Acoustic Emission Control of Strain State in Simple Loading Condition

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Abstract. In this paper, review, technique and experimental research results of strain parameters correlation with acoustic emission signal properties are presented. Researches are carried out in condition of simple one- and two-step compression. Results obtained were used for assessing accumulation of properties in terms of technological inheritance in cutting and burnishing processes.

Introduction

When engineering and optimization of machine parts hardening technology by surface plastic deformation with technological inheritance (TI) taken into account phenomenological theory is used. Mentioned theory is based on end-to-end description of physical state of part surface layer on all its productive life stages in uniform terms and categories of continuum and fracture mechanics. The fundamentals of this approach is built on the conception of continuous surface layer formation and plasticity reserve depletion during surface plastic deformation. Metal condition evaluation is performed using mechanical parameters such as degree of shear deformation Λ, degree of plasticity reserve depletion Ψ (DPRD) etc.

However, the complexity of mechanical parameters identification restrain possibility of using this approach in actual practice. On the other hand, physical nature of inherited phenomenological theory makes it possible to employ physical research methods for obtaining high quality results [1].

One of such methods that accounts for nature of plastic deformation on micro-level is acoustic emission method. Acoustic emission (AE) is defined as transient mechanical waves generated due to localized physical changes in a solid material under mechanical or thermal stresses and fracture. AE wave is an acoustic impulse with wide frequency spectrum. The fundamental features of the AE signals include count, cumulative event count, signal energy $E_C$, amplitude, duration, signal power, e. t. c. Some problems require pulse-height distribution and frequency spectrum researches. These parameters have different information capability and should be selected according to research type and equipment available.

AE method is widely used during mechanical tests for revealing correlation between AE parameters and number of accumulated defects in metal loading process. AE parameters reproduce nature of strain accumulation and enable to apply phenomenological approach more objectively. AE method is commonly used for fracture prediction because of its capability of revealing real damage and assessing probability of defects, which is crucial for durability estimation of machine parts.
As has been mentioned above, there is a problem in establishing relationship between phenomenological parameters of surface layer and AE parameters since TI mechanics is expressed in macro-parameters (Δ, Ψ - macro-level) while AE reproduces micro-level (dislocation density, slip lines developing). However, there is a correlation between dislocation arrangement alteration and mechanical characteristics of surface layer [2-4].

AE method is in common use for control and examination of parts and assembly units for various machinery.

I. Baran, M. Nowak and W. Darski [5] investigated the possibility of using AE method to determine the technical state of the slide bearings in engines with self-ignition. The tests were carried out on three sliding bearing: without defects, with an opening and with longitudinal and circumferential scratches. Results obtained have shown considerable difference in AE signals for each type of bearing, especially in root mean square (RMS) and frequency distribution of signals. The sensitivity of the AE method allows one to record the signals, which indicate the transition from the fluid friction into the mixed friction.

J. Yan et al. [6] have applied AE method to diagnose valve leakage, which is one of most common defect. It was revealed that in the process of fluid leakage high frequency (100 kHz – 1 MHz) AE signals are generated and that they can be easily identified by environmental noise from the factory. The results showed stable positive correlation between disk wear and RMS and between foreign objects size and AE parameters. Error of actual leakage measurement with leakage calculated by AE signals is less than 8 %.

A. Keshtgar and M. Modarres [7] investigated relationship between particular features of AE signals and fatigue crack initiation on wrought aluminum specimens. Fatigue experiments were implemented under cyclic loading with frequency of 20 Hz and loading ratio of 0.5. The minimum and maximum applied loads were 4.5 kN and 9 kN, respectively. The fatigue cracks were monitored by direct measurement using an optical microscope. Signals from the AE sensor were filtered using a band pass filter (200 kHz – 3 MHz) to eliminate emissions from outside sources. It was discovered that the first detected jump (more than 50% sudden increase) in intensity of AE signals having a relatively fast rise time and high amplitude corresponds to the crack initiation.

