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Application a laboratory stand for multi-symptoms tests for high cyclic fatigue of constructional material

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Abstract

This paper describes a need of diagnostics present ship plants according to current technical state. In order to reach competent physical quantity describing fatigue of materials by congregated energy. This paper describes using some diagnostics methods (acoustic emission AE, vibration, thermovision, deformation) in order to definition fatigue state of construction material. The author tries to find correlation between measured quantities which describe continuous process of fatigue wear. Innovation of this research allows use a new, little-know and little-recognized acoustic emission method by energetic fatigue research. Besides the results of AE will verified by use well-knowing and described research methods that are using to appreciate fatigue materials (vibration, thermovision, deformation). Used diagnostic methods were verified with photos of cracked scrap. The conclusion describes suggestion of research results. They will be needed to classification of fatigue symptoms that are measured by the above methods and are giving competent diagnostic dependence. This paper deals the results of elementary research on laboratory stand. They will be used to diagnostic of ship plants and their driving elements (shafts, cams, valves).

Keywords: *ship plants, drive elements, energetic methods for fatigue materials, vibration methods, acoustic emission*

1. Introduction

The fatigue of materials is continuous process that attends maintenance of machines. It is in all constructional element working with changeable loading so it is in many working machines. Present researches and experiences show that elements work in loading area making stresses under durable value of fatigue stresses is non-failure. The breakage is at the time result of wear or excessive loading [1, 2, 3] (fig. 1, fig. 2). It should think however how can determine technical state of device or its individual parts, if they were exposed for excessive loading or bad maintenance (f.e. disappearance of oil lubrication), appearance of notch or concentration stresses. This situation concerns especially driving elements of machines working with changeable loading. In this situation would be local weakness of material and start of crack. The breakage influences for shorter time of maintenance, less reliability and uncertainty of technical state.

Continuous monitoring of susceptible and important machine's elements is realized in lots of devices and constructions. For reliability very important is determination technical state according to continuous monitoring (maintenance according to present technical state). It concerns devices that demand high reliability like marine power plants and turbogenerators. According to this knowledge user can provide next sensible maintenance and moment of damage. This measuring technique is helpful to prevent and decrease damage and accidents. This technique and automatic systems can create modern diagnostic systems and limit human’s mistakes.

2. The purpose of test stand building

The purpose of test stand building has been determination the degradation of material’s property (especially constructional materials used to driving elements of marine power plants). This test stand is used to determination of fatigue strength limit for standard test pieces. In this case we can get Wöhler characteristic of material that is loaded of oscillatory bending moment. The method of making fatigue tests on this test stand is knowing very well and described at national standard PN-76/H-04326. The test stand is now provided with modern measuring apparatus that can describe fatigue state. This test stand is very useful to making basic tests by use apparatus detect fatigue of material at first time loading.

The tests making on this test stand have the purpose that we can describe a fatigue state of material by use present apparatus and methods. The described test stand is introduction to next experiments that are realized as doctorate study. A topic of the doctorate study includes diagnostic of some driving elements of marine power plants that are hazarded oscillatory loading, especially by use Acoustic Emission’s parameters as diagnostics symptom.

3. The test stand and the using measuring apparatus

The test stand was built probably in 50’th year XX century by workers and lectors worked on Mechanical Department of Gdansk University of Technology for making fatigue tests. The appearance and construction is similar to any test stands had been described on speciality literature [4]. The test stand was renovated and accommodated for test of fatigue process by use modern apparatus.

For recording quantities describing fatigue state of material’s test piece the test stand is provided with following measuring apparatus:

- Acoustic Emission (AE-system AMSY-5 of Vallen),
- vibration (vibration meter SVAN 956 of Svantek),
- temperature (thermovision camera of FLIR),
- deflection (dial indicator [0,01mm]),
- basic quantity (loading, number of cycles, time, rotational speed).

