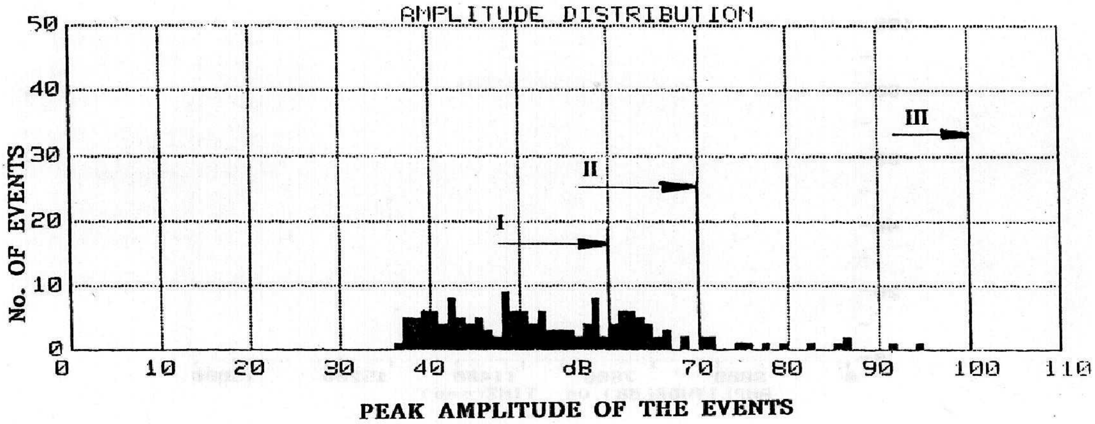

Fig. 4 : Showing Amplitude distribution for the test shown in fig 3.

The material was failing by splitting during final drawing from 6mm to 4.16mm and also while spooling and stranding.

Experimental

Delayed cracking tests while simultaneously monitoring AE were carried out on partially splitted wire samples by hanging a dead weight to one of the split ends. AE as a function of time was monitored by a 150 KHz resonant sensor and were analyzed by a spartan-AT, AE system from M/s PAC, USA.

Results and Discussion

The AE data presented in Figures 5 and 6 show that the signals generated are within 35-65 dB. It shows that the AE activity is of two types : one with lesser number of counts and low amplitude signals, and other with higher number counts

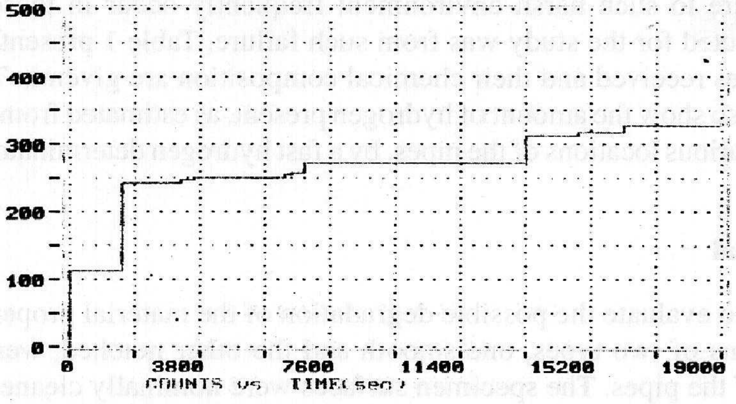

Fig. 5 : Total count vs. time during delayed cracking test of a partially splitted wire rod (high carbon steel)

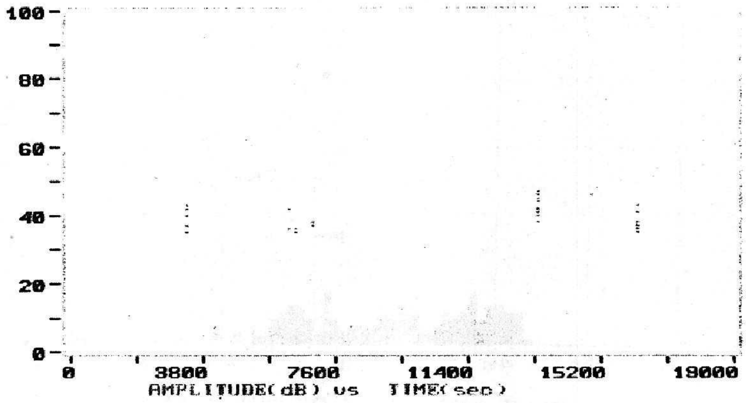

Fig. 6 : Showing amplitude distribution for the test shown in fig. 5

and higher amplitude signals. This is owing to the micro cracks generating les vigorous signal and a more rigorous signal is generated when the microcrac coalesce to form a macrocrack, and therefore a small increment in split.

