ENHANCEMENT OF EFFICIENCY OF TRIBOLOGICAL TESTING BY USING ACOUSTIC EMISSION MEASUREMENTS

I. Rastegaev, D. Merson, A. Vinogradov

Laboratory for the Physics of Strength of Materials and Intelligent Diagnostic Systems, Togliatti State University, Belorussskaya str., 14, Togliatti, 445667, Russia, E-mail: RastIgAev@yandex.ru, D.Merson@tltsu.ru, alexei.vino@gmail.com
www.intelligent-lab.ru

ABSTRACT

The last two decades saw an explosive growth of research activities in the non-destructive testing and quality control of a broad variety of tribological materials and units. The substantial amount of data has been accumulated to date, proving the efficiency of the modern acoustic emission (AE) technique for tribological examinations of materials and coatings using a single-contact tribometer. In the present work we review the available knowledge and align it with our original investigations using standard linear reciprocating tribometers (ball-on-disk, ball-on-cylinder, ball-on-plate) and the rotary tribometers (ball-on-disk, ball-on-plate, cylinder-on-cylinder and four-ball friction machines).

Key words: friction and wear, deformation mechanisms, health monitoring, real-time analysis.

1. Introduction

The use of standardized types of contact friction machines and methods, e.g. [1-5] allows for reasonably interpretable, reproducible and comparable results obtained by different researchers. A strong demand still exists in accelerated tribological testing routines without compromising the ability of restoration of the history of contact surfaces damage during the test. One effective way to solve this problem is to replace the "post mortem" microscopic investigations and weighting studies by the "in-situ" acoustic emission (AE) monitoring.

Several threshold-based AE techniques aimed at reaching this goal are known [6]. However, the AE analysis of AE therein is limited to few most common parameters such as the number of oscillations in the signal N, total count \(N_{\Sigma}\), count rate \(N_t\), signal amplitudes A and their distribution \(n(A)\), and "pseudo" energy / power loosely defined as combinations of the above parameters as \(A\cdot N\), \(A\cdot N_{\Sigma}\), \(A\cdot N\) or \(A^2\cdot N\). These parameters have historically gained their popularity due to simplicity in their hardware implementation. On the other hand, the use of some of them, e.g. A, N and their derivatives, has been physically justified [6] as follows. Under normal conditions of friction (linear wear law) and permanent influencing factors (load \(P\), sliding speed \(v\), area of the damaged layer / lubricant layer \(S_0\) appears to be proportional to N, the number of wear particles formed is proportional to the AE amplitude \(n_{\Sigma}\) \(\sim A\), the volume rate of wear \(\Delta m\) is proportional to \(A\cdot N\), and the identification of the source type of AE control the
running, the transition between the different mechanisms of wear and performance of lubricants is determined by the $\Delta A$, $\Delta \dot{N}$ and $\Delta n$ ($A$). Identification of the AE source, control of wear-in, transition between different wear mechanisms and lubricant efficiency is related to variations in respective parameters $\Delta A$, $\Delta \dot{N}$ and $\Delta n$ ($A$).

From definitions given in ref. [7] it follows that $N_Σ$, $N$ and $\dot{N}$ are only indirectly related to the source power (through the number of counts exceeding the discrimination threshold $A_{th}$). To the contrast, the amplitude $A$ does not deliver any information of the source activity. Parameters $\bar{A} \cdot \dot{N}$ and $A^2 \cdot \dot{N}$ are strongly threshold dependent. They are hardly to be well calibrated due to lower bond limits threshold limits by the threshold and the upper bond limits by the throughput rate limits. Besides, due to these limitations of the conventional AE apparatus, the $\bar{A} \cdot \dot{N}$ and $A^2 \cdot \dot{N}$ values are crudely evaluated either for the pulses of amplitudes which are significantly higher than the threshold or for the large averaging time (typically of 1 s) [6].

