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Correlation between features of acoustic emission signals and mechanical wear mechanisms

Alan Hase [a,*], Hiroshi Mishina [b], Masaki Wada [c]

[a] Department of Mechanical Engineering, Faculty of Engineering, Saitama Institute of Technology, 1690 Fusaiji, Fukaya-shi, Saitama 369-0293, Japan
[b] Department of Artificial System Science (Tribology Laboratory), Graduate School of Engineering, Chiba University, 1-33, Yayoi-chō, Inage-ku, Chiba-shi, Chiba 263-8522, Japan
[c] Department of Precision Mechanical System Engineering, Polytechnic University, 4-1-1, Hashimotodai, Midori-ku, Sagamihara-shi, Kanagawa 252-5196, Japan

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ABSTRACT

The recognition of wear mechanisms is important for effective maintenance of dynamic machinery, because the selection of an appropriate maintenance solution is dependent on the particular mechanism of wear that occurs at the frictional interface. To permit the recognition of wear mechanisms by means of an acoustic emission (AE) monitoring technique, the features of AE signals generated during adhesive wear and during abrasive mechanical wear were examined. For adhesive wear, friction and wear experiments were conducted by using a micro-sliding friction tester of the pin-on-block type with various combinations of pure metals that showed different adhesion forces. For abrasive wear, the experiments were conducted by rubbing an iron pin on emery papers with various grain sizes. AE signal waveforms generated in each wear mechanism were recorded and a frequency analysis was performed. AE signals detected during adhesive wear showed a large peak in the high-frequency region, whereas AE signals detected during abrasive wear showed a few peaks in the low-frequency region. These results permit the recognition of wear mechanisms by the AE technique.

1. Introduction

Mechanical damage to sliding areas of machinery is chiefly caused by wear. The main types of mechanical wear produced by sliding friction are adhesive wear and abrasive wear. Adhesive wear is caused by sticking of the surfaces to one another and subsequent tearing off of surface material. Abrasive wear is caused by plowing and cutting of the surface. A change in the primary wear mechanism (wear mode) at a frictional interface can sometimes accelerate the progress of wear. Such a change in wear mechanism can occur, for example, when the surface layer becomes worn out or when hard particles become embedded in the surface. It is important to be able to recognize the wear mechanism that is occurring at a given time to permit appropriate maintenance of dynamic machinery, since the appropriate solution is dependent on the particular mechanism of wear taking place at the frictional interface. For instance, under sliding friction with imperfect fluid lubrication, lubricants can decrease the amount of adhesive wear but they can increase abrasive wear [1]. The mechanism of the wear that occurs is generally judged from observations of the worn surfaces and the particles generated by the wear; however, considerable time and experience are needed for accurate identification of the wear mechanism by this method.

Acoustic emission (AE) signals are produced when elastic stress waves are generated as a result of deformation and fracture of a material. AE signals are generated when friction and wear processes occur at a frictional interface. Application of AE monitoring permits in-process measurement to be made of the state of wear of materials, e.g. the prediction of seizing [2,3], oil rupture [4], the formation of wear particles [5,6], mild-to-severe wear transitions [7,8], or the failure of coatings [9,10]. Furthermore, quantitative relationships between AE signals and the state of wear have been examined for the individual mechanisms of adhesive wear [11,12] and abrasive wear [13]. Generally, adhesive-wear and abrasive-wear mechanisms tend to coexist and a detailed investigation of the features of AE signals generated in mechanical wear is necessary for practical applications, because the quantitative relationships between AE signals and wear vary depending on the nature of the wear mechanism.

Until now, there have been no reports of any studies on the differences in the AE signal waveforms produced by various wear mechanisms. In this study, to permit the recognition of the mechanism of wear that is operative under given conditions by using the AE technique, we examined the features of AE signals generated during wear by the two main mechanisms: adhesive wear and abrasive wear.

* Corresponding author. Tel/fax: +81 48 585 6827.
E-mail address: alan_hase@sit.ac.jp (A. Hase).

