Acoustic Emission in Elementary Processes of Friction and Wear: In-Situ Observation of Friction Surface and AE Signals*

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Abstract

The relationship between acoustic emission (AE) signals and tribological phenomena in the elementary processes of friction and wear is examined. The elementary processes of friction and wear were observed by a frictional surface microscope, which installed a friction system into the view of an optical microscope. In this paper, the elementary processes are focused on the plastic deformation of the friction surface and the formation of wear particles between friction surfaces. In-situ experiments with the frictional surface microscope were performed by a pin-on-block type sliding test for iron and zinc. The friction surface and its side face were also observed by an atomic force microscope. The results show that two types of AE signals—a continuous AE signal of low amplitude and a burst-type AE signal of high amplitude—are detected in the elementary processes of friction and wear. The continuous AE signal of low amplitude is detected by the generation of slip lines and wear elements. The burst-type AE signal of high amplitude is detected by the formation of a transfer particle.

Key words: Tribology, Acoustic Emission, Wear, Friction, Transfer, Slip Line, In-Situ Observation, Atomic Force Microscope

1. Introduction

Acoustic emission (AE) refers to the generation of elastic stress waves by the deformation and fracture of materials. Because friction and wear, the so-called tribological phenomena, are phenomena that involve deformation and fracture, AE is generated in friction and wear processes. Thus, by measuring AE as AE signals with an AE transducer, it is possible to identify and estimate friction and wear phenomena occurring at a frictional interface.

AE signals detected under tribological phenomena include a large amount of information related to friction and wear phenomena. This is because AE is directly caused by deformation and fracture of machine parts. Thus, the AE method has a high detection capability regarding abnormal conditions and the potential ability to detect dangerous
conditions of bearing operation\(^2,3\). Moreover, because the AE method is able to monitor dynamically the present state in real time, it is very useful for the in-process measurement of sequential changes in the tribological characteristics of friction systems. For successfully recognizing and estimating tribological phenomena using the AE method, a clarification of the relationship between AE signals and friction and wear phenomena is extremely important. Over the past few decades, various studies have been conducted on the correlations between AE signals and friction and wear phenomena\(^4-10\). However, the relationship between AE signals and friction and wear phenomena has not been established yet.

As far as the present authors know, all previous studies were conducted experimentally by repeated rubbing. In particular, under dry repeated rubbing, the formation and the behavior (collision and removal) of wear particles at the frictional interface affect AE signals greatly\(^11,12\). Thus, the phenomena under repeated rubbing become a many-body problem that includes friction surfaces and wear particles between them (strictly speaking, atmospheric substances must also be included). Accordingly, it is difficult to determine quantitative correlations between AE signals and friction and wear phenomena. Therefore, we have experimentally examined the relationship between AE signals and friction and wear phenomena under the phenomenon simplified using a single-side virginal rubbing system\(^13-15\). However, the relationship with microscopic friction and wear phenomena at a frictional interface remains unclear.

Evaluation of the friction surface is generally performed by observation and/or analysis of the friction surface before and after rubbing. The friction surface, however, always changes according to the progress of friction and wear processes. An observation of the friction surface in real time, in-situ observation, is a key experimental approach for elucidating the mechanism of friction and wear. Thus, to investigate the fundamental relationship between AE signals and friction and wear phenomena, we conducted the in-situ observation of friction and wear phenomena occurring at the frictional interface and measured AE signals generated during the elementary processes. This paper discusses the relationship between AE signals and plastic deformation of a friction surface and generation of wear particles.

2. Experiments

2.1. Experimental apparatus and measuring system

In the actual experiment, AE signals were measured while observing the elementary process of friction and wear in real time using a frictional surface microscope (in-situ observation system), which installed a friction system into the view of an optical microscope\(^16\). Figure 1 shows a diagram of the friction system and the block diagram of instrumentation for signal acquisition. Friction and wear experiments were performed with a pin-on-block-type test rig. AE signals generated by friction and wear were detected with an AE sensor, which was mounted to the block specimen using a jig. Here the distance between the AE sensor and the part that undergoes friction was about 15 mm. The AE sensor was made of PZT piezoelectric ceramics (wideband-type transducer, frequency band: 500 kHz–4 MHz). We employed the wideband-type AE sensor in the experiments, because much of the information relating to friction and wear, especially wear, is contained in the frequency component of the AE signals above 500 kHz\(^2\).