S. A. Niknam et al. [8] investigated the usage of AE method for unbalanced analysis in rotary systems. The parameter of interest in this study was PAC-energy parameter that covered the significance of count, duration and peak amplitude in AE signals. As a test object self-aligning ball bearings or three kinds were used: new, used and faulty. To make a faulty bearing, a groove was made by using electrical discharge machine on the inner race of a bearing. To impose the unbalance force two unbalanced disk with the off-center holes were used. As a result, the categorical data analysis based on generalized linear models was presented. It was observed that the faulty bearing was the most significant in producing more AC-energy and the effect of used bearing was more significant than new bearings in this respect. The results demonstrated the possibility of using AE method for detecting and estimating unbalance in rotary systems.

L. Gao et al. studied the possibility of AE method application for fault diagnosis of low-speed heavy-duty gears [9]. The authors developed special de-noising technique based on redundant second-generation wavelet. It was revealed, that with the wear process developing of gears the amplitude of mesh frequency increased and so did the ultra-harmonics amplitudes. The examination of gears confirmed detected regularities. Developed technique allows one to effectively process AE signals for on-spot fault diagnosis of fears.

K. Shrama et al. [10] investigated crack initiation and growth on mild steel specimens using AE method and Digital Image Correlation (DIC). The specimens were subjected to fatigue load ranging from 41 % to 85 % of the ultimate tensile strength. Part of the specimens were exposed to alternating spraying of 5 % NaCl solution. A combination of AE and DIC was used to monitor the strains values and fatigue crack growth during the fatigue tests. Cumulative counts and cumulative absolute energy are two parameters that were used to develop plots that correlate to the fatigue crack growth process with time. The results obtained showed the capabilities of AE method for detecting fatigue fractures.
V. Greshnov [4] examined the alteration of surface layer condition depending on dislocation arrangement changing while plastic deforming. That research work is of great interest since it makes possible to monitor the metal damage from micro-level (dislocation) to macro-level (visible crack). The author considers plastic deformation and metal fracture as a united kinetic, multi-stage, stochastic and activated (mechanically and thermally) process driven by fault motion and transformation of various kinds. For non-monotonous processes with multiple loading micro-crack density increment was assessed as follows:

\[
dN_{m(i)} = \left[ \frac{10^{-5} \sigma_i^2 (\varepsilon_i)}{(a \mu G b)^2} - N_{m0(i-1)} k_{md(i)} \right] d\varepsilon_i
\]

where \( dN_{m(i)} \) is micro-crack density increment on \( i \) loading stage; \( N_{m0(i-1)} \) is accumulated micro-crack density after \((i-1)\) loading stage; \( k_{md} \) is factor of proportionality. The author used addition principle of metal damage and generalized equation \( \sigma_i (\varepsilon_i) \) obtained in [11].

By metal damage (fissuring, faultiness), V. Greshnov means degree of plasticity reserve depletion since he accepted known equation derived by A. Bogatov [12]:

\[
\omega = \sum_{i=1}^{n} \frac{a \Lambda_{i-1}}{\Lambda_i} d\Lambda
\]

where \( \omega \) represents elementary volume metal damage after \( n \) deforming stages (monotonous, quasi-monotonous); \( a = a(\kappa, \nu, H, T) \) – parameters dependent on material nature, thermo-mechanical conditions and the kind of deforming.

We use the approach as in expression (1) on transformation from micro-level to macro-level. It can be seen that metal damage accumulation depends on strain and strain rate with stress state taken into account, while micro-level in the end is considered as faultiness of initial microstructure state.

Considering that, initial metal state has no micro-damage and \( \Psi = 0 \), we can assume that at surface layer loading metal micro-damage results in certain plasticity reserve depletion, which in turn involves AE signal generation. We will take a closer look as to how metal damage occurs while surface layer loading and its connection with AE signal generation.

All known models can be expressed as follows:

\[
(\dot{N}, A, E, W) = f(\Delta \rho),
\]

where \( \Delta \rho \) is dislocation density alteration.

It has been noted by many authors, that there is a relationship between AE parameters and strain rate \( \dot{\varepsilon} \) since plastic flow velocity depends on dislocations motion rate (density alteration) in sliding direction [13-14]:

\[
\dot{\varepsilon} = b \frac{d\rho}{dt},
\]

where \( b \) is Burgers vector.