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2. Experimental procedure

Friction and wear experiments were performed by using a pin-on-block-type micro-sliding friction tester. Fig. 1 is a schematic showing the experimental setup. The pin specimen was slid once on a block specimen by using a one-axial piezoelectric actuator. A normal load was applied by placing a weight on the stationary part of the pin specimen. To determine the sliding distance, the displacement of the pin specimen was measured by a noncontact displacement sensor attached to the side of the stationary part of the specimen. To examine the relationship between wear phenomena and AE signals, the two main wear mechanisms, adhesive wear and abrasive wear, were reproduced as follows. For adhesive wear, the experiments were conducted with various combinations of three pure metals with different adhesion forces between the three materials: iron-to-iron, copper-to-iron, and silver-to-iron (pin-to-block). When the adhesive wear experiments were complete, the worn surface was examined by atomic-force microscopy (AFM) to compare the state of adhesion. For abrasive wear, the experiments were conducted by rubbing an iron pin on emery paper attached to the block specimen. Here, emery papers with grain sizes of #400 and #800 were used. The nose shape of the pin specimen was a hemisphere of diameter 4 mm and its length was about 10 mm. The surfaces of both the pin and block specimens were finished to $R_{max} < 50$ nm by mechanical polishing. Both specimens were degreased by washing in acetone before each experiment. The purity and hardness of the materials used as the pin and block specimens were as follows: iron (99.9%, 97 HV), copper (99.99%, 80 HV), and silver (99.99%, 90 HV). The experimental conditions are listed in Table 1. All the experiments were carried out in air at room temperature (about 20 °C) and ambient relative humidity (about 40%). No lubricant was used in the adhesive-wear experiments, whereas paraffin oil was used as a lubricant in the abrasive-wear experiments.

The AE signals generated by the friction and wear processes were detected by means of an AE sensor mounted on the upper surface of the pin specimen, as shown in Fig. 1. Fig. 2 shows a block diagram of the instrumentation used for the acquisition of the AE signals. The AE sensor used in the experiments was a wideband transducer (frequency band: 500 kHz to 4 MHz). Because the voltage of the signals detected using the AE sensor was quite low, the signals were amplified to a level of 90 dB by a

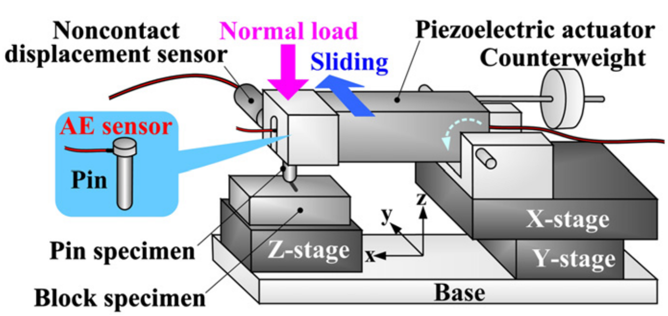

Fig. 1. Schematic showing the experimental setup.

Table 1
Summary of the experimental conditions.

Normal load W, N	0.49
Sliding velocity v, μm/s	100
Sliding distance L, μm	50–200
AE amplification factor, dB	90
AE band-pass filter, MHz	High-pass filter: 0.5 Low-pass filter: 3

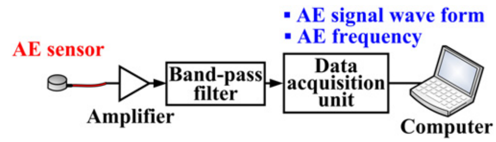

Fig. 2. Block diagram of the instrumentation used for the acquisition of the AE signal.

preamplifier and main amplifier. The AE signals were then passed through a band-pass filter to eliminate noise signals. AE signals that exceeded a trigger voltage of 200–500 mV were detected with a fast waveform digitizer (resolution: 12 bit; sampling frequency: 100 MHz). A frequency analysis was then performed to identify the waveforms of the AE signal.