2. Experimental

From the above preceding section it follows that, the threshold-less strategy of AE data recording can be most beneficial for maximum efficiency of the integral evaluation of AE during sliding wear. Thus, in the present work we employed continuous recording of the AE Envelope $Y$ and the root-mean-square, RMS, obtained in the analogue circuits as:

$$Y(T) = \frac{1}{T} \int_0^T |A(t)| dt \tag{1}$$

$$\text{RMS}(T) = \sqrt{\frac{1}{T} \int_0^T A(t)^2 dt} \tag{2}$$

where $T$ is the integration time and $A(t)$ is the instant voltage at the sensor output as a function of time. The time $T = 0.1$ s was empirically chosen to smooth out the electric noise yet to follow the details of AE bursts. To characterize the AE waveforms, they were digitally recorded. Each frame of 1.3 ms duration contained 8192 readings. Frames were triggered periodically by timer with 19 ms period. Hence, during the time interval $T$ of 6 AE frames were captured. AE recording was carried out in a frequency range 50÷1000 kГц with total gain 40 dB using a home-built system having ADC boards La-1.5PCI-14 and La-N20-12PCI at the core. The maximum irregularity of the sensor frequency response in this band did not exceed $\pm$ 5 dB. The sampling rate for parametric data and AE envelope and RMS was 1 kHz, while the AE waveform were samples at 6.25 MHz.

The tribological tests were performed on (i) a four-ball friction tribometer, (ii) universal tribometer with a rotating and reciprocating stage Nanovea and (ii) an original valve-roller friction machine designed at AutoVAZ Ltd., Togliatti, Russia. The test schematics for turning, rotation, circular and spiral movement and reciprocal sliding is shown in Fig. 1, where $P$ is the load, $w$ and $v$ are the cyclic and linear velocities, respectively, $e$ is the axis offset implement: spinning, rotation, circular and spiral movement and reciprocal sliding. The AE sensor was securely mounted on a housing in the intimate vicinity to the friction pair.

The following contact materials were used as typical friction pairs: the balls of the bearing steel ShH-15 of 12.7 (Fig.1a) and 6.0 mm (Fig.1b), the plates of steels 20 and 45 of 30×40×5 mm (Fig.1b), cylinder of 40HGNM steel or Aluminum alloy AMG3 of ø 8 mm and rollers made of cast Iron Gh190 of 50 mm diameter and 5 mm width (Fig.1c). Both dry and lubricated friction conditions were used with the following lubricants: water, SHRUS-4M, Renolit IP 1619, LITOL-24, Unirex-3, FIOL-1, SAE 10W-40 «Lukoil-Standard».
The standard tribological techniques, which were used in the present work, are mainly summarized as:

1. Comparative analysis of wear ($\Delta m$) at constant influencing factors ($P = \text{const}$, $v = \text{const}$) for a given constant period of testing time ($t[s] = \text{const}$);
2. Comparative analysis of time $t[s]$ to the appearance of the signatures of critical wear at $P = \text{const}$ and $v = \text{const}$;
3. Step-wise increasing loading ($\uparrow P$) at constant linear velocity of the reciprocating motion $v = \text{const}$) and identification of the load $P_k$ or $P_c$ when scoring or edging sets in, respectively.

Microscopic investigations and the calculation the volume of the edged metal and the area of the frictional seizure were performed by means of the 3D surface profilometry of the wear spots. The Olympus LEXT OLS4000 laser confocal microscope was used for this purpose.

3. Results of AE analysis

Despite the differences in test procedures, schedules and types of friction all observed patterns of the AE Envelope and RMS can be reduced to the two types presented in Fig. 2.

Fig. 2. AE patterns during friction testing using (а) four ball tribometer and (б) universal tribometer with a reciprocating motion.