D. Merson suggested model that establishes a link with not only dislocation arrangement but stress-strain state as well [13]:

\[
W = D \frac{\nu \dot{\varepsilon}^2}{\sigma^2}
\]

In expression given the author employs such analogous concepts as dislocation movement velocity and strain rate, that were used, for example, in Eq. 4. \( D \) -parameter (constant for sample given) represents its physical and mechanical properties. The author claims that AE signal power depends on
surface area on which deformation occurs. However, such assertion is right only if constant volume of material is engaged in deformation, otherwise AE signal should be attributed to material volume.

Analysis of this model allows one to suggest that AE signal power while metal deforming is function of direct components: physical and mechanical material properties, geometry of specimen (part) and stress-strain indicators.

Such assumption does not contradict A. Kibalchenko’s researches in which the author distinguishes AE signal power from deformation in metal cutting as part of deformation power [15]:

\[ W = k \cdot W_d = k \tau_s \dot{\varepsilon} S, \]

where \( \tau_s \) is material shear yield stress, \( \dot{\varepsilon} \) is strain rate, \( S \) is volume of metal being deformed, \( k \) is factor which takes into account portion of process energy emitted in form of AE.

Studies conducted show that AE signal power in this case too depends on same constants and strain rate, without stress-strain indicator taking into account though.

Thus, AE signal is connected with dislocation density alteration on the one hand and with strain rate on the other hand (in plane strain condition with strain rate intensity \( \dot{\varepsilon} \)) [4].

Models examined are of a great research value, but using of dislocation density in practice especially in engineering calculations when manufacturing processes designing presents a challenge for research workers.

In the context of present work TI theory has been developed in course of estimation of surface layer physical inherited condition in terms of AE signals. Relationship between mechanical condition parameters and AE parameters has been used later on for identification inherited mechanical condition and surface layer condition control at any loading stage. In doing so the results of various sources on AE signal parameters control has been taken into consideration which showed that in simple loading condition count rate \( \dot{N} \) and signal amplitude \( A \) held an ample information capability.

**Experimental researches technique**

Due to some complications of integrated criteria \( \Psi \) and \( \Lambda \) estimation at machine cutting and surface plastic deformation, which occur in deformation sign changing conditions, at first relationships between mechanical parameters and AE signal have been investigated in more simple condition.

The aim of experimental researches was to obtain steady correlation between surface layer mechanical parameters and AE signals. Press compression with simultaneous AE signal recording was performed at metal test lab on “AZOT” stock company (Kemerovo city).

Researches were carried out on two batches of specimens. Barrel-type annealed state specimens made of 1045 carbon steel were subjected to AE investigations. Table 1 shows initial data for specimens of the first batch, where \( D_0, h_0; S_0; V; P; HV \) are dimensions before loading, sectional area, volume, loading force and original hardness respectively. Through preliminary hardness test four groups of specimens were sorted out. Specimen’s data of second batch (AE signals included) is given below. Specimens of that batch were also made of 1045 steel but from other delivery lot. Tests were carried out in uniaxial compression condition of uniform and monotonous character; maximum load was 500 \( kN \).

The compression was performed by installing specimen 3 in special device 4, which was mounted onto lower press crossbar 5 (fig. 1). AE information recording was carried out during all the loading time. At the same time, loading condition control was implemented by annotation recording when reaching of certain value (with interval of 50 \( kN \)).
Figure 1. Experimental set-up: 1 – pre-amplifier; 2 – AE sensor; 3 – specimen; 4 – special device; 5 – press lower crossbar