The sensors were installed with directions for use for measure quantity that describe actual fatigue state. It is especially important a graduation of measuring apparatus because they have to inform about actual material’s property. This attention concerns especially Acoustic Emission and thermovision camera

The Acoustic Emission apparatus is provided with right filters that can record (after right process) frequency spectrum of material’s cracks. Classification of right signals and random noises is laborious and demands right experience. Application of Acoustic Emission in described tests was possible only with experience that were got in earlier projects. This experience allows right correct Acoustic Emission apparatus and its software [5]. By temperature measurement we should especially attention that the measurement of emitted radiation spectrum informs about right temperature of test piece (the correct emission factor). The tests had show that the warmest point is not in this same side and “drifts”. The fig. 1 shows a side where the sensors were installed:

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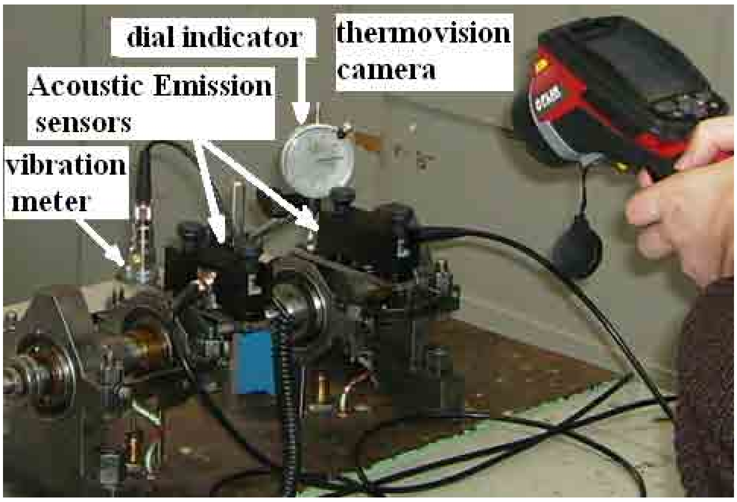

Fig. 1. Installation of sensors

The loading of test piece is caused by weights that are hung under test stand and make constant bending moment by stiff string system – fig. 2:

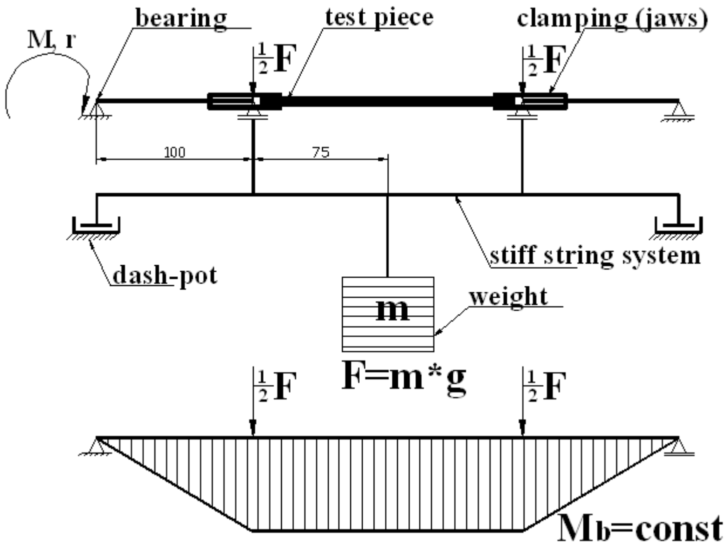

Fig. 2. The loading of test piece

The oscillatory stresses are caused by rotation of test piece that is loaded bending moment. If we know the properties of material we can count a number of cycles (fatigue life) and vice versa. The properties of material and chemical constitution were identified by tension test in certification laboratory of Gdansk University of Technology. The tension test helped to identify the right material of test pieces. The material of test pieces is unalloyed weldable fine-grained steel S355N. If we know dimensions of the stiff string system (fig. 2) we can count very easy stresses that are in test piece. The final relation is following:

$$\sigma_b = \frac{M_b}{W_x} \cong \frac{\frac{1}{2}F \cdot l}{0{,}1d^3} = \frac{\frac{1}{2} \cdot 22kg \cdot 9{,}81\frac{m}{s^2} \cdot 100mm}{0{,}1 \cdot (8mm)^3} = 9{,}58 \cdot 22 = 211MPa \tag{1}$$

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The installation of Acoustic Emission sensor and vibration sensor together on one bearing housing causes to get comparable information (fig. 1). The information will analyse in the next experiment. This method allows to locate cracks of test piece. The time of cracks and velocity of wave propagation (steel) allow to count the place of cracks (fig. 5, fig. 6). The two-dimensional analysis (two Acoustic Emission sensors) was made by use special Visual Class program.