3. Results

3.1. Identification of wear mechanisms by observations of worn surfaces

Fig. 3 is a micrograph showing the wear track for the pin specimen. Fig. 3(a) and (b) was obtained from two experiments in which pin specimens were rubbed under dry conditions on an iron block polished to a mirror finish and on emery paper of grain size #400 under lubricated conditions, respectively. The mode of wear can be identified from the micrographs shown in Fig. 3. In Fig. 3(a), damage associated with adhesive wear, in which fine transfer particles adhere to the surface can be seen. Although the size of the particles generated by adhesive wear differed depending on the pair of materials involved, the type of damage was similar for all the pin materials used. On the other hand, the peculiar type of damage associated with abrasive wear, in which abrasive grains produce grooves on the surface of the pin specimen, can be seen in Fig. 3(b). Although the depth of the grooves produced by abrasion depended on the grain size of the emery paper, a similar type of damage was observed when coarser (#800) emery paper was used. Therefore, the results clearly show that the type of wear phenomenon (adhesive wear or abrasive wear) could be reproduced in the two experiments.

3.2. AE frequency characteristics of the experimental system

Before examining the experimental results for frequency analysis of AE signals, it was necessary to identify the effects of background noise and of the resonance point for the entire experimental system (not just the AE sensor). The frequency characteristics of the AE signals were examined by means of a pencil-lead breaking test. The resonance point in the experimental system can be evaluated by analyzing the AE signal that is produced when a pencil lead is broken at the tip of the pin specimen. A frequency analysis of the background noise signal was also performed. The frequency spectrum of the AE signals from the breaking pencil lead and the background noise signal in the experimental system are shown in Fig. 4(a) and (b), respectively. Fig. 4(a) shows that multiple frequency peaks in the signal from the breaking pencil lead were present in the region below 0.2 MHz. Here, only the signal from the breaking pencil lead signal was measured, with an amplification factor of 60 dB and without a band-pass filter. This is the resonance point for the experimental system, which shows a frequency distribution similar to the frequency characteristics of the AE sensor used. These frequency peaks need to be eliminated by processing with a band-pass filter. Also, it can be seen from Fig. 4(b) that a principal frequency peak in the background noise signal occurred at around

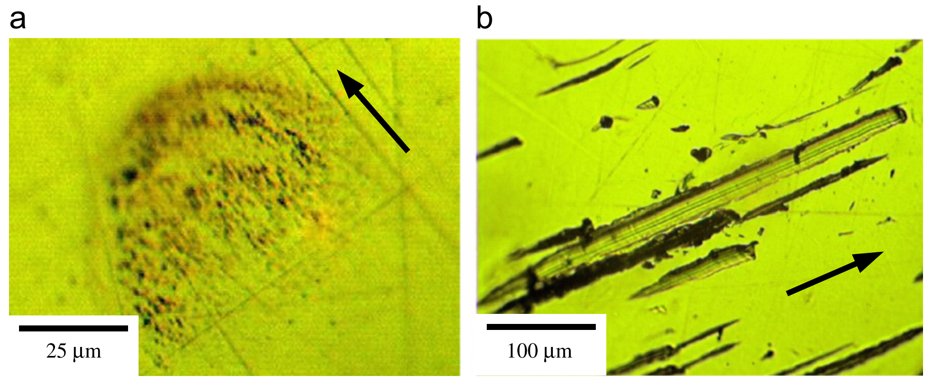

Fig. 3. Micrographs of wear tracks for pin specimens: (a) adhesive wear (Fe/Fe, dry); and (b) abrasive wear (Fe/#400, lubricated). The arrow in each micrograph indicates the direction of sliding.

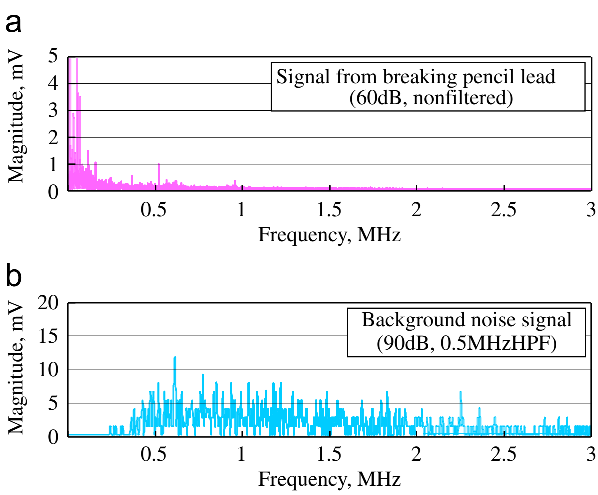

Fig. 4. AE frequency characteristics of the experimental system: (a) signal from a breaking pencil lead (60 dB, no filter); and (b) background noise signal (90 dB, 0.5-MHz high-pass filter).