Table 1

| Specimen number | $h_0$, mm | $D_0$, mm | $S_0$, mm² | $V$, mm³ | $HV$ | Group number | $P$, kN |
|-----------------|------------|-----------|------------|-----------|-------|--------------|--------|
| 1               | 19.8       | 19.9      | 311        | 6158.305  | 174-177 | 1            | 250    |
| 2               | 19.9       | 19.9      | 311        | 6189.408  | 177-183 | 1            | 350    |
| 3               | 20         | 19.8      | 308        | 6158.15   | 174-177 | 1            | 450    |
| 4               | 20.3       | 20        | 314        | 6377.433  | 171-177 | 2            | 350+250 |
| 5               | 20.1       | 20.1      | 317        | 6377.905  | 166-171 | 3            | 350+250 |
| 6               | 20.1       | 19.9      | 311        | 6251.613  | 162-166 | 3            | 250+350 |
| 10              | 20.1       | 20        | 314        | 6314.601  | 171-174 | 2            | 250+350 |
| 11              | 20.1       | 20        | 314        | 6314.601  | 152-154 | 4            | 250    |
| 12              | 20.4       | 19.9      | 311        | 6344.921  | 162-166 | 3            | 350    |
| 13              | 20.2       | 19.9      | 311        | 6282.716  | 171-174 | 2            | 200    |
| 14              | 20.4       | 19.9      | 311        | 6344.921  | 166-171 | 2            | 250    |
| 15              | 20.4       | 19.6      | 302        | 6155.059  | 171-177 | 2            | 300    |
| 16              | 20.1       | 19.9      | 311        | 6251.613  | 162-166 | 3            | 350    |
| 17              | 20.2       | 20        | 314        | 6346.017  | 158-162 | 4            | 400    |
| 18              | 20.7       | 19.9      | 311        | 6438.228  | 158-162 | 4            | 150    |
| 19              | 20.5       | 19.9      | 311        | 6376.023  | 166-171 | 2            | 250    |
| 20              | 20.3       | 19.9      | 311        | 6313.818  | 166-171 | 3            | 350    |
| 21              | 19.9       | 20        | 314        | 6251.769  | 158-162 | 4            | 450    |

AE specimens control was performed on AE monitor “Vulcan 8SM”. The system represents an eight channel signal-processing unit interfaced with PC. The digital signal from monitor was received by PC serial port. Further signal processing was carried out with monitor support software package. For the signal recording the resonance sensors NS2002 (Acoustic Emission Sensor) with 200 kHz working
frequency were used. As a pre-amplifier model NA200 (Acoustic Emission Pre-amplifier) was used with 190B filter type.

AE parameters investigation at mechanical tests was implemented by using two signal detectors mounted onto special “tray” device due to specimen small size and its deformation. For better acoustic contact, wave-conducting liquid poured beforehand in device was used. The sensors were mounted on specially machined surfaces (optimal roughness – Ra 6.3). Before sensors installation, the surface was lubricated with “LITOL-24” grease.

AE monitor allows one to obtain the following information from loading area: count rate – \( \hat{N} \) and signal amplitude \( A \), dB. Monitor software package produces this information in graph forms: signals amplitude distribution (fig. 2) and “cumulative count rate versus time” (fig. 3).

![Figure 2. Signals amplitude distribution: \( n \) – counts](image)

![Figure 3. Cumulative count rate: \( n \) – counts, \( t \) – loading time](image)

For obtaining the information in a text form, the processing procedure was performed using monitor software package. For further processing the data was converted into tabular processor files by tabulating (fig. 4). To make the processing more convenient data for each specimen was presented as shown in fig. 5.

| Date   | Time    | Frame   | Sensor Number | First sensor amplitude | Second sensor amplitude |
|--------|---------|---------|---------------|------------------------|-------------------------|
| 17-Jul-11 | 11:25:28 | OBR-14-2 |               |                        |                         |
| 17-Jul-11 | 11:25:37 | START   |               | 35 Т                    |                         |
| 17-Jul-11 | 11:26:23 | 0       | 10            | 65                     | 58                      |
| 17-Jul-11 | 11:26:23 | 64      | 10            | 46                     | 41                      |

Figure 4. Initial data table fragment
Degree of shear deformation $\Lambda$ for monotonous deformation and degree of plasticity reserve depletion were calculated using technique reported in [17]. Results are presented in table 2.

To reveal the relationship between mechanical parameters of metal condition and AE parameters cumulative count rate $\dot{N}$ and signal cumulative amplitude $A$ were used. Results obtained are presented in Table 3.