The results of tests, experience and literature show high scatter of Wöhler characteristic for oscillatory bending test. A number of cycles for constant loading (fatigue life) differs over 100%. It is necessary to make statistical verification.

4. Tests

The tests were made according to Wöhler characteristic. The fatigue strength limit was determined according to literature, experience and material's certificate. The next step consisted in start from high loading and reduce it and observe the parameters. The range of loading and measurements was determined after break a few test pieces. The test was made for fifteen test pieces and makes introduction to the next tests and statistical verification.

The measurement of vibration, deflection and temperature were taken reading after particular number of cycles (discrete measurement). The characteristic of measurement for particular test pieces was described on this way (fig. 4). The test was planned in this case, that reading of parameters were made for every test pieces after particular number of cycles. In this way we can get comparable information about analysis of fatigue process. The measurement for parameters of Acoustic Emission (AE) was read continuous off. This way caused get the quantities describe a shape of AE wave (RMS, number of level's overflows).

The analysis of results allows to state that amount of dissipative energy in cyclic loaded driving elements could be a information about fatigue state of material. The range of hysteresis lop (co-ordinate system stress - strain) describes amount of energy *U* that is necessary to deformation of material at every cycle. Some of energy is wasted for internal friction in microstructure of material [2,8]. In this case losses of energy make increase of temperature. The final relation between the total losses of energy in material *W* and strain's energy *U* is following 2 [8]:

$$W = U\left(\frac{\sigma_{rz\_z}}{\sigma_a}\right)^{\Theta} \qquad (2)$$

where:

$\sigma_{rz\ z}$ – true stresses by break (by tensile test),
σ_a – amplitude of stresses,
Θ – factor describes intensity of increase of energy *W* with energy *U* together with increase of cycle's number N_f described relation for plastic materials 3,
e_{rz} – true strain for $\sigma_{rz\ z}$.

$$\frac{1}{\Theta} = 0{,}085 + 0{,}37 e_{rz} \qquad (3)$$

Every loss of energy is described range of hysteresis lop and is propagated as elastic wave in material. A shape and parameters of this wave are measured by AE sensors. The results of test show that for low number of cycles the energy at one cycle is "sufficient high". The signal

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generated of this way is measured by AE sensors. The results of test show that for big number of cycles the energy at one cycle is “low” and the crack’s energy losses in material could not measure by AE sensors. The temperature and AE are good correlation of parameters that describe losses of energy in cyclic loaded test piece. The fig. 3 shows increase of temperature for one test piece measured by use the thermovision camera for followed cycles. The fig. 4 shows characteristic of temperature and strain cycles-dependet for four test pieces loaded the same weight. The table 1 includes basic data and results of tests.