Remarks

Presence of hydrogen in a high carbon steel can be effectively determined b monitoring AE during delayed cracking tests.

CASE - 2 : AE MONITORING DURING TENSILE TESTING OF A PIPELINE STEEL WHICH FAILED CATASTROPHICALLY WHILE IN SERVICE

Oil exploration industries use plain carbon steel pipes to lift-off natural ga mainly hydro-carbon and CO_2 at a pressure of 1500 PSI. Brittle failures resultin from exposure to such harsh environment frequently occur in these steel. Th material selected for the study was from such failure. Table 1 presents the detail of the samples received and their chemical composition are given in Table 2. Th same table also show the amount of hydrogen present, as estimated from the sample taken from various locations of the pipes, by a fast hydrogen determinator (HYMAT 200).

Experimental

In order to evaluate the possible degradation of the material properties, tensil test specimens of two types, one smooth and the other notched, were prepare from each of the pipes. The specimen surfaces were nominally cleaned to remov surface coatings and any corrosion products without any machining. During th tensile tests, to check the characteristic signals of embrittlement, AE from the tes

Table 1 : Details of the pipes investigated

Pipe code	Condition	Dimensions outer dia/min thickness [mm]	Nature of failure
P1	Virgin	115/7.5	–
P2	Failed	115/7.0	Long crack (no burst)
P3	Failed	110/3.5	Burst
P4	Used	115/6.8	
P5	Used	114/6.8	
P6	Used	115/7.5	

Table 2 : Chemical composition of the pipes investigated [% wt]

Sample	C	Mn	Si	S	P	Cr	Mo	H_2 (ppm)
P1	0.52	0.55	0.23	0.020	0.028	0.018	0.012	2
P2	0.50	0.44	0.26	0.026	0.023	0.010	0.012	12
P3	0.51	0.52	0.20	0.025	0.011	0.03	0.014	13
P4	0.51	0.47	0.22	0.018	0.014	0.03	0.012	1
P5	0.44	0.56	0.28	0.021	-	0.04	0.016	1
P6	0.47	0.45	0.21	0.027	0.014	0.03	0.011	5