0.6 MHz. Because the amplitude of the background noise signals was small, it did not affect the experimental results.

3.3. *AE signal measured in adhesive wear*

Fig. 5 shows AFM images of the worn surface of the iron block after rubbing for each of three combinations of materials: (a) Fe/Fe, (b) Cu/Fe, and (c) Ag/Fe. In adhesive wear, wear elements (elementary particles of wear) which compose transfer particles and wear particles are generated on the worn surface [14–16]. Fig. 6 shows the AE signal waveform and the AE frequency spectrum of a typical AE signal detected during adhesive wear. The results for the material combinations (a), (b), and (c) in Fig. 6 correspond to the observations (a), (b), and (c) in Fig. 5. Fig. 5 clearly shows that wear elements and transfer particles are produced after rubbing between all three pairs of materials. Burst-type AE signals were detected only when debris adhering to the worn surface was observed. It therefore follows that AE signals produced during adhesive wear originate mainly from the generation of wear elements and transfer particles.

By comparing the AE signal waveforms shown in Fig. 6, we can see that the amplitude of the AE signal differs depending on the combination of materials that is used. From the AFM observations shown in Fig. 5, it appears that the quantity of wear elements and transfer particles generated on the worn surface is related to the amplitude of the burst-type AE signal. Furthermore, from the AE frequency spectrum shown in Fig. 6, we can see that a primary peak occurs at around 1.1 MHz during adhesive wear. This feature in the AE frequency spectrum also applied to other pin materials. From the results shown in Fig. 4, the frequency peak is not related to background noise or to resonance of the experimental system. Because the AE frequency is affected by deformation and fracture phenomena, it appears that the frequency peak that occurred at around 1.1 MHz during adhesive wear is related to the generation of wear elements and transfer particles.

3.4. *AE signal measured in abrasive wear*

Fig. 7 shows the AE signal waveform and the AE frequency spectrum of typical AE signal detected during abrasive wear. Fig. 7(a) and (b) shows the results obtained by rubbing of an iron pin on abrasive papers with grain sizes of #400 and #800, respectively. In abrasive wear, cutting and plowing of material on the sliding surface occur, as shown in Fig. 3(b). It therefore follows that the burst-type AE signals shown in Fig. 7 originate from cutting (shear fracture) and plowing (plastic deformation).

By comparing the AE signal waveforms shown in Fig. 7, we can see that the amplitude of the AE signal differs depending on the size of the abrasive grains. It appears that the amplitude of the burst-type AE signal is related to the removal capability of the abrasive grains. Furthermore, from the AE frequency spectrum shown in Fig. 7, we can see that several peaks are distributed in the region between 0.25 MHz and 1 MHz during abrasive wear. Although the amplitude of the spectrum depends on the size of the abrasive grains, the features of the AE frequency spectrum are similar for both grain sizes. Also, the features of the AE frequency spectrum were similar for other pin materials. It is therefore apparent that the frequency peaks distributed in the region 0.25 MHz to 1 MHz in abrasive wear are related to cutting and plowing of material.

4. Discussion

The first point that we need to discuss is which phenomena are the sources of AE signals during each mechanism of mechanical wear. Fig. 8 shows a schematic of the AE sources in adhesive wear and in abrasive wear.

