Acoustic Events during Fatigue Test of Structural Steels

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Abstract. Acoustic emission sensors were applied recording noises during low cycle fatigue tests in steel materials. The test specimens were machined from the base metal (15H2MFA) and the anticorrosive cladding metal (08H18N10T) of the VVER-440/V-213 (Russian designed PWR) reactor pressure vessel.

During the first period, the measurements were carried out with isothermal condition at 260°C on GLEEBLE 3800 servo-hydraulic thermal- mechanical simulator. The tests were run under uniaxial tension-compression loading with total strain control. The programmed waveform was triangular for all the fatigue tests with the frequency of 0.08 Hz. The cyclic loading was started from the compressed side. It was observed that besides rare acoustic emission events regular 10msec Acoustic Barkhausen Noise (ABN) burst were recorded due to 50Hz AC current drive for heating and maintaining the constant temperature. The amplitude of MABN was higher under pressure than during relaxing and drawing-out by a factor of 2-5.

We have carried out also thermo-mechanical fatigue experiment with the same strain-controlled mechanical cycle and simultaneous thermal cycle between 150°C and 270°C. The total number of cycles was terminated, when the force level necessary for the original elongation had been reduced to 75% of its original value. Visual examination showed always some at least surface cracks after stopping the fatigue test. ABN events registered during the beginning cycle exhibited different spectra from the middle and especially from the last cycles before the end of the test, where also double ABN bursts could be recorded. At the end of the test explicit AE events could be found by a new technique.

The most interesting result is the possibility to use ABN for testing reactor materials, which could have practical application for fatigue testing.

Introduction

There are more than 55 references in [1] mainly on early investigations of using acoustic emission (AE) for monitoring of fatigue crack detection and propagation. Recently an excellence review paper appeared [2]; however, not too much successful AE was reported there in combination with fatigue test.

This paper deals with acoustic signals recorded and analysed during the fatigue test of two different steels. The main aim of the research project was to investigate the low cycle thermal-mechanical fatigue (LCF) of nuclear reactor materials to model those changes, which affect the reactor pressure vessel structural materials during heating up and cooling down in a long term. The cyclic load during LCF causes pulsating plastic strain and the strain can generate acoustic emissions (AE). Our original intent was to measure AE and to compare the signals with the structural changes in the material as well as to develop methodology to recognise when AE events take place at various fatigue stages. We developed special AE measuring device while we also used a commercially available AE measuring system.

However, during registering the AE signals we noticed that besides the AE events there are many other acoustic bursts registered by the AE measuring systems which were identified as Acoustic Barkhausen Noise (ABN). We believe that these are also AE events just they are generated not by stresses in the material due to outside thermal and/or mechanical loading or microstructural changes but from the internal stresses caused by magnetic forces in the material. Therefore they also belong to AE events and bravely can be used for material characterisation.

In this paper we present the AE and ABN signals recoded during LCF, where 50Hz alternating current (AC) was used for heating the steel specimens and holding them at certain temperature while mechanical cyclic loading took place.

We argue that we really have had ABN since it has not been obvious. Contrary to traditional Barkhausen noise investigation, we did not have any magnet yoke.

Description of the experiment

The fatigue tests were performed on a servo-hydraulic thermal-mechanical physical simulator (model GLEEBLE-3800). The tests were run under uniaxial tension-compression loading with total strain control. We show three different fatigue test programs in this paper. The typical uniphase thermal-mechanical program had periodic load and temperature change with time period of 12 sec (see Fig. 1/a). The cyclic loading was started from the compressed side. We had measurement with the same force but at constant temperature. Finally we made a few measurements at constant temperature with similar 12 sec periodicity, but after every 20th period we kept the strain constant for 30 seconds at the maximum strain and then changed to the other end for 30 sec (see Fig1/b). To maintain the fast cooling according to Fig. 1/a, we had to apply a combination of cooling air blow with heating (to hold the strait temperature line), which really disturbed our acoustic measurements.