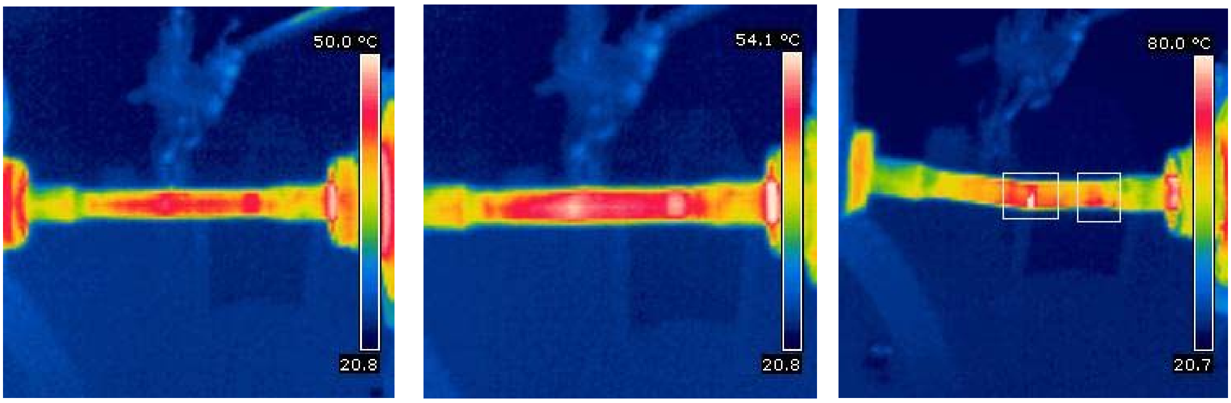

Fig. 3. Increase of temperature for followed cycles and moment of crack

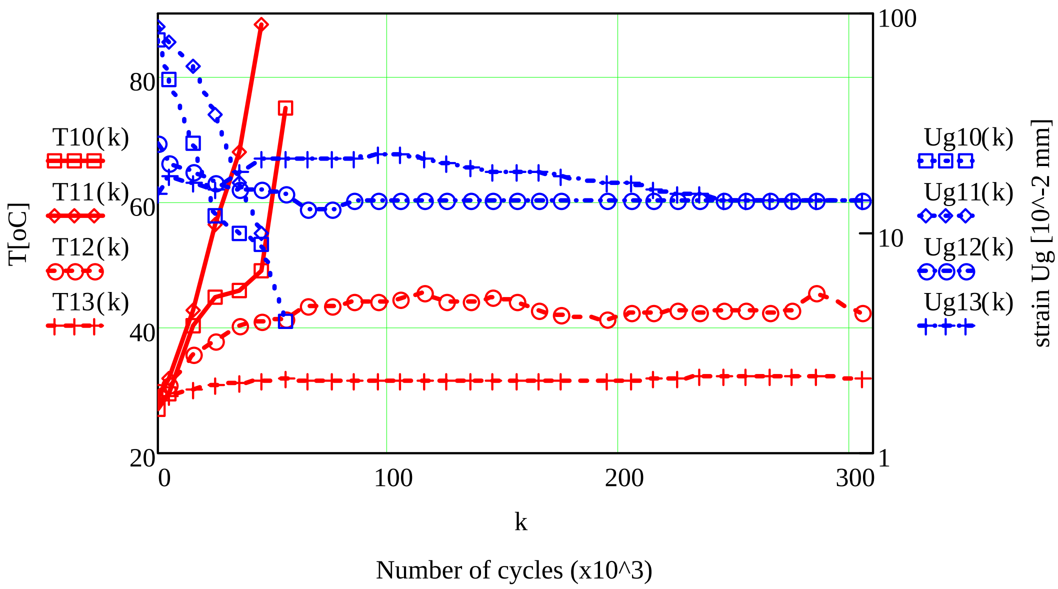

Fig. 4. The temperature T[°C] (red line) and strain Ug[10^{-2}mm] (blue line) cycles-dependet k for four test pieces: 10, 11, 12 i 13 (loading 22kg)

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Tab. 1. Basic data and results of tests for four test pieces

	Test piece 10	Test piece 11	Test piece 12	Test piece 13
number of cycles until crack	$55x10^3$	$45x10^3$	$509x10^3$	$1450x10^3$ didn't crack
max. temperature after 20 $x10^3$ cycles	48,1 ^oC	53,6 ^oC	39,0 ^oC	31,3 ^oC
strain after 20 $x10^3$ cycles	0,59 mm	0,42 mm	0,09 mm	0,08 mm
absolute change of AE amplitude (after moment of strain hardening)	4,4%	4,2%	1,5%	0,1%
visible crack's location (AE signal)	YES	YES	WEAKLY	NO
amplitude of stresses	211 MPa	211 MPa	211 MPa	211 MPa

The results show that thanks to AE method is possible separation of signal that genesis is from fatigue source. High elementary energy which is emitted in one cycle is measured by AE apparatus. Fig. 6 shows signal location described by number of location events and measure by AE sensors. For 10 and 11 test pieces (short fatigue life) we can very clearly see the signals generated in the middle range of test piece between AE sensors (the crack place). For 12 test piece (fig. 5, fig. 6) we can see this same signal generated in middle range but noise from bearings is stronger. In this case we could not detect a material defect and a crack location. The signal of 14 test piece doesn't show fatigue cracks. This analysis is acknowledged by temperature, strain and basic data in table 1.