In adhesive wear, wear elements are generated by the processes of adhesion and breakage at a junction (the real area of contact). Also, transfer particles are formed by aggregation (transfers in a group) of wear elements between sliding surfaces. Because AE waves are generated by the release of the strain energy produced by deformation and fracture of the material, the deformation and breakage of surface asperities are identified

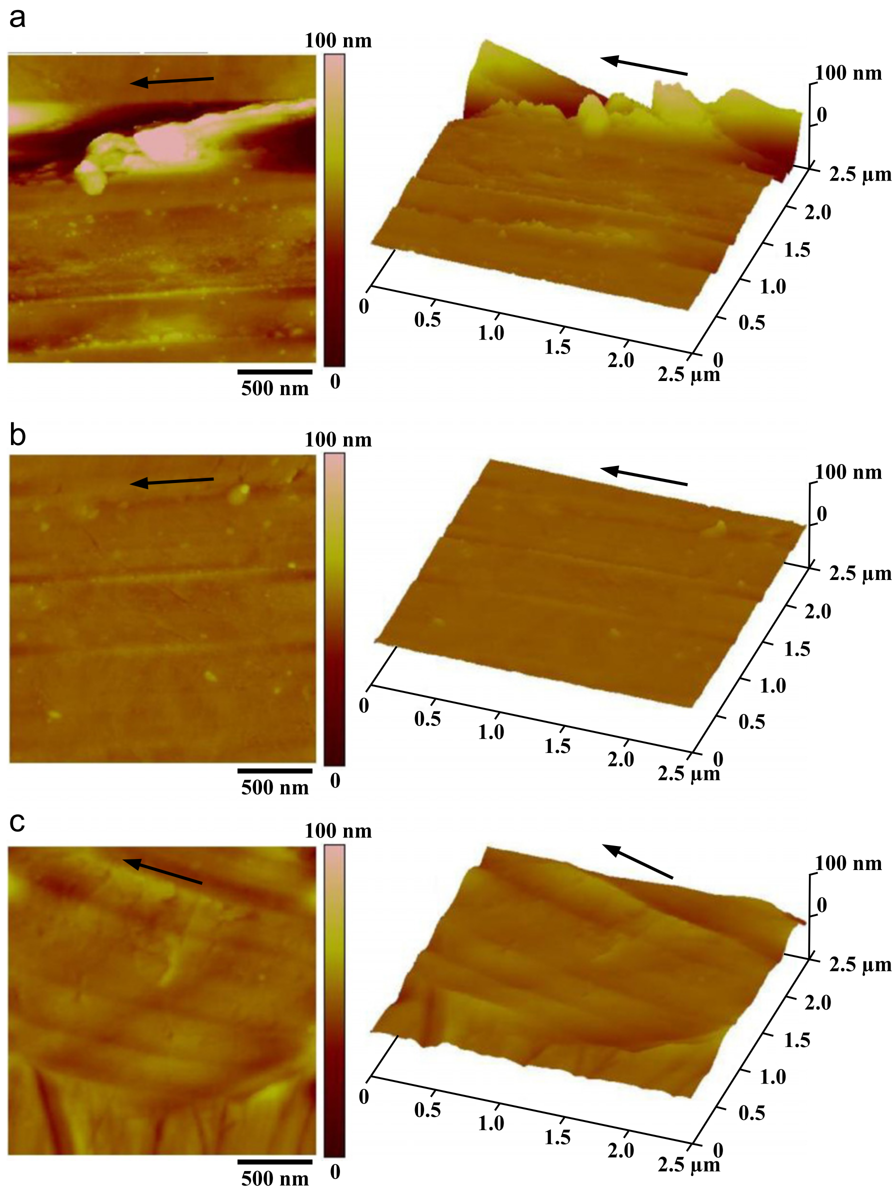

Fig. 5. AFM images of worn surfaces of iron blocks after rubbing: (a) Fe/Fe; (b) Cu/Fe; and (c) Ag/Fe. The arrows indicate the direction of sliding.

as the sources of AE signals during the elementary process of adhesive wear. However, in the experiments, burst-type AE signals were detected only when wear elements and transfer particles were observed on the worn surface. The reason why the AE signals generated by the deformation of the sliding surface were not detected is that the strain energy released during the breakage of surface asperities is greater than that released during deformation. To put it more concretely, plastic deformation of the surface asperities is a homogeneous deformation process and the strain rate is low, whereas breakage of the asperities is a nonhomogeneous deformation process and occurs rapidly. It therefore follows that the source of AE in adhesive wear is mainly the generation of wear elements (and transfer particles), as shown in Fig. 8(a).