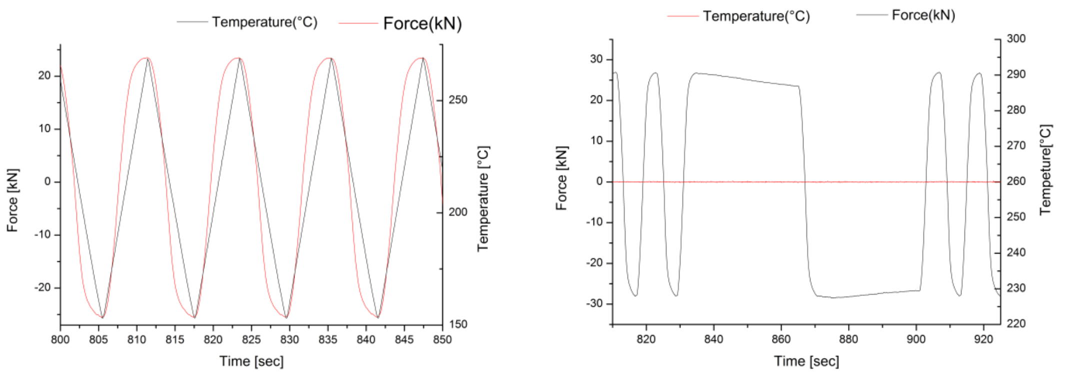

Fig.1. Change of force and temperature in a/ normal fatigue tests, b/ fatigue tests with waiting breaks

AE sensors of A-15AM type were used for AE measurements. They are resonance type with not very narrow resonances at 150 kHz. It is worth to remember this when comparing autospectra later. They have a built in preamplifier. Due to the test equipment construction we did not have space close enough to the test section. First we tried to fix the sensors at the end of the cylindrical specimen but there was no suitable place there. Finally we found that due to high forces applied at the fixtures of the simulator, the flat surface of the compressing yoke (see Fig.3.) seemed to be a rather good sensitive place.

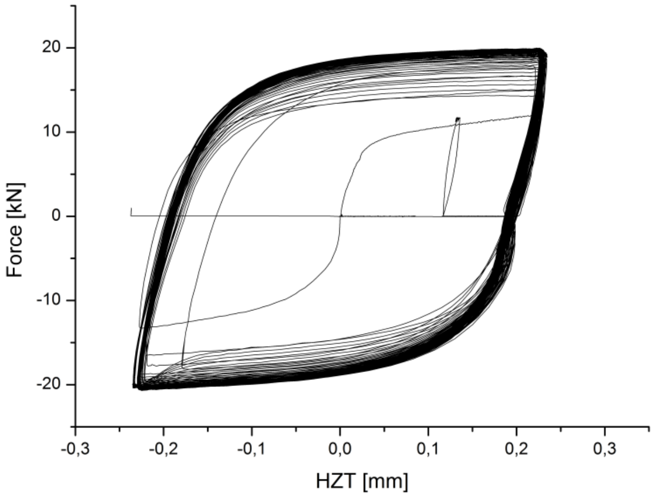

Fig.2. Typical low cycle force-strain hysteresis curve from our measurement stopped after 189 cycles with 9 longer cycles including when real cracks were seen and the initial force dropped by 25%

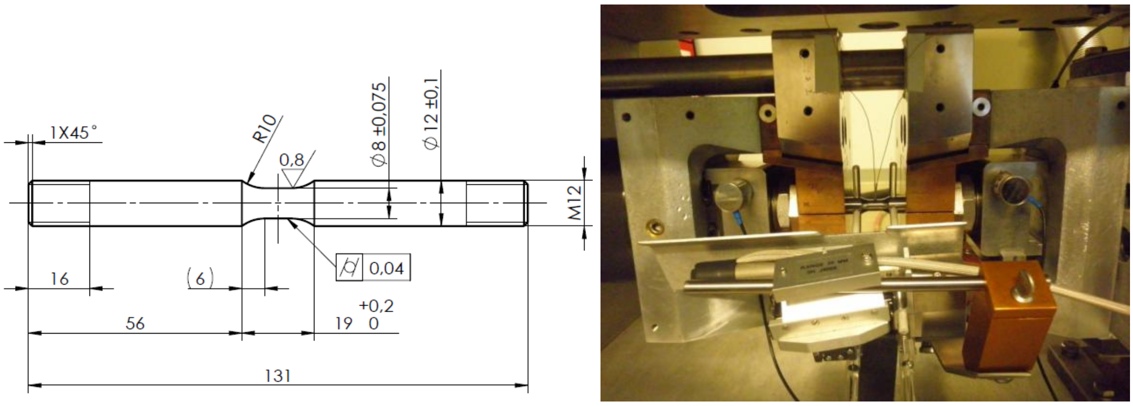

Fig.3 The specimen and the position of the AE sensors on the pressing yoke

We used two types of conditioning amplifiers, one was built by our MAID Lab and it is called MAIDGyver [3], while the other one is a part of the commercial AE measuring device Sensophone AED-40 [4]. The data collection was also made parallel.