This results show that loss of energy in cyclic loaded material describe its duration (fatigue life). We can very right measure this process by use Acoustic Emission. A low diagnosticability is for test pieces have long fatigue life (big number of cycles until crack) and low storage of energy in material.

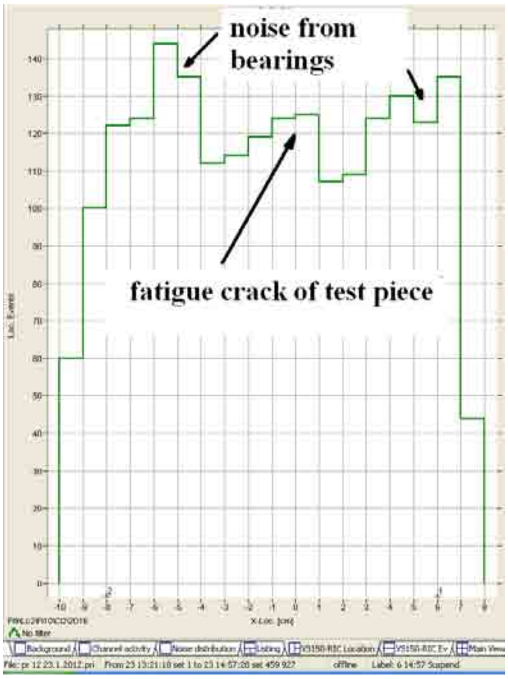

Fig. 5. The number of location events were measured in range between AE sensors

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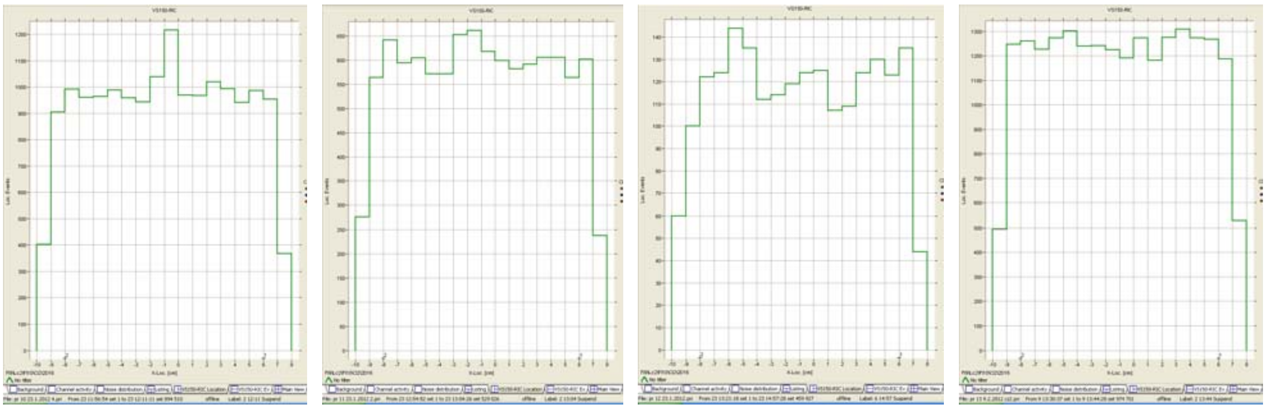

Fig. 6. The location of crack range (from left: test piece 10, 11, 12, 13)

It is a correlation between amplitude of AE signal and fatigue state of material. At the moment of strain hardening (point on characteristic where strain-line is curved) the amplitude of AE is decreasing (tab. 1, fig. 7. fig. 8). The decrease is more clear for test pieces which have a low fatigue life (10 and 11 test piece). The decrease is weakly clear for test pieces which have a high fatigue life and unclear strain hardening (12 test piece). A change of AE amplitude is not visible for uncracked test piece (13 test piece). The moment of crack is described increase of AE amplitude. The general rule for energetic evaluation of multi-symptoms tests of fatigue material is described following: strain hardening – decrease of strain – lower energy – lower AE amplitude – stabilization of temperature.