### Table 2

Degree of shear deformation estimation results

| $t$, s | $\Delta h_i$ | $\Delta R_i$ | $\varepsilon_y$ | $\varepsilon_x$ | $\dot{\varepsilon}_y$ | $\dot{\varepsilon}_x$ | $H$ | $\Lambda$ |
|-------|-------------|-------------|----------------|----------------|----------------|----------------|-----|---------|
| 1     | 0.01052     | 0.0042      | 0.000687       | 0.000365       | 0.000687       | 0.000365       | 0.000687 | 0.000687 |
| 2     | 0.02104     | 0.0084      | 0.001373       | 0.000731       | 0.001373       | 0.000731       | 0.001374 | 0.001374 |
| 3     | 0.03156     | 0.0127      | 0.00206        | 0.001097       | 0.00206        | 0.001097       | 0.002061 | 0.002061 |
| 4     | 0.04208     | 0.0169      | 0.002747       | 0.001463       | 0.002747       | 0.001463       | 0.002749 | 0.002749 |
| 5     | 0.0526      | 0.0212      | 0.003433       | 0.001829       | 0.003433       | 0.001829       | 0.003436 | 0.003436 |

### Table 3

AE Signal cumulative amplitude

| Number | Group | HV      | $P$, kN | $\sum \dot{N}_i$ | Mean amplitude | Cumulative amplitude |
|--------|-------|---------|---------|-----------------|----------------|---------------------|
| 1      | 1     | 174-177 | 250     | 984             | 46.1           | 56112               |
| 2      | 1     | 177-183 | 350     | 574             | 46.4           | 42838               |
| 3      | 1     | 174-177 | 450     | 680             | 45.4           | 46554               |
| 4      | 2     | 171-177 | 350     | 672             | 46.83          | 31593               |
| 5      | 2     | 171-177 | 250     | 447             | 44.2           | 19815               |
| 6      | 3     | 166-171 | 200     | 233             | 44.1           | 10305               |
| 7      | 3     | 162-166 | 250     | 676             | 45.5           | 30410               |
| 8      | 3     | 162-166 | 300     | 728             | 46.25          | 33780               |
| 9      | 3     | 162-166 | 350     | 637             | 46.8           | 29720               |
| 10     | 3     | 166-171 | 400     | 1138            | 43.1           | 49310               |
| 11     | 4     | 152-154 | 150     | 335             | 45.68          | 15349               |
| 12     | 4     | 158-162 | 250     | 563             | 47.1           | 26659               |
| 13     | 4     | 158-162 | 350     | 737             | 45.8           | 34016               |
| 14     | 4     | 158-162 | 450     | 1000            | 45.2           | 45435               |
Since during AE investigation the issue reliability of results received constantly arises, the following versions of their processing were verified:
- signals registered in null frame were considered as significant ones;
- signals registered in null frame as well as signals in frames next to null were considered as significant ones given they had large amplitude;
- signals having amplitude more than 40 dB were considered as significant ones (this enables eliminating probability of noises, random and reflected signals registration);
- all received signals were considered as significant ones.

The drops of number of registered impulses from sequence for number one specimen are attributed to the fact that at the earliest loading not only specimen is deformed but special devise as well. During next loadings, the devise does not “sound” anymore and thus valid data are registered.

Assessment of cumulative AE parameters was carried out in the following way: the amount of events was registered every second and placed in the column $\dot{N}$. Cumulative amplitude $\sum A$ was registered in a similar manner (Table 4).

**Table 4**

| $t, s$ | $\varepsilon_y$ | $\varepsilon_x$ | $\xi_y$ | $\xi_x$ | $H$ | $\Lambda$ | $N_i$ | $\sum N_i$ | $\sum A$ |
|-------|-----------------|-----------------|--------|--------|-----|----------|------|------------|---------|
| 1     | 0.00109         | 0.00058         | 0.00109| 0.00058| 0.00109| 0.00109 | 1    | 1          | 55      |
| 2     | 0.00218         | 0.00117         | 0.00218| 0.00117| 0.00218| 0.00218 | 1    |            |         |
| 3     | 0.00327         | 0.00175         | 0.00327| 0.00175| 0.00327| 0.00327 | 6    | 7          | 381     |
| 4     | 0.00436         | 0.00234         | 0.00436| 0.00234| 0.00436| 0.00436 | 1    | 8          | 429     |
| 5     | 0.00545         | 0.00293         | 0.00545| 0.00293| 0.00545| 0.00545 | 8    |            |         |

As strain rate was variable, the extra factor was introduced to consider this point at a degree of shear deformation calculation for specimens of third and fourth groups:

$$k = \frac{1}{U}$$

(7)

where $U$ represents strain rate.