For acoustic emission signal recording, we have different methods. First we had a continuous data storage, which recorded all the incoming signals sampled by 2MHz. Then in post processing we frequently applied the threshold detection of the hits (and events). In this method, the algorithm selects those events from the sampled signals which exceed a pre-defined threshold level. We also made use of the Sequential Probability Ratio Test (SPRT). SPRT is a method, which compares the probability density functions using the ratio of two conditioned probabilities [5]. We can apply both methods real time and post-processing as well. Finally we also had a traditional AE equipment (AED-40 [4]).

Table 1. Chemical composition of test materials (mass%)

Material	C	Si	Mn	S	P	Cr	Ni	Mo	V	As	Co	Cu
15H2MFA	0.13- 0.18	0.17- 0.37	0.30- 0.60	max. 0.025	max. 0.025	2.50- 3.00	max. 0.40	0.60- 0.80	0.25- 0.35	max.0.05	max. 0.02	max.0.15
08H18N10T	≤0.08	≤0.8	≤1.5	≤0.020	≤0.035	17.0- 19.0	10.0- 11.0	–	–	–	–	≤0.30

We had cylindrical specimens with 12 mm threads to fix them and 8 mm diameter of the test section in the middle (see Fig. 1). The specimens were machined from the base metal (15H2MFA) and the anticorrosive cladding metal (08H18N10T) of the VVER-440/V-213 (Russian designed PWR) reactor pressure vessel. The nominal chemical compositions and mechanical properties are given in Table 1.

Results of measurements

Fig.4. shows the general behaviour of the two acoustic signals during combined temperature and mechanical fatigue treatment for 15H2MFA. As it had been expected there was an obvious correlation between the cycles presented on Fig. 1/a in these response acoustic signals. One can see (Fig. 4) also that the signal was higher during tension than during compression. Disregard all periods where air cooling took place since it covers all the other acoustic events at least during compression.

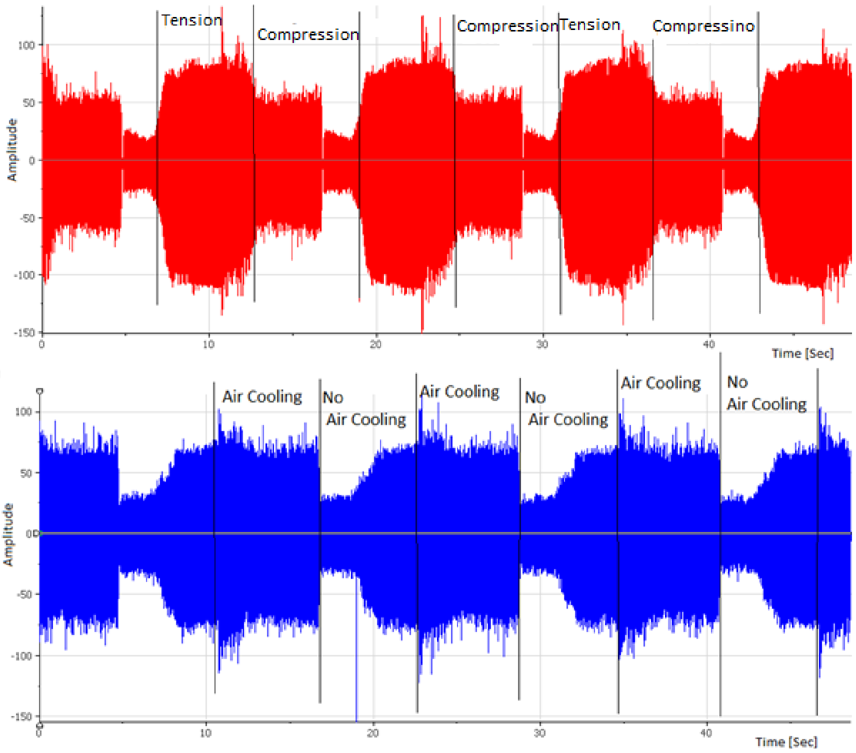

Fig.4. Acoustic signals measured on the two ends of 15H2MFA specimen

However, zooming in the time signal we found there were bursts in every 10 msec (see Fig. 5). It can also be noticed, that amplitude of bursts were about four times higher during tension (“pull”) than in compression (“pressure”). The acoustic signal during air cooling exhibited the burst level in compression but during tension periodic bursts were popping out.