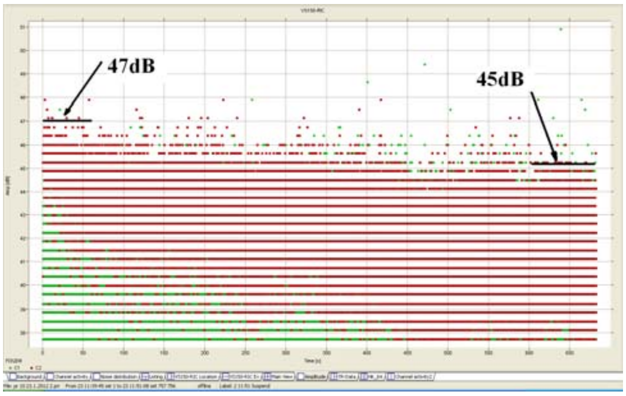

Fig. 7. The change of AE amplitude [dB] at moment of the strain hardening – 10. test piece

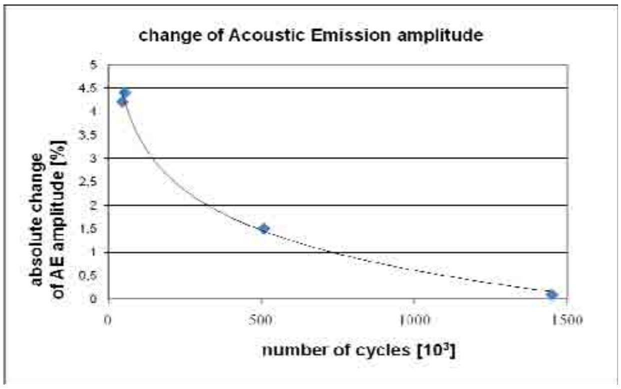

Fig. 8. The change of AE amplitude at moment of the strain hardening cycles-dependet

The process of fatigue material can be described by frequency spectrum of vibration. A measurement was taken reading after particular number of cycles because a memory of vibration meter was limited (discrete measurement). With following decrease of section of test piece a rigidity of joint is decreasing. This process shows high amplitude in particular frequency spectrum of vibration (analysis FFT fig. 9, fig. 10). Spectrum of high amplitude of frequency is in the range of first harmonic (after noise’s filtering - noises from bearings). The next analysis can find range of frequency which is symptom of fatigue material. The frequency: second harmonic (100Hz) and four’th harmonic (200Hz) are symptoms of following fatigue crack of material.

A visible increase of energy signal which is measured by AE sensors is not sufficient measure by vibration sensors. Fig. 9 shows frequency spectrum of vibration before loading. With following degradation of material (fatigue material) the second harmonic (100Hz) and four’th harmonic (200Hz) are more visible – harmonic which are characteristic for fatigue crack of shafts. The measurement for four test pieces loading this same weight (tab. 1) does not show increase of

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amplitude in frequency spectrum of vibration for second harmonic and four'th harmonic (analysis FFT - fig. 10) – however the increase of AE parameters is visible. This measure shows that vibration method is useful for diagnostic of technical state at the final life of devices (10 - 20% life before break-down).The vibration method is useful because by use analysis FFT we can recognize defect (characteristic frequency spectrum of vibration) but we can not describe quantitative (by amount) damage or sufficient describe diagnostic of fatigue state of material.