Since the voltage level of signals detected with an AE sensor is quite low, the signals were amplified with a preamplifier and a main amplifier to the level of 86 dB. AE signals were passed through the high-pass filter of 100 kHz to eliminate noise signals. An AE mean value, the voltage signal that was passed through a half-wave rectification, an envelope process (discharge time constant: 0.1 ms) and an averaging process using a discriminator
after passing through the filter, were measured and evaluated. Frictional resistance was measured using strain gauges attached to the flat spring on the fixed part of the pin and converted into a coefficient of friction and evaluated. In addition, changes in phenomena at the frictional interface were simultaneously recorded as a video image by the in-situ observation system.

2.2. Experimental conditions

The material used as a pin specimen was stainless steel (JIS SUS304, hardness: 190 HV). Iron (purity: 99.5%, hardness: 97.3 HV, average crystalline particle diameter: 83 µm) and zinc (purity: 99.99%, hardness: 32.9 HV, average crystalline particle diameter: 9.5 µm) were used as a block specimen. We used stainless steel, which is harder than the block materials, as pin specimens to focus on friction and wear phenomena of the block. Both the friction surface and observation surface of the block specimen were finished by buffing. The observation surface of the iron block was etched by nital, and that of the zinc block was etched by 5% nitric acid. Friction surfaces of both specimens had a surface roughness of less than $R_{\text{max}}$ 0.1 µm. The average values of surface roughness for the block specimen were $R_{\text{a}}$ 3 nm, $R_{\text{q}}$ 4 nm, and $R_{\text{max}}$ 25 nm.

In the present experiments, two friction and wear experiments that focused on (a) friction phenomenon and (b) wear phenomenon were performed using two types of nose shapes of the pin. By means of these experiments, the tangency between both specimens was changed to a line contact or a surface contact; the former was to observe the deformation process of the friction surface (friction process) and the latter was to observe the generation process of the wear particles (wear process). Sliding conditions and the nose shape of the pin for the two experiments are summarized in Table 1. The outer diameter of pin specimens was 4 mm, and the nose shapes were formed as follows: (a) in the experiments for friction, the curved surface of about 60 µm radius was formed to the tip, which had a vertical angle of about 90 deg.; (b) in the experiments for wear, a plane of width 0.5 mm in the direction of sliding was formed to the tip. The depths of both, with width orthogonal to the sliding direction, were about 0.2 mm. We can consider the tangency from the observational viewpoint as a two-dimensional contact between the pin side (cylinder or plane) and the block side (plane). The size of the block specimen was 30 × 15 × 10 mm.

Experiments were performed by rubbing only a constant sliding distance repeatedly in the same direction under the sliding conditions shown in Table 1. All the experiments were performed in air, at room temperature and under unlubricated sliding conditions.

![Friction system and block diagram of instrumentation for signal acquisition.](image-url)
Table 1  Sliding conditions and nose shape of a pin for two experiments.

<table>
<thead>
<tr>
<th></th>
<th>(a) For friction process</th>
<th>(b) For wear process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load</td>
<td>2.4, 4.8 N</td>
<td>2.4 N</td>
</tr>
<tr>
<td>Sliding velocity</td>
<td>0.02 mm/s</td>
<td></td>
</tr>
<tr>
<td>Sliding distance</td>
<td>3 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Repeated frequency</td>
<td>5 times</td>
<td>20 times</td>
</tr>
<tr>
<td>(same direction)</td>
<td></td>
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</tbody>
</table>

Nose shape of the pin

3. Results

3.1. In-situ observation of deformation of friction surface by rubbing

The first question to be examined regarding tribological phenomena is the deformation process of the friction surface by rubbing at real contact points (adhering part or junction) between two solid surfaces. First, we will describe the results of the experiments that focused on friction phenomenon using the pin specimen whose tip was a curved surface (Table 1(a)). In a line contact, the deformation process of the friction surface by rubbing becomes a main phenomenon, because the contact stress concentrates under the pin.

Figure 2 shows the in-situ observation of the deformation immediately under the friction surface for the iron block. Here Fig. 2(a)–(c) shows the deformation process at the first rubbing (dry, normal load: \( W = 2.4 \) N), and (d) is an enlarged view of \( A \) in (c). Triangles, \( \nabla \), indicate the nose position of the pin specimen. The direction of movement of the pin is from left to right. From this figure, the generation of slip lines (or slip bands) by rubbing can be seen. The slip lines occur along the grain boundary of crystal grains to draw a circular arc in the perpendicular direction to the sliding. Repetition of sliding friction makes the slip lines cross each other, and the density of the slip lines immediately under the friction surface increases. Although the phenomenon is uneven in each crystal grain, plastic deformation of the friction surface progresses as the slip lines cross, and also the wear phenomenon by transgranular fracture in the deformed crystal grain was partly observed.