A real hunt was initiated to find the source of those bursts, since 10msec was clearly connected to 50 Hz or AC power in our network. However, any attempt to connect those bursts to electromagnetic noises failed and finally we had to realize that the burst are coming from the investigated material. The most probably explanation was the so called Barkhausen noise, which is really manifested in similar pictures (cf. [6]). We had other arguments as well. First of all, when substituting the ferritic material 15H2MFA by the austenitic 08H18N10T at the absolutely same condition the amplitude of those burst dropped seriously sometime below the background noise level. On Figs 6 and 7 the acoustic signals are presented for ferritic and austenitic steels correspondingly at the absolutely same conditions. The burst in austenitic material was so small that it cannot be seen in compressing period, since there the background noise was higher. But small periodic peaks were found only during the tension part of the curve. In compression part what we see is only random noise. There were also few large AE events in during compression (see Fig. 7), which were even larger than the dynamics of our record (above 2V). Unfortunately later it turned out that most of them were due to friction on jaws. During tension there were only few AE events with small amplitudes.

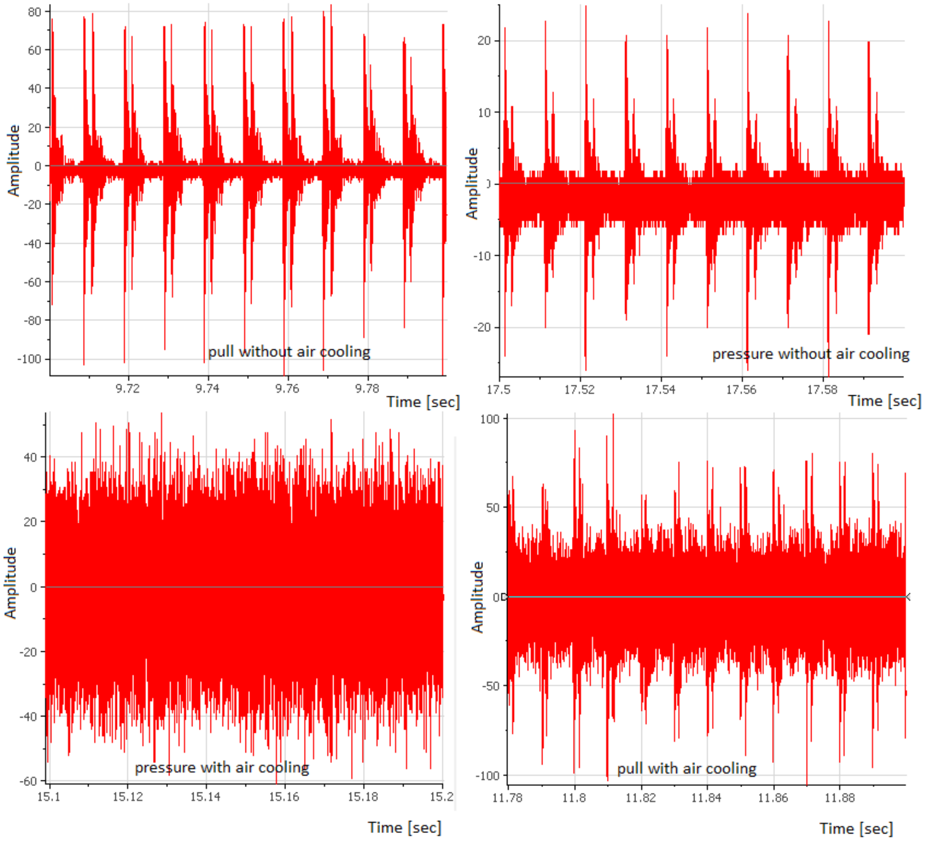

Fig.5. Periodic burst were found in acoustic signal

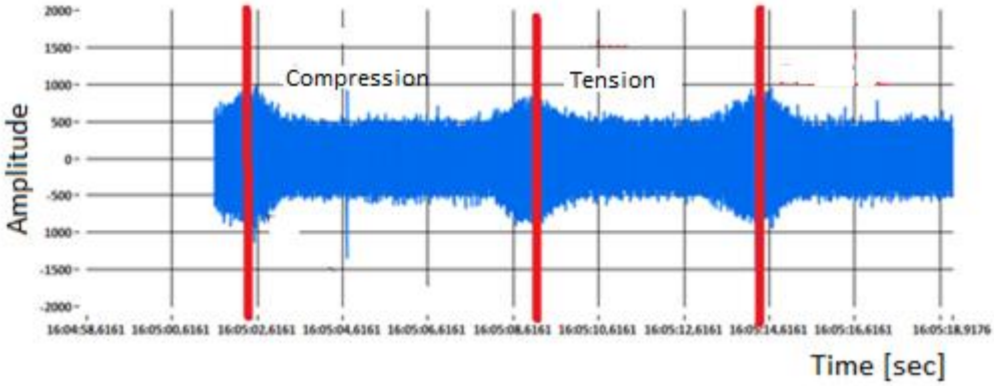