It was observed that the behavior of the AE envelope $Y$ and RMS does not differ significantly under similar conditions. In what follows we shall label them by the same symbol $\hat{U}$. Main experimental findings are summarized as follows.
3.1. The presence of the groups of AE bursts with amplitudes $\bar{U}_{\text{peak}} = (1.1 \div 3)\cdot \bar{U}_{\text{bg}}$ (where $\bar{U}_{\text{bg}}$ is the background voltage) and $\Delta \tau = 0.1 \div 0.5$ s or longer (where $\Delta \tau$ is the time interval where $\bar{U} > \bar{U}_{\text{bg}}$) is accompanied by the appearance of individual points of bonding on the wear spot with the total area of 20÷30 % (Fig. 2a and 3a).

3.2. Intensive bursts with $\bar{U}_{\text{peak}} = (\geq 3)\cdot \bar{U}_{\text{bg}}$ and $\Delta \tau \approx 0.3 \div 0.5$ s give rise to a large variance in $\bar{U}$ compared to the background. These intensive bursts in all cases signified scoring caused by bonding-debonding mechanism with the total area greater than 50% (Fig. 2b и 3b).

3.3. The steep increase of $\bar{U}$ to the magnitudes $\bar{U}_{\text{peak}} = (\geq 3)\cdot \bar{U}_{\text{bg}}$ with high variance and duration as long as $\Delta \tau \approx 1 \div 5$ s at $P \approx P_k$ or $\Delta \tau = 10 \div 80$ s at $P < 0.6 \cdot P_k$ in all cases accompanied scoring caused by plastic edging (Fig. 3c). The characteristic AE feature of this process is that the lower bond level of $\bar{U}$ is always higher than $\bar{U}_{\text{bg}}$ (Fig. 2a);

3.4. Increasing $\bar{U}_{\text{bg}}$ value without clearly pronounced peaks such as those outlined in 3.1÷3.3 is related to the progressive increase of the area of the wear spot. The average $\bar{U}_{\text{bg}}$ level in this case is by a factor of 1.1÷1.5 less than the minimal level of AE accompanying scoring. The wear type is mainly the abrasive-fatigue resulting in the total area of individual disparate points of localized bonding between contacting solid surfaces and their breaks of 15÷20 % of the total damaged area (Fig. 2b и 3a);

3.5. The running-in process during the beginning of friction is accompanied by the background level $\bar{U}_{\text{bg}}$, reduction, which levels out during the steady normal wear. During scoring the high AE level $\bar{U}$ is also associated with the increase in the wear spot area though this occurs in a more complex way than in 3.4. After scoring has become evident on the AE diagram, the following running-in levels out the AE signal although the background level $\bar{U}_{\text{bg}}$ is 1.1÷3 times higher than that before scoring. (Fig. 2);

3.6. Scoring can be accompanied by a gradual increase/reduction of the AE level $\bar{U}$ according to 3.2 и 3.3, which indicates that scoring occurs nearly uniformly over the whole contact area (Fig. 2a). Several stages can be observed during the increase/reduction of the AE level $\bar{U}$ resulting in several peaks/valleys of $\bar{U}$, which reflect the respective stages in the wear spot growth or in the alternating scoring in the case of the multipoint contact between the friction surfaces (Fig. 2b);

![Fig. 3. The typical morphology of the wear spots: (a) abrasive-fatigue wear, (b) scoring and разрывом областей контакта, (c) plastic edging, (d) example of 3-D surface map of the wear spot. Blue color highlights the area of scoring.](image)

The analysis of a bulk volume of experimental data allows us to conclude that the features of major wear mechanisms can be reliably identified by the AE technique. Once the AE system is trained in such a way that a characteristic for a given mechanism AE pattern is recognized (see the next section), the use of the AE technique enables substantial shortening of the testing time due eliminating microscopic observations. Moreover, it may help to calculate the mass wear and to establish the moments of transition between dominating mechanisms of damage. In what follows we shall illustrate this conclusion in the case studies below.