![Figure 2](image-url)
3.2. Relationship between fluctuation of AE signals and deformation process of friction surface

We considered AE signals of more than 1 mV to be significant signals because the background noise less than this was continuously present under the current experimental system. Here, for the AE mean value evaluated in the experiments, the DC component of the background noise was subtracted from the output AE signals beforehand.

Figure 3 shows the fluctuation of the AE mean value in the generation of slip lines by rubbing shown in Fig. 2. Moreover, the tendency in the fluctuation of the AE mean value is shown by a moving average of the AE mean value. We can see from this moving average that the position at which the AE signal level (the moving average deviations) drops suddenly corresponds to the position on the grain boundary of crystal grains: \( G_1 \) and \( G_2 \) in Figs. 2 and 3 correspond respectively. Outside the observational viewpoint of Fig. 2, and in other places as well, the grain boundary of crystal grains were similarly present in the position at which the AE signal level dropped. Figure 4 shows the observation of the sliding surface for the iron block at the first rubbing under a low normal load (wet, \( W = 0.48 \) N). When the experiment was performed under a low normal load, the generation of slip lines (immediately under the friction surface as shown in Fig. 2) was barely observed (see Fig. 4) and significant AE signals were not detected. The value of the AE count rate (the event number of burst-type AE signals generated per unit time) within the range of 1–2 mV at the first rubbing was 6–10 cps. This is a value very close to the number of the generated slip lines. Therefore, it is assumed that the AE signals of 1–2 mV were caused by the generation of slip lines (or slip bands) by rubbing.

Figure 5 shows the fluctuations of the AE mean value and the coefficient of friction under dry conditions (\( W = 4.8 \) N) at (a) the first rubbing and (b) the fifth rubbing. As in Fig. 5, the AE signal level at the fifth rubbing was greater than that at the first rubbing. A similar tendency was indicated under unlubricated conditions using the zinc block and under lubricated conditions. It is believed that this is the influence of strain hardening by crossing the slip lines. We can see here that large burst AE signals greater than 5 mV were detected.
in addition to continuous AE signals caused by the generation of slip lines shown in Fig. 3. It is assumed that the large burst-type AE signals were caused by the abrupt plastic deformation of the friction surface and the wear phenomenon described later.

For the zinc block, results of the fluctuation of the AE mean value and the in-situ observation of the deformation immediately under the friction surface are shown in Figs. 6 and 7, respectively. This data was obtained at the first rubbing. Yield of several crystal
3.3. In-situ observation of generation of wear particles

Next we will describe the results of the experiments that focused on wear phenomenon using the pin specimen whose tip was a plane surface (Table 1(b)). In a surface contact, the generation process of wear particles between friction surfaces becomes a main phenomenon because the contact stress between sliding surfaces is distributed.

Figure 8 shows the in-situ observation of the generation of wear particles between the rubbing surfaces for the iron. The result of Fig. 8(a)–(d) was obtained at the 14th rubbing (dry, \( W = 2.4 \) N). In the part marked B in Fig. 8(a), the subsequent generation of wear particles was observed. Initially, in stages (a)–(b), wear elements that transferred (adhered) onto the pin and the block were aggregated, and a transfer particle \( T \) was formed. Then (c) the transfer particle transferred to the pin side. Finally, (d) it was removed as a wear particle \( W \) to the side face of the pin. This process of generation of wear particles is a so-called mutual transfer and growth process occurring during adhesive wear\(^{17}\). The size of the transfer particle observed here was about 9 µm. Transfer particles and wear particles of micrometer sizes were observed in other cases as well.

3.4. Relationship between fluctuation of AE signals and generation of wear particles (mutual transfer and growth process)

Figure 9 shows the fluctuations of the AE mean value and the coefficient of friction at...

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grains occurred simultaneously under the tip of the pin because the crystal grains of the zinc were smaller than those of the iron. The moving average of the AE mean value was increased, particularly when large plastic deformation occurred, as shown in Fig. 7(b).
the formation of the wear particle (mutual transfer and growth process) for the iron block shown in Fig. 8. Here the burst-type AE signal of about 4 mV corresponds to the formation of the transfer particle $T$ in Fig. 8(a)–(b). The subsequent two burst-type AE signals of about 2 mV correspond to the transfer of the transfer particle (Fig. 8(c)) and the removal of the wear particle (Fig. 8(d)). Moreover, we can see that continuous AE signals are detected within the range of 1–2 mV. It appears that these were caused by the generation of minute

![Fig. 10](image)

Fig. 10  AFM images of the Fe block at the first rubbing (dry, $W = 2.4$ N): (a) side face of the friction surface; (b) the friction surface. Dotted line shows the ridge line; $E$ and $T$ indicate a wear element and a transfer particle, respectively. Arrows $\rightarrow$ show direction of sliding.