Fig.6. Signal of the ferritic steel during fatigue test

We have to notice, however, that the austenitic steel had some ferritic content which could be proven using a simple magnet. In another investigation (presented at this conference [7]) where TWIP steel was used in which the ferritic content was zero these bursts did not appeared at all. We also made a real Magnetic Barkhausen Noise (MNB) experiment, where real 50Hz yoke was used to initiate MBN and we resulted in similar burst standing 10msec from each others Fig. 8.

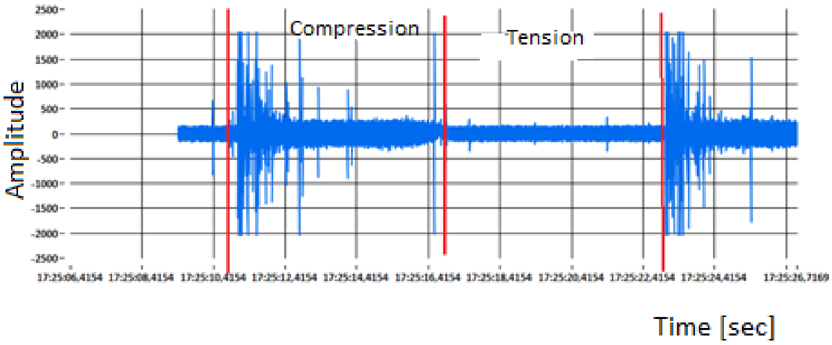

Fig.7. Acoustic signal of the austenitic steel during fatigue test

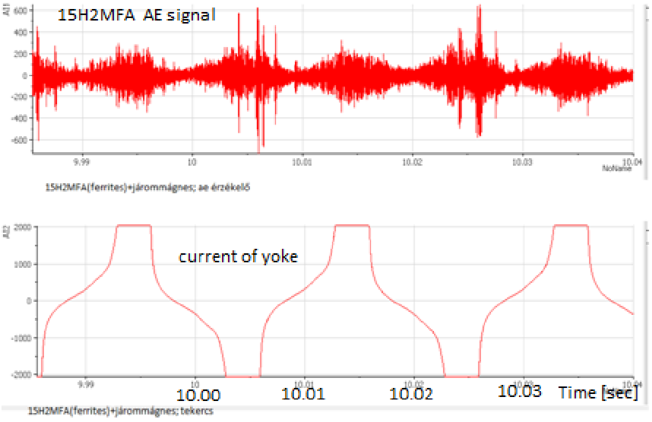

Fig.8. AE signal measured on 15H2MFA generated by yoke with 50 Hz AC

But we did not have any magnetic yoke to produce magnetic field in Gleeble. Where the magnetic field was coming from? We had to realize that it was coming from the 50Hz AC which is used in Gleeble for heating and maintaining the temperature in a programmed way. In this simulator the heating is made by electric current of low voltage and high amperes flowing through the sample. It is a resistance heating which produces magnetic field inside the material (see Fig. 9) according to formula:

$$B_x = 2 \cdot 10^{-7} \frac{i_x}{x} = 2 \cdot 10^{-7} i \frac{x}{r^2}$$

where x<r

This is multiplied by the permeability of the material which might be as high as 4000 in ferritic materials and about 100 times less in austenitic materials. Estimating the field in 15H2MFA it can reach up to 4 Tesla.