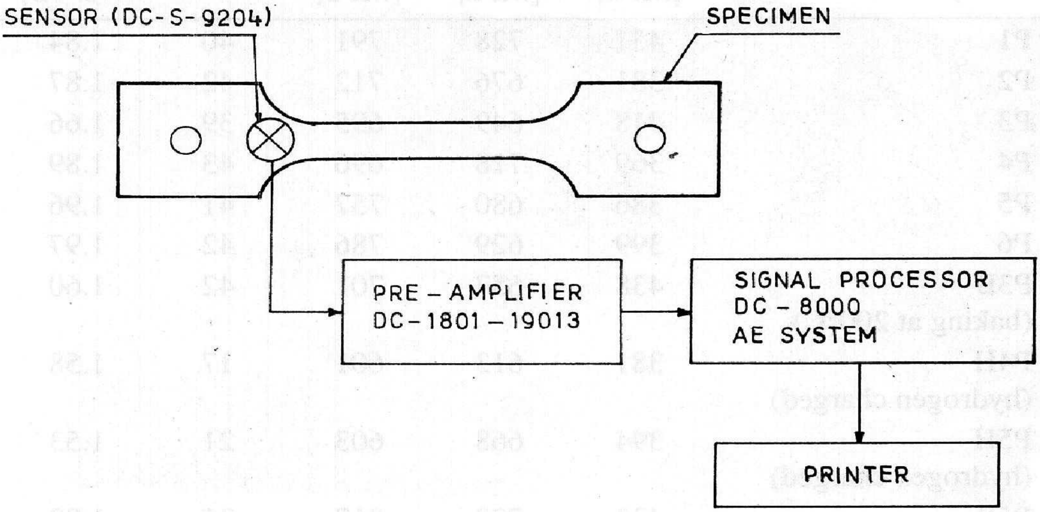

Fig. 7 : A schematic view of the experimental set-up for the pipeline steel

pieces were monitored using a Dunegan 8000 AE system with computer for data acquisition and post processing. A 150 KHz resonant piezoelectric probe with 40 dB pre-amplifier was employed for sensing the signal. A schematic view of the experimental set-up is shown in Fig. 7. The mechanical properties obtained from the tensile tests are listed in Table 3.

In order to examine the nature of the analyzed AE data, vis-a-vis HE, a few tensile test specimens were cathodically charged with hydrogen in 1N H_2SO_4 solution poisoned with 4 ppm $NaAsO_2$. Charging was done for two hours with a current density of 30 mA/cm2 which led to a pickup of 10-12 ppm hydrogen. Tensile test data obtained from such test specimens are also included in Table 3, where as the extent of hydrogen detected in charged specimens are given in Table 4.

Results and Discussion

An examination of the tensile properties listed in Table 3 indicate that although the yield strength (YS) and the tensile strength (TS) vary significantly from pipe to pipe, these do not exhibit any definite trend with the extent of service exposure. Percent elongation (in as-received condition), which is measure of ductility has also been found to be nearly the same.

Table 3 : Summary of tensile test data collected from smooth and notched specimens

Sample	YS [MPa]	TS [MPa]	Notch [MPa]	% El	NSR (NS/YS)
P1	431	728	791	40	1.84
P2	381	676	712	42	1.87
P3	418	649	695	39	1.66
P4	369	718	696	43	1.89
P5	386	680	757	41	1.96
P6	399	629	786	42	1.97
P3B (baking at 200°C)	438	657	701	42	1.60
P4H (hydrogen charged)	381	613	601	17	1.58
P5H (hydrogen charged)	394	668	603	21	1.53
P5B (baking at 200°C)	433	727	817	35	1.89

Hydrogen pick-up in steels, during services is a result of electrochemical reaction through the formation of local action cells. This is mainly responsible for the non-uniform distribution of hydrogen in the pipes. Chemical analysis of a sample, nearest to the failed region, from P2 indicated presence of significant amount of hydrogen (12 ppm) whilst the same pipe showed negligible hydrogen (1 ppm) in samples cut from the tensile test specimen ends. A small percentage of moisture and CO_2 under high pressure of the gas in the pipe can provide favourable condition for hydrogen pick-up. Rust, which is electrochemical reaction may also lead to hydrogen pick-up. Sample P3, incidentally, showed extensive rusting of the external surface.

The notch strength ratio (NSR), defined as the ratio of smooth specimen yield stress and notched specimen tensile stress and is a measure of the materials resistance to fracture, has been calculated for all the samples received. As shown in Table 3, the NSR for pipe 3, the pipe which failed catastrophically in service, is significantly lower than the rest of the samples. Hydrogen pick-up may be one of the reasons for its lower resistance to fracture. The results of the tests, that were conducted on samples artificially charged with hydrogen (specimen P4H and P5H) indicate that hydrogen pick-up has significant effect on NSR, which in this material attained a value as low as 1.53 as has been reported in Table 3. This in contrast to only a marginal drop in the YS and TS value of the material.

Table 4 : Summary of the AE signals collected during tensile tests

Sample	Smooth, bs	Notched, bn	Hydrogen [ppm]
P1	368	307	2
P2	301	228	1
P3	130	525	6
P4	345	111	1
P5	138	241	1
P6	204	310	1
P3B	235	102	1
P4H	120	212	9
P5H	30	207	5
P5B	281	110	1

The average number of AE counts per events for both smooth and notched specimens, denoted as bs and bn respectively, have been estimated from the slope of the counts vs. event plot. Table 4 is a record of such data. This has been plotted in the form of a histogram (Fig. 8), which reveals that the virgin sample, P1 has the highest whilst the hydrogen charged sample, P5H, has the lowest b in smooth speci-