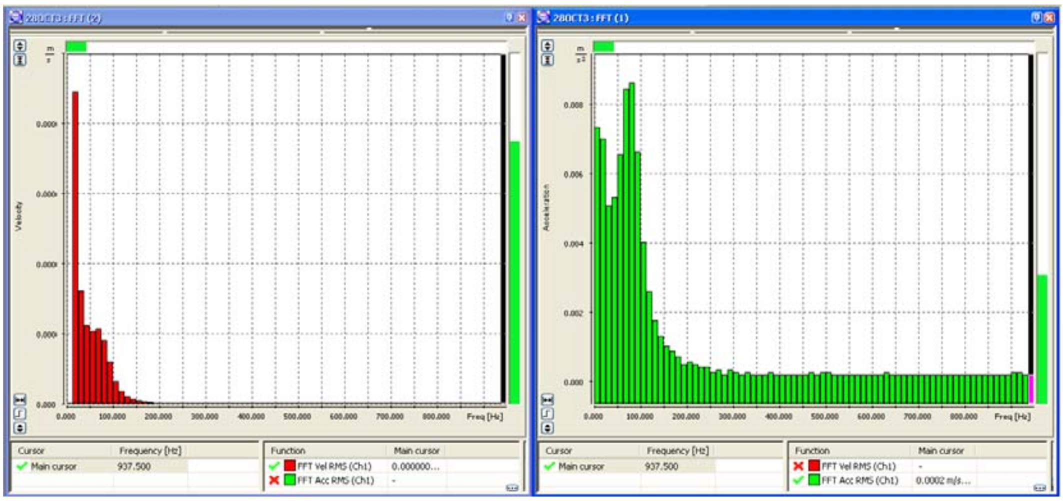

Fig. 9. Analysis FFT for test piece before loading (spectrum): velocity (left) and acceleration (right)

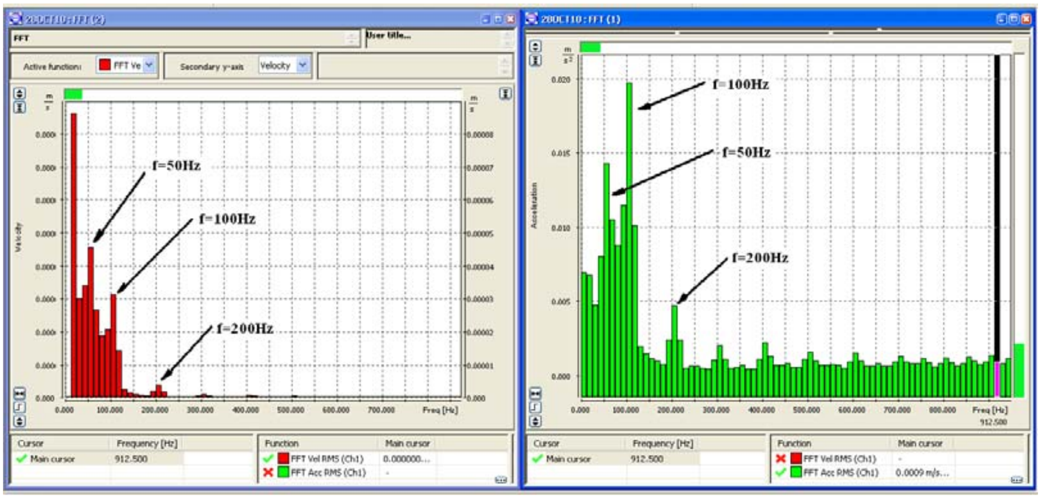

Fig. 10. Analysis FFT for test piece during test: velocity (left) and acceleration (right)

The used parameters give diagnostics information about progress of fatigue material and its quantitative describing. However for describing structure of material were made metallographic photos of fatigue scrap (fig. 11). They were useful for verification of measured parameters and for more precise describing of fatigue process and for explanation their run. This procedure can help to describe state of material in crack point together with results of measurement. This procedure can help to compare fatigue scrap with run of measured parameters.

The parameters of overnamed apparatus and fatigue scraps show loss of energy in one cycle and describe state of material. Fig. 11 shows 10 and 12 test piece. The fatigue scrap for 12 test piece is characterized small spacing between crack's lines and big ratio between fatigue range and plastic-brittle range. This fatigue scrap shows big number of cycles to break-down and small loss of energy in one cycle. This statement is described by results of AE, strain and temperature. The fatigue scrap for 10 test piece is characterized for low cyclic test. A big loss of energy in one cycle

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is characterized big spacing between crack's lines. This statement is described by results of AE, strain and temperature (very clear location of crack – fig. 6).