In our case Gleeble physical simulator produces not continuous 50 Hz sinusoidal signal, but interrupted parts of 50 Hz sinus with saturation length proportional to the needs of heating estimated by control. Therefore the shapes of the burst are very different from the usual ones. On Fig. 10 one can see the bursts registered by an AE sensors, plus the signal from a coil wounded around the axis of the specimen near to the test section. It is clearly shown, the current or voltage from the coil which is the derivative of the magnetic induction in the steel.

Thus we had to conclude that in the case of ferritic steel rather large ABN effect was present, which was first, regarded as a disturbing effect to investigate AE events and connect them to the fatigue of the material. Later, in the light of the results (see next section), we think that ABN could also be used for the same purposes as AE, and in fact it is also an AE, just from other origins.

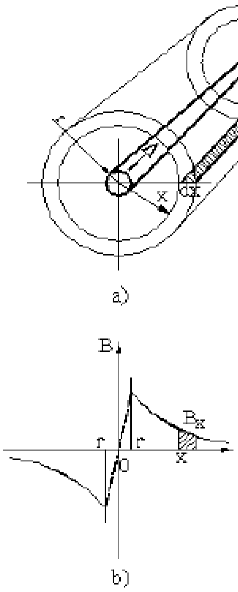

Fig. 9. The magnetic field in and around the specimen

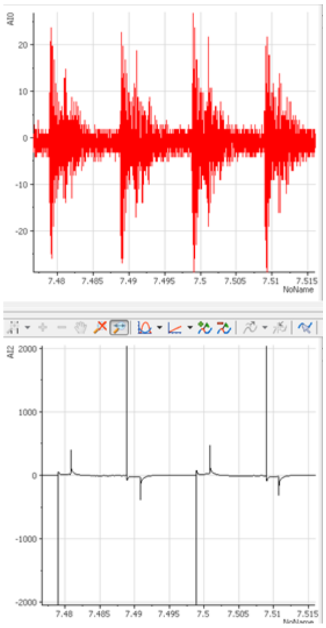

Fig.10. ABN bursts measured by AE sensors and MBN bursts measured by coils

Change of the ABN in ferritic steel during fatigue test

Repeating the experiment without air blowing (and stopping for 2x30 seconds at constant strain) we found that the amplitude of those periodic bursts is rather uniform but it has two growing parts at the beginning and end of the tension part in ferritic material (see Fig. 6), where also few real AE events are also popping out. The effect of tension was also confirmed by tensile test carried out on the same material that we are reporting in this conference [7]. It was also proven, that while the amplitude during the tension and compression was nearly the same (within the uncertainty) at the beginning of the fatigue test, it has grown up to 20% to the end of the fatigue test during tension part of the 12 sec period, when the fatigue reached 25% in the drop of force needed for the same strain (stopping condition of the fatigue test).

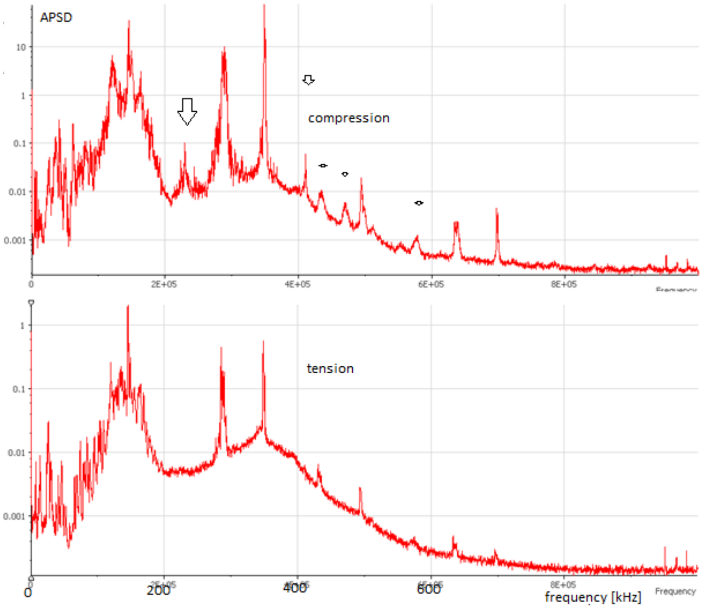

Fig.11. Differences in auto power spectral density (APSD) during tension and compression

Since the ABN in 15H2MFA steel has rather large amplitude, the typical level is about 500 mV, only very extensive AE events may appear above that level. And really, three are only few events having 500-2000mV amplitude, as it can be seen on Fig. 12 where the average ABN is higher than 500 mV.