The results from the adhesive-wear experiments indicated that the amplitude of the AE signal is related to the quantities of wear elements and transfer particles on the worn surface. As mentioned above, the main source of AE in the elementary processes of adhesive wear is the generation of wear elements. Although it appears that an AE pulse wave is certain to occur as a result of the generation (transfer) of one wear element on the nanoscale, the AE signal generated by the transfer of a single wear element cannot be detected because the signal level is quite low. However, a burst-type AE signal can be detected when the AE pulse waves are all in phase, because wear elements do not transfer singly but do so in groups in the area of real contact. With regard to the AE signal detected from this process, the amplitude of the AE signal will differ depending on the quantity of the wear elements that are generated, because the density of the AE pulse waves will change accordingly. The combination of materials affects not only the size of wear elements but also their quantity, which increases with increasing adhesion force between the two sliding materials [14]. Therefore, the amplitude of the AE signal is large when the adhesion force between the two materials is large.

On the other hand, in abrasive wear, the sliding surface is grooved by abrasive grains. In this case, cutting (shear fracture) and plowing (plastic deformation) occur between the contact area of the abrasive grain and the sliding material. Because the strain energy released by plastic deformation is lower than that released by fracture, as discussed above, shear fracture at the sliding surface is the main source of AE in the process of abrasive wear, as shown in Fig. 8(b).