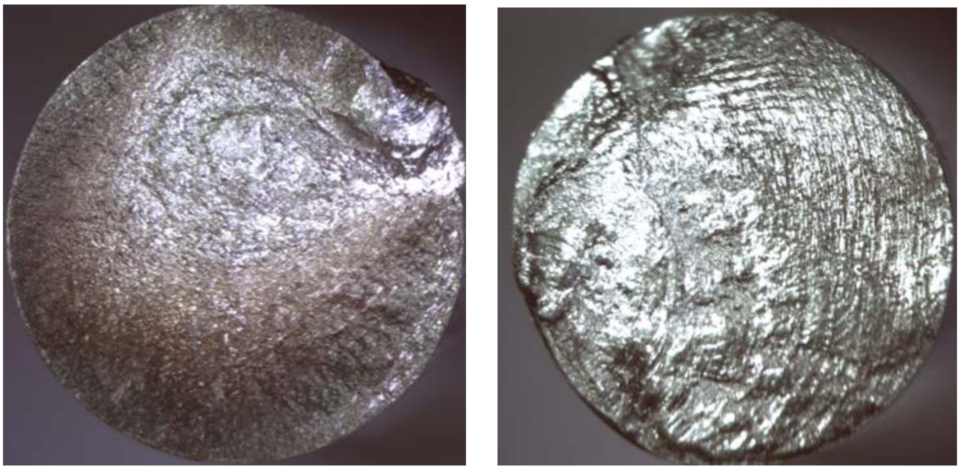

Fig. 11. Metallographic photos of fatigue scrap (left: 10. test piece; right: 12. test piece)

The metallographic photos show that diagnostic of technical state for machines by use loss of energy in cyclic loading material is very useful. The used apparatus is very useful for this tests.

A right shape of AE wave and its characteristic frequency (analysis FFT), amplitude and RMS will be helped in next tests to associate in individual groups for common runs of waves. In this process will be made classifiers which could help to separation a individual frequency responsible for useful signal (fatigue material) and noises. The next analysis of results will be made by use special Visual Class program.

5. Conclusion

The results of made tests give interesting conclusions. It is common correlation between measured parameters: Acoustic Emission, vibrations, temperature and deflection. This statement was very probable because process of fatigue material is continuous process and following degradation of structure of material has to give changeable symptoms. Moreover fatigue material is energetic process which is characterized cyclic strain that makes increase of temperature and strain hardening. It should mark that the highest temperature which is measured at test is not always in crack point. This observation could show that material has internal defects or heterogeneous structure. However at the moment of crack the highest temperature was always in crack point. The strain hardening is characterized decrease of strain and this makes less deflection and less moment of inertia (less moment of rotational mass) and increase of rotational speed.

A previous tests give information that we can see relation between AE and vibration parameters [6]. The frequency and amplitude which are results of fatigue material are visible by use AE apparatus more earlier. A fatigue material which is energetic process is characterized for loss of energy in material and change its properties which are recording by use AE apparatus. The Acoustic Emission gives information about damage location and amplitude's value. Thanks to this information we can estimate state of fatigue material as function of loss of energy in material. Thanks to this information we can decide about maintenance and work of drive system in the future. When we compare a vibration method and Acoustic Emission we have to make statement that the vibration method allows to estimate a fatigue material by use a characteristic frequency (frequency spectrum) and not by use change of amplitude (RMS).

A big scatter of number of cycles until crack for test pieces loaded this same weight was caused probably influence of strain hardening of primary material during rolling. All test pieces were cut and made from the one steel plate (this same material S355N). The test pieces were

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turned in this cause that axis of test piece is parallel to direction of rolling. The test pieces which were cut from surface layer had a higher internal work-hardening (internal stresses and direction of grains as a result of plastic working) that could be a reason of higher fatigue strength [8] (fig. 4).

It is relation between number of cycles and measured parameters. This is a general statement and true for all test pieces. We can make statement that we can predict a future time for crack of test piece on the basis of measured parameters. This statement says measured parameters give information about quantitative (by amount) description of fatigue material and how many cycles a test piece can work.

In the next part of test will be introduced changes in material (cut notch) and continuous change of loading for test pieces work over a fatigue strength. This method will show technical state of machines or their parts work with overloading and with internal preliminary fatigue wear. This method will allow determine a relationship between diagnostic parameters and predict possibility of fatigue life.

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