The magnitude of the ABN bursts depends on the compression and tension. This is demonstrated on Fig. 13 where we zoomed in the acoustic time signal of the beginning of the second peak from the Fig. 12 where the ABN starts to grow and reaches the maximum value. The change in amplitude is well seen on Fig.11 where the auto power spectral densities (APSDs) are compared for compression and tension. Besides the amplitude difference there are also additional peaks marked on Fig.11 during compression.

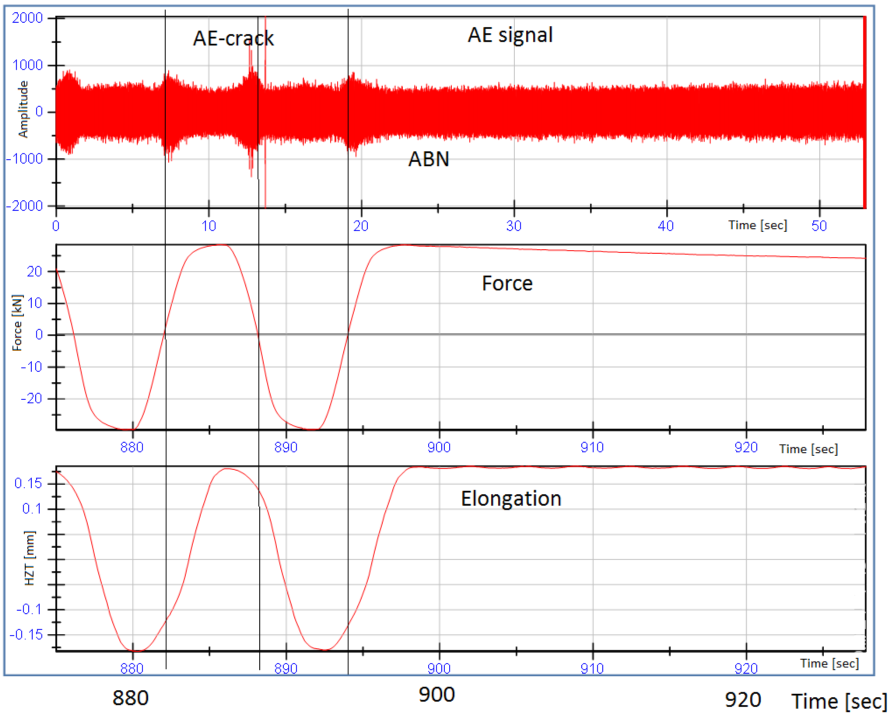

Fig.12. ABN (acoustic Barkhausen response) in the beginning of the fatigue test at F=27kN

The amplitude of the ABN seems to change during fatigue test. Towards the end of the test we observe, that the amplitude of ABN is larger during tension, than during compression (see Fig. 13) the difference in the amplitude may reach more than 20%.

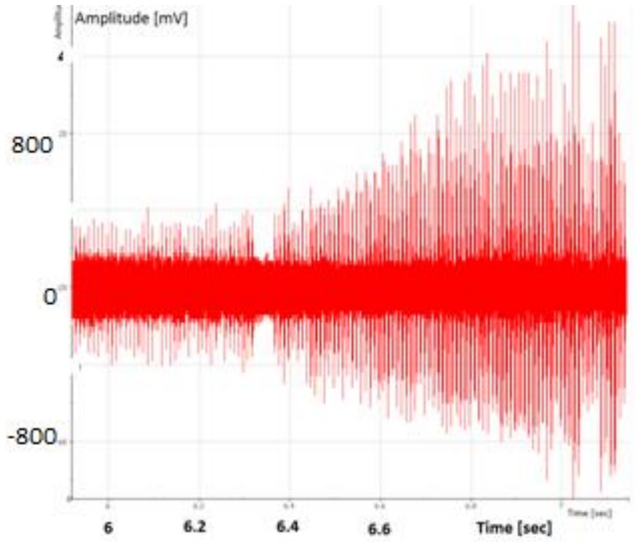

Fig.13. The growing amplitude of ABN bursts when tension starts

It is also interesting to compare the Fig. 12 and 14. The first one refers to the beginning of the fatigue test. The maxima in the amplitude of ABN are nearly there where the tension force crosses the zero level, while in Fig. 14 those maxima are at the point where tension force starts to grow and ends. We could trace the place of those maxima and we found that they are following the hysteresis curve (Fig. 2) starting at the top and ending near to the right upper corner of that curve. We started systematic investigation in this direction.