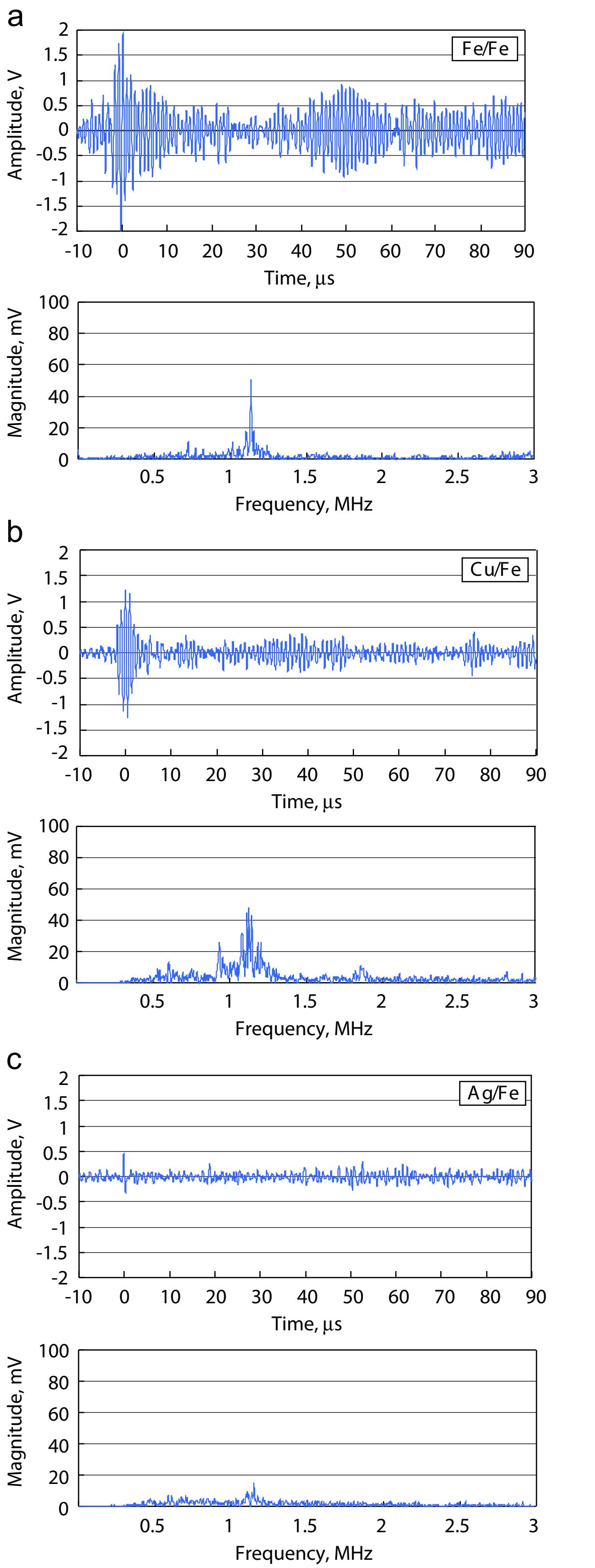

Fig. 6. AE signal waveforms (upper plots) and the AE frequency spectra (lower plots) for typical AE signals detected during adhesive wear: (a) Fe/Fe, (b) Cu/Fe, and (c) Ag/Fe.

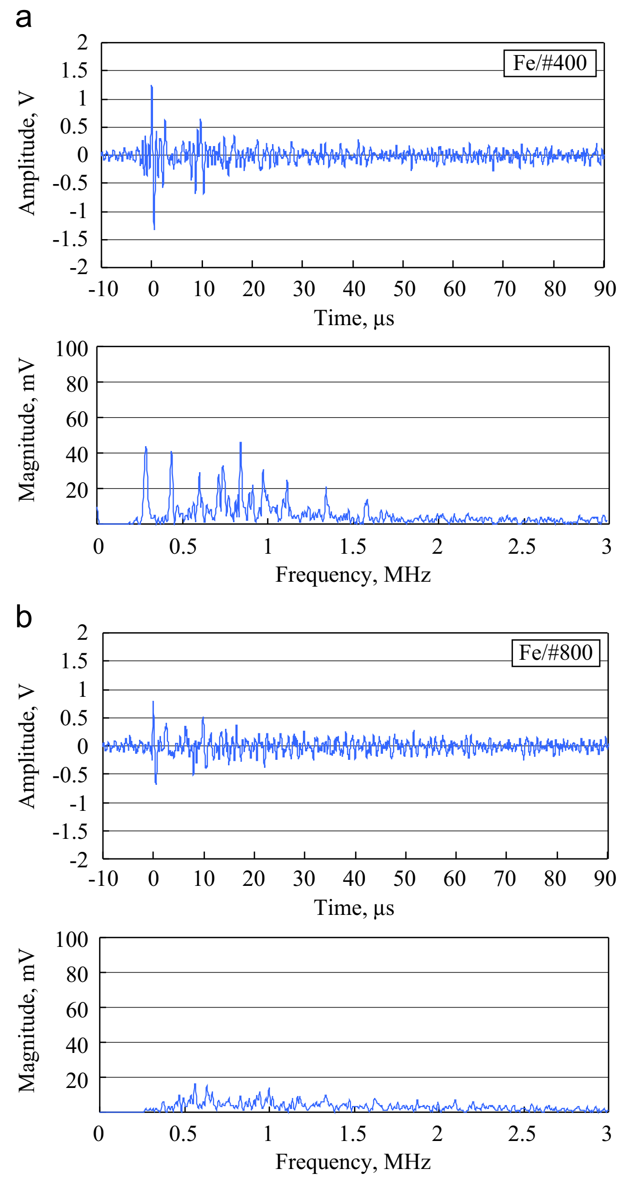

Fig. 7. AE signal waveforms (upper plots) and AE frequency spectra (lower plots) for typical AE signals detected during abrasive wear: (a) Fe/#400 and (b) Fe/#800.

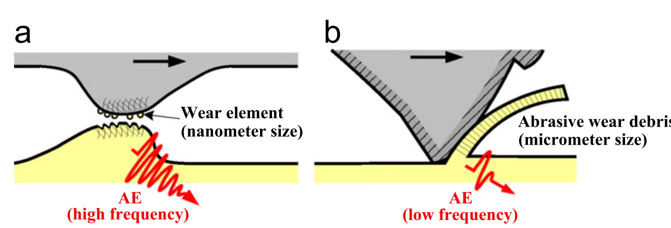

Fig. 8. Schematic of sources of AE in (a) adhesive wear and (b) abrasive wear.