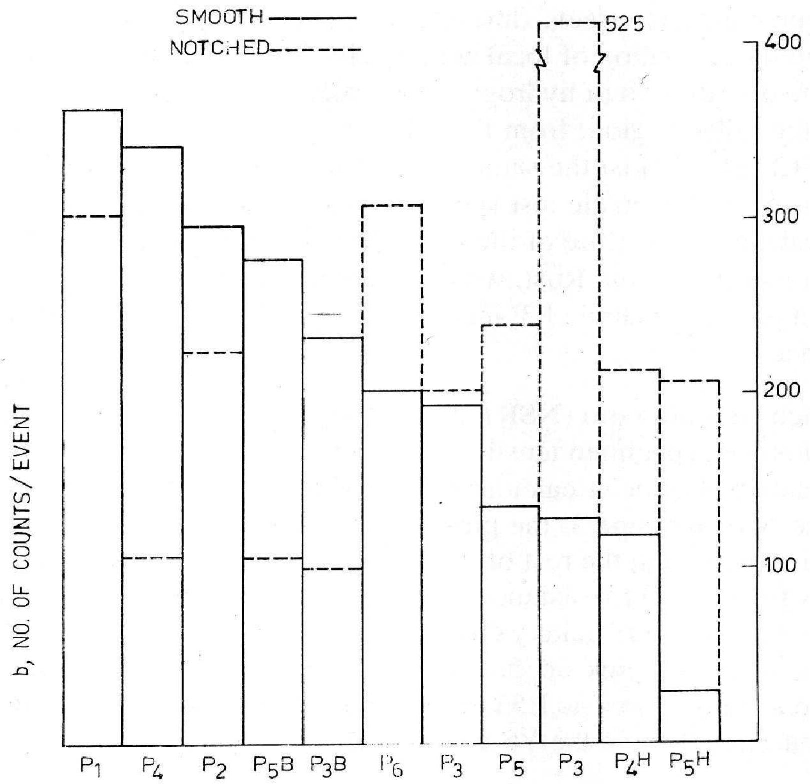

Fig. 8 : Histogram showing that no. of counts per event (b) is a function of hydrogen pick-up (pipeline steel)

mens. Also the position of P3 is close to the hydrogen charged specimen. Thi indicates the overall hydrogen pick-up, as compared to the sample P1, is the leas in P4 and the highest in P3 amongst the service exposed samples. Therefore, on may conclude that P3 was most susceptible to failure.

Presence of notch in tensile test sample leads to a significant change in the A activity. Fig 8 shows that the counts per event in the notched specimen is highe than that in smooth wherever there is significant hydrogen pick-up and the mate rial is more susceptible to rupture. Detail examination of the amplitude distribu tion plot of both smooth and notched specimen reveals that the pipe P3 as well a artificially hydrogen charged specimen emit similar high amplitude signals (Fig 9). This indicates that the fracture behaviour in these are identical. Therefore, i may be concluded that the Pipe P3 exhibits characteristics of embrittlement due t hydrogen pick-up.

The above analysis reveals that the failure is directly associated with hydroge pick-up and loss of section size due to corrosion. Sample P2, which has failed