600
Case 1. Figure 5a shows experimental AE data obtained during standard testing using the four-balls tribometer aimed at determination of the loads corresponding to the onset of scoring Pk and bonding Pc at constant applied loads with different lubricants and friction pairs. Figure 4 shows that the systematic use of the integral AE parameters is quite useful for indentification of scoring and bonding without microscopic investigations. Importantly is that if one compares the results of determination of Pk and Pc by measuring the limiting wear and by the AE peaks denoted as $P_k^{AE}$ and $P_c^{AE}$, respectively, the results of both methods appear identical, i.e. $P_k = P_k^{AE}$ and $P_c = P_c^{AE}$. Therefore one can propose to shorten the testing time by measurements of $P_k^{AE}$ and $P_c^{AE}$ during a stepwise increase of the applied load on one and the same set of balls and lubricant with the time elapsed between subsequent steps not longer than 2÷5 s. Let the obtained in this express AE method loads be labeled as $AE_{P_k}$ and $AE_{P_c}$. In this case, due to the formation of the contact area and partial heating during the previous load steps, the values of the load and $AE_{P_k}$ and $AE_{P_c}$ are obtained slightly higher (by 10 ÷ 20 MPa) above Pk and Pc, respectively, obtained in independent tests. In this regard, one can clarify actual loads Pk and Pc by standard methods, but only within $AE_{P_k}$ minus 30 MPa and $AE_{P_c}$ minus 30 MPa. The use of the AE technique has shortened the testing time by a factor of 50 if compared to the standard method, Fig. 4.

![Fig. 4. Results of AE measurements during tests performed on the four-ball tribometer: (a) standard loading schedule and (b) the proposed step-wise “continuous” loading scheme.](image)

Case 2. Different tribological testing (especially long-term tests which are accompanied by scoring) results often in pretty much the same wear spots because the surface artifacts signifying a certain damage process have been overridden by the routine wear process during long-term testing. The ambiguity always arises if the questions are asked when a catastrophic wear sets in and which mechanisms govern the damage? The measurements of integral AE characteristics and conclusions 3.1-3.6 allow us to answer these questions quite reliably. Figure 6 shows the AE record disclosing the history of damage evolution on the friction surfaces, which demonstrate that the contact materials in different thermal conditions do not equally respond to the load. However, the AE record indicates the start of scoring (Tsc), running-in after scoring (Trun) and points when changes occur in wear mechanisms (Ti).

Case 3. During long term tribology testing it is plausible to record AE periodically by timer. However, the exact moment of scoring can be missed on the AE diagram in this case. Notwithstanding, the occurrence of scoring can be reliably recognized with a reasonable accuracy by increasing $U$ level in comparison with normal wear conditions (cf. 3.5 and Fig. 6a).
Fig. 5. Typical example of the AE records corresponding to three tests during reciprocating motion of the friction pair ShH-15-steel 45, разной поверхностной термообработки (the depth of the damaged layer corresponding to the wear is less than the depth of the hardened layer).

Fig. 6. Typical example of AE during a step-wise loading and scoring formation.

As a summary, let us notice that all observations of AE during a broad variety of wear processes investigated using standard tribological procedures overviewed in this section can be used quite straightforwardly for a training of a simple automated system aimed at identification of damage mechanisms and at a cost effective express wear testing under different lubrication conditions.

4. Conclusions

It is shown that real-time AE monitoring and analysis delivers valuable information which can be crucial for understanding of wear processes and improving the quantitative outcome of tribological testing. In particular, the following common issues can be addressed with an aid from the AE technique:

1. Determination of the critical regime of friction;
2. Time and area of roughness burnishing; and wear of protective coatings or a hardened layer;
3. Comparison of wear of various lubricants on the basis of the dominant mechanisms, the timing and sequence of their actions;
4. Acceleration of the tribological tests and reduction of their cost without loss of quality and reliability of the results.

Financial support from the Russian Ministry of Education and Science under grant-in-aid 11.G34.31.0031 is gratefully appreciated.
6. References

[4] ISO 20808 Fine ceramics (advanced ceramics, advanced technical ceramics) - Determination of friction and wear characteristics of monolithic ceramics by ball-on-disc method (standard)
[5] DIN 50324 Tribology; testing of friction and wear model test for sliding friction of solids (ball-on-disc system) (standard)