To make sure there is a consistency of hereditary mechanisms, extra experimental run was carried out. Analysis of second batch specimens was conducted in the same way. Since the loading rates of two baxes were closely matched, additional data processing was not performed (Table 5).

**Table 5**

| Specimen number | $h_0$, mm | $D_0$, mm | $S$, mm² | $V$, mm³ | $HV$ | $P$, kN | Degree of shear deformation $\Lambda$ | $\sum N_i$ |
|-----------------|-----------|-----------|---------|--------|------|-------|-----------------------------------|---------|
|                 |           |           |         |        |      |       | On current stage | Total     |         |
| 32-1            | 20.7      | 19.7      | 305     | 6309.46| 179-183| 220   | 0.054   | 0.054   | 372      |
| 32-2            | 19.52     | 20.3      | 323     | 6309.46| 179-183| 280   | 0.078   | 0.132   | 496      |
| 33-1            | 20.15     | 20.1      | 317     | 6393.77| 174-183| 200   | 0.212   | 0.212   | 710      |
| 33-2            | 19.5      | 20.43     | 328     | 6697.22| 174-183| 300   | 0.058   | 0.058   | 869      |
| 34-1            | 20.1      | 20.12     | 318     | 6390.60| 174-187| 225   | 0.073   | 0.073   | 473      |
| 34-2            | 19.55     | 20.5      | 330     | 6386.73| 174-187| 275   | 0.041   | 0.041   | 389      |
| 38-1            | 20.75     | 19.85     | 309     | 6421.38| 170-183| 240   | 0.047   | 0.047   | 583      |
| 38-2            | 19.55     | 20.45     | 328     | 6421.30| 170-183| 260   | 0.058   | 0.058   | 270      |
Results and discussion

Fig. 6 shows relationships between degree of shear deformation and cumulative count rate for compression test.

Statistical treatment of experimental data made it possible to obtain the following equation:

\[
\hat{N} = 1218 \cdot \exp\left(-\frac{(\Lambda - 0.6)^2}{0.17}\right)
\]  

(8)

It was revealed that loading history has a significant effect on AE signals generation (fig. 7). At the one-stage loading of number 14 specimen by 250 kN force the degree of shear deformation \( \Lambda \) amounts to 0.34, of number 16 specimen by 350 kN \( \Lambda \) amounts to 0.42. It is clearly seen that at one-stage loading the curves actually coincide.

At the second stage of number 14 specimen loading by 350 kN the degree of shear deformation keeps growing but there is no increase of cumulative count rate until point reached at first loading. Only at the certain threshold crossing there is a leap of AE signal as distinctive kink of the curve demonstrates. The degree of shear deformation \( \Lambda \) amounts to 0.2 in doing so.

The feature of second batch experiments lies in the fact that after first loading stage and following specimens unloading second loading stage was performed by greater force. It is should be noted that total force magnitude for all specimens was 500 kN.
Figure 7. Cumulative count rate versus degree of shear deformation for two-stage loading: 14-1 and 14-2 – 1st and 2nd loading stage for number 14 specimen; 16 – 1st stage for number 16 specimen

Fig. 8 shows relationships between cumulative count rate and degree of shear deformation during compression test for second batch of specimens.

Figure 8. Cumulative count rate versus degree of shear deformation for total loading of number 32-38 specimens (numbers in figure correspond with specimens’ numbers)

**Conclusions**

Analysis of two-stage loading of specimens showed that:
- the loading history has a significant effect on AE distribution pattern and AE signal value;
- greater value of cumulative AE signal on second loading stage at the same degree of shear deformation value is more for number 33 specimen, which on the first stage was loaded by lesser force and on the second stage by greater force. This rule applies for all specimens.
greater total degree of shear deformation value (greater faultiness) leads to greater cumulative count rate.

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