![Fig. 11](image)

Fig. 11  In-situ observation of frictional interface for the Zn block at the second rubbing (dry, $W = 2.4$ N). Here $T$ and $W$ indicate a transfer particle and a wear particle, respectively. Arrow $\rightarrow$ shows direction of sliding.

![Fig. 12](image)

Fig. 12  Fluctuations of AE mean value and coefficient of friction on the Zn block at the formation of a wear particle through a mutual transfer and growth process (dry, $W = 2.4$ N).
slip lines and wear elements.

To confirm this, we observed the friction surface and its side face (in-situ observation side) after the first rubbing for the iron block with an atomic force microscope (AFM). Figure 10 is a result obtained from AFM observations. The dotted line in the figure indicates a ridge line, which is the boundary between the friction surface and its side face. We can confirm from Fig. 10(a) that the minute slip lines are generated at a surface part of the friction surface by sliding only once. In addition, about 56 wear elements \( E \) (including wear elements that are not indicated by arrows) and two transfer particles \( T \) were observed on the friction surface in Fig. 10(b).

Figures 11 and 12 show the in-situ observation of the generation of wear particles and the fluctuations of the AE mean value and the coefficient of friction for the zinc block, respectively. Figure 11 is a result observed at the second rubbing (dry, \( W = 2.4 \) N). Here, for zinc as well as iron, the formation of the transfer particle \( T \) whose size was about 5 \( \mu \)m and its transfer to the pin side were observed. At this time, two burst-type AE signals were detected (Fig. 12(b) and (c)). In addition, the first burst-type AE signal of about 8 mV in Fig. 12 was detected by the removal of the wear particle \( W \) whose size was about 20 \( \mu \)m. Therefore, it follows that large burst-type AE signals shown in Figs. 9 and 12 were caused by the formation and transfer of transfer particles. Although the number of rubbings for zinc was fewer than that for iron, the AE signal level was large oppositely. By comparing Figs. 2 and 7, we can say that this is attributable to the difference in the size of the plastic deformation zone. Moreover, it appears that the difference in AE characteristics for materials affected the AE signal level.

It follows from Figs. 9 and 12 that the AE signals are better suited for the evaluation of friction and wear phenomena as compared to the coefficient of friction. This is because the AE method can detect the microscopic phenomena occurring between sliding surfaces that cannot be detected by the coefficient of friction.

4. Discussion

We observed AE signals corresponding to the elementary processes of friction and wear, which include the plastic deformation of crystal grains under the friction surface and the generation of wear particles, by the in-situ observation of sliding surfaces using a frictional surface microscope. In this section, we will discuss AE sources generated under these elementary processes.

The elementary processes of friction and wear start from the plastic deformation of crystal grains beneath the point of contact, as shown in Figs. 2 and 7. This is slip deformation occurring as a result of the action of frictional compressive stress beneath the contact part of the pin. The experimental results show that the generation of the slip lines (or slip bands), which can be observed with the optical microscope, corresponds to the detection of AE signals whose amplitude is as low as 1–2 mV. The AE pulse is composed of a collective motion of the dislocation group whose phase became complete\(^{18}\). Therefore, the generation of the AE pulse of low amplitude is attributable to the generation of slips occurring by the collective motion of the dislocation group. Moreover, the observed decrease in the AE signal level when the pin slid on the grain boundary can be explained from the motion of the dislocation group. That is, the grain boundary acts as an obstruction to the accelerating motion of the dislocation group.

Furthermore, not only AE signals were detected constantly at the generation of slip lines (bands) but also large burst-type AE signals of more than 5 mV were detected (Fig. 5). These burst-type AE signals may be caused by abrupt plastic deformation of the friction surface (including the generation of micro cracks in the crystal grain), and wear, described later. This is interpreted as the localized inhomogeneous deformation occurring
The same deformation and fracture process by friction and wear applies to the case of zinc\(^{(19)}\). For zinc, although slip lines cannot be as clearly observed as with iron, the AE pulse may be generated by the generation of the slip lines in the crystal grain. Moreover, because several crystal grains beneath the friction surface of the zinc block were plastically deformed at the same time, it appears that the generation of the AE pulse was concentrated, and then the moving average of the AE mean value was increased. We can see this tendency from the comparison of Figs. 9 and 12. However, AE characteristics of materials are affected by the difference in the crystal structure: iron has a body-centered cubic lattice; zinc has a hexagonal close-packed structure. In a tension test, the amplitude of AE signals generated from metals with a hexagonal close-packed structure was larger than that of metals with a different crystal structure\(^{(20)}\). Thus, the difference in the AE signal level between Figs. 9 and 12 can be explained by the effect of the crystal structure.