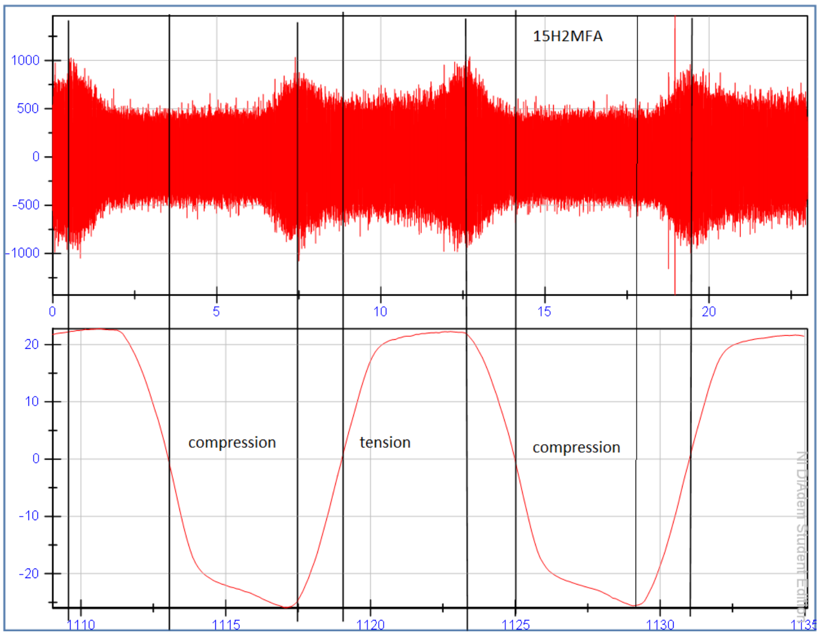

Fig.14. Barkhausen response toward the end of fatigue test, when the force had been started to decline F=22kN

Conclusions

LCF experiments were carried out in a Gleeble simulator changing both the temperature and the mechanical loads periodically with 0.08 Hz to simulate operation induced fatigue in reactor materials (15H2MFA and 18H18N10T). Meanwhile acoustic signals measured by AE sensors were sampled with 2MHz sampling time. Traditional AE parameters as well as time and frequency analysis were carries out off-line.

It has been shown, that due to 50Hz AC heating to control the temperature in the steel, ABN were detected in very 10 msec when the heating current was present in ferritic material. In spite the fact that there was no magnetic field coming from outside (there was no yoke at all) we produced magnetic field in the material due to dynamical changing AC current, which rotated the basic magnetic domains producing both spikes in magnetic coils and typical ABN signals. We have shown that magnetic rotation of the domains was caused by AC current.

The number of AE events did not allowed drawing any conclusion on the correlation between the AE and the fatigue. Even the slightly growing number of AE events towards the end of fatigue life had not enough statistics to make conclusion. We believe this is partly due to rather high ABN covering small AE events.

On the other hand ABN, which is rather high in ferritic steel opened the possibility to monitor the different stages in ferritic materials. The magnitude of ABN seems to follow the stresses inside the ferritic material, thus it could be used to estimate remaining stresses in the material. The spectra of ABN are different if there is compression or tension in the ferritic materials that opens the way to distinguish those stages. The magnitude of ABN is different to the end of fatigue. The observed wandering of the place of maximum at the beginning and end of tensile along the hysteresis can be a measure of the fatigue process of the material.

We believe that ABN events are also AE events just they are generated not by stresses in the material due to outside stresses, strains, thermal stresses or phase transformation, but from an inside stress caused by magnetic forces in the material. We showed they can be generated by high currents. Therefore they also belong to AE events and bravely can be used for material characterisation and the stage of the material like AE events.

Acknowledgement

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