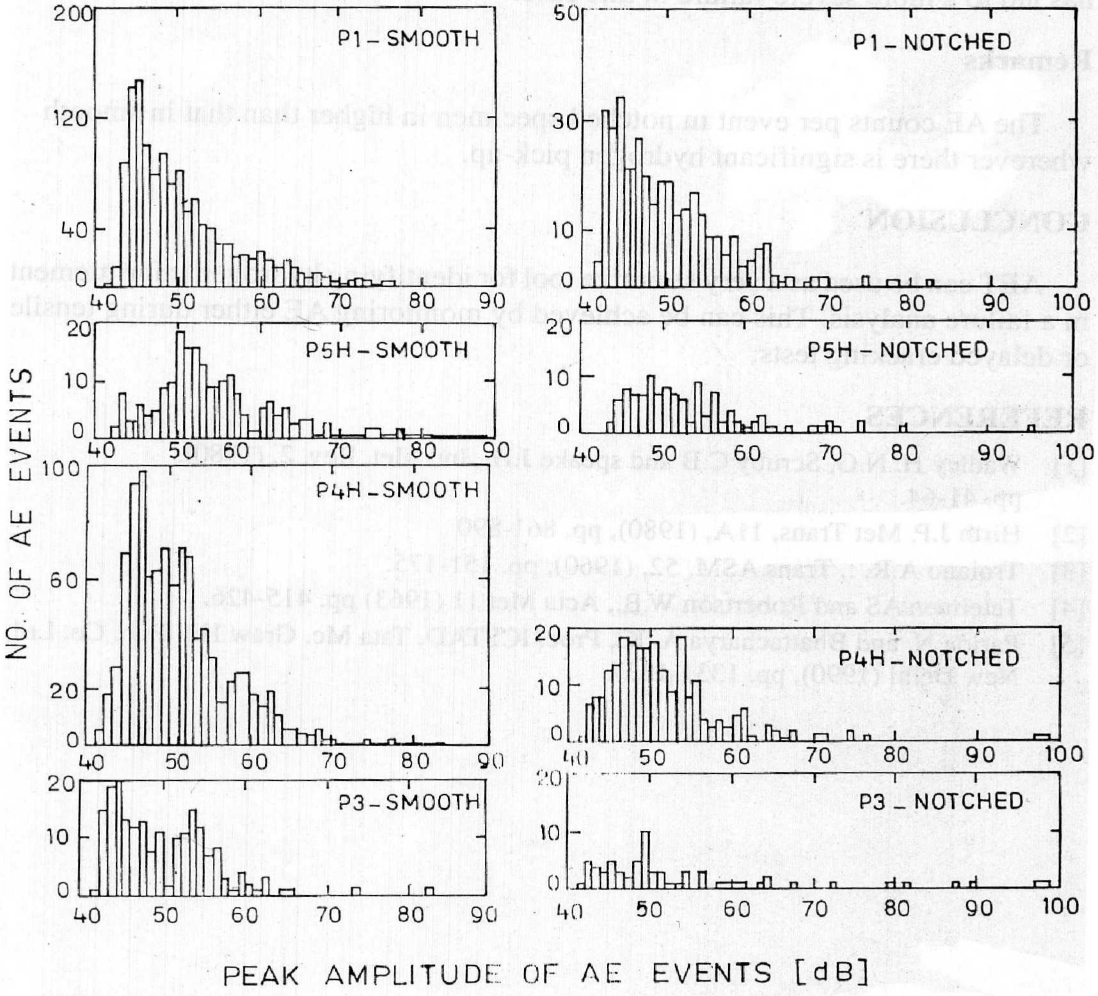

Fig. 9 : Showing the effect of hydrogen in the amplitude distribution plot (pipeline steel)

showed a hydrogen content as high as 12 ppm close to the region of the rupture, However, there was no loss of section size. It is worth noting that the sample P6, which has survived 18 years of service, has also picked-up hydrogen. Yet, this did not fail because the loss of section size due to corrosion was minimal. The burst pipe, on the other hand, has not only picked-up hydrogen but also has undergone a significant loss of section size due to corrosion. The combined effect nevertheless has led to a more severe failure in this case.

Remarks

The AE counts per event in notched specimen in higher than that in smooth wherever there is significant hydrogen pick-up.

CONCLUSION

AET can be used as a very sensitive tool for identifying hydrogen imbrittlement in a failure analysis. This can be achieved by monitoring AE either during tensile or delayed cracking tests.

REFERENCES

[1] Wadley H. N.G, Scruby C.B and speake J.H., Int. Met. Rev. 2, (1980), pp. 41-64.

[2] Hirth J.P, Met Trans, 11A, (1980), pp. 861-890

[3] Troiano A.R. :, Trans ASM, 52, (1960), pp. 151-175.

[4] Tetelmen AS and Robertson W.B., Acta Met 11 (1963) pp. 415-426.

[5] Parida N. and Bhattacharya A. K., Proc. ICSTAD, Tata Mc. Graw Hill Pub. Co. Ltd, New Delhi (1990), pp. 1331-1337.