Next we will discuss the relationship between the number of repeated rubbings and AE signals. The density of slip lines increased with an increase in the number of rubbings. It then caused work hardening at the same time as plastic deformation. The depth of the plastic deformation zone settles to a roughly constant value\(^{(21)}\). Considering only the deformation by friction, even if the number of rubbings was increased, AE should be barely detected because of the Kaiser effect. However, in fact, the AE signal level increased, as shown in Fig. 5, because the wear process began immediately after the plastic deformation of crystal grains beneath the friction surface. For the coefficient of friction in Fig. 5(b), the fluctuation is larger than that at the first rubbing. This is due to the effect of transfer particles between the rubbing surfaces, which was generated as a result of the progression of adhesive wear with an increase in the number of rubbings. It was found from the AFM observation in Fig. 10(b) that wear elements and transfer particles are generated by rubbing only once. Therefore, the AE signal level increased because the ratio of AE signals caused by wear increased in addition to the continuous AE signals caused by plastic deformation as mentioned above. As a result, the AE signal level increases. Then the AE signal level would be decided by the amount of wear (transfer) described later.

Dislocation density increases with progression of the slip deformation of the surface by rubbing. It is known that a fine structure, with which dislocation is intertwined (such as a cell structure or a plane defect), forms with an increase in dislocation density\(^{(22)}\). In this process, the AE signal level generally decreases because the deformation becomes homogeneous. On the other hand, when the fine structure is shorn at the point of contact of the surface asperities, and adhere (transfer) to the surface of the pin, a large AE pulse would be generated by the microscopic transgranular fracture. It seems to an AE source at the generation and transfer of wear elements. In the experiments under a low-load condition of 0.48 N, the generation of slip lines beneath the friction surface could not be observed directly with the in-situ observation system (Fig. 4). Immediately below the friction surface, however, the slip deformation certainly occurred, as shown in Fig. 10(a). At this time, no significant AE signals of more than 1 mV were detected. Thus, it appears that the observed continuous AE signals of low amplitude (1–2 mV) in Fig. 9 were caused not by the progress of slips but mainly by the generation and transfer of wear elements.

The size of the wear elements was 15–40 nm, which is almost the same as that of metal ultrafine particles\(^{(23,24)}\). By the generation and transfer of one wear element, therefore, it appears that AE cannot be detected. From the AFM observation in Fig. 10(b), approximately 56 transferred wear elements could be observed in the area of the friction surface of 2.5 × 2.5 μm. Here, assuming the wear elements were uniformly transferred throughout the area of contact, 9 × 10\(^6\) wear elements were generated simultaneously on rubbing the pin whose nose shape was a plane surface (apparent contact area: 1 mm\(^2\)). The AE energy of AE signals generated by the transfer (removal) of wear elements of 10\(^6\) in a group exceeds sufficiently the resolving power which was estimated in the previous
Therefore, an AE pulse is generated by transfer of wear elements in a group from a real contact area and it can be interpreted as AE signals caused by the microscopic wear process.

Finally, we will discuss AE signals at the formation of wear particles. Wear elements that were transferred (removed) from the block side formed a transfer particle by the aggregation and union of those between the rubbing surfaces. In particular, when the transfer particle was formed, a large burst-type AE signal was detected (Figs. 9(b) and 12(b)). Because back transfer is not a direct fracture from inside of a material unlike the generation (transfer) of wear elements, the amplitude of burst-type AE signals tends to be smaller than that in the generation of wear elements. It appears that this is caused by the release of the elastic stress energy stored in a transfer particle(11,12).

It should be concluded, from what has been said above, that AE signals measured under friction and wear processes are composed of continuous AE signals of low amplitude caused by the generation of slip lines and wear elements, and burst-type AE signals of high amplitude caused by the generation of a wear particle (formation, transfer and removal of a transfer particle).

5. Conclusions

By in-situ observations of the elementary processes of friction and wear for iron and zinc, we have investigated the relationship between AE signals and deformation and fracture phenomena occurring at a frictional interface. In conclusion, it was found that a continuous AE signal of low amplitude is detected by the generation of slip lines (or slip bands) in crystal grains and by the generation and transfer of wear elements. Moreover, it was found that a burst-type AE signal of high amplitude is detected by the formation of a wear particle.

We plan in the near future to observe and analyze AE signal waveforms generated in the elementary processes of friction and wear and investigate the relationship between AE signals and the number of transferred wear elements.

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