The results from the abrasive-wear experiments show that the amplitude of the AE signal is related to the size of the abrasive grains. The multiple abrasive grains simultaneously cut and plow the sliding surface in the contact area. Thus, a burst-type AE signal is generated not only by a single event of shearing, but by groups of such events, as in the case of adhesive wear. Because the AE signal level is proportional to the length of contact between the cutting edge and the sliding material in abrasive wear [13], larger abrasive grains produce an AE signal of greater amplitude. Therefore, the reason why the amplitude of the AE signal differs with the size of the abrasive grains is the difference in the area of the shear region.

Next, we will discuss the features of the AE frequency spectrum in detail. Because the AE frequency spectrum is influenced by the responses of the specimen, the transducer, and the measuring system (amplifier and filter), the frequency spectrum of the AE signals generated at the point of release does not necessarily correspond to that of the detected AE signals. Although the frequency characteristics of the AE sensor can affect the frequency spectrum of the detected AE signals, this influence was barely apparent in the AE frequency spectrum obtained from the friction and wear experiments. Furthermore, the background noise signal and the resonance point in the experimental system had hardly any effects on the experiments. Also, the features of the AE frequency spectrum for each wear mechanism showed similar tendencies regardless of the types of material in frictional contact. From the experimental results, the features of the AE frequency spectrum were therefore clearly dependent on the type of mechanical wear that occurred; the frequency peak that occurred at around 1.1 MHz in adhesive wear is related to the generation of wear elements and transfer particles, whereas the frequency peaks distributed in the region from 0.25 to 1 MHz in abrasive wear are related to cutting and plowing of the material.

The rise time of the AE signal influences its frequency spectrum. As a result, it is quite likely that the scale and velocity of deformation and fracture are factors that might affect the frequency spectrum of the AE signal. For the AE source in adhesive wear, the size of the wear elements is 10–30 nm in diameter, which is independent of the nature of the material [14]. The generation and transfer of wear elements occur instantaneously in the contact area. In adhesive wear, therefore, one large frequency peak is found in the high-frequency region. On the other hand, with regard to the AE source in abrasive wear, the size of wear debris is of the order of micrometers, as observed from the groove on the worn surface shown in Fig. 3(b). At the beginning of cutting and plowing (shear deformation), crack growth occurs at the contact area between the abrasive grain and the material. Shear deformation then occurs continuously in the shear zone between the rake face of the abrasive grain and the material. The slip intervals in shearing deformation vary depending on the contact state, such as the rake angle and the depth of cut. In abrasive wear, therefore, several peaks with different frequencies occur in the low-frequency region.

Fig. 9 shows a correlation map for the AE frequency spectrum (⇔: frequency band, ↑: frequency peak) for several phenomena associated with deformation and fracture. The vertical axis represents the amplitude of the AE signal and the horizontal axis represents its frequency. In the figure, the magnitude of the AE signal on the vertical axis is sequenced roughly because this shows marked changes depending on the type of AE sensor, AE filters, the experimental system (the distance and propagation paths of the waves from the respective AE sources to the sensors), and experimental conditions. The AE frequency spectra obtained in our experiments are shown by thick lines. In addition, the figure summarizes features of AE frequency spectra for various phenomena such as tensile testing [17,18], fatigue testing [19], crack propagation [20], particle behavior [21], sliding friction [22] and wear [23]. Although various factors affect the frequency components, this correlation map makes clear that the distribution of the AE frequency changes depending on the mode of deformation and fracture. Each wear mechanism (adhesive wear and abrasive wear) produces its own type of AE frequency spectrum, which is not dependent on the nature of the materials involved. In addition, the features of the AE frequency spectrum are similar between different experimental systems for various materials that show the same wear mechanism (wear mode), as shown in Fig. 9. The reason why the frequency region for abrasive wear overlaps that for tensile testing and crack propagation is that the generation of AE in abrasive wear is related to crack growth and plastic deformation, as mentioned above. For phenomena involving mild wear and particle behavior, the primary frequency domains occur in the region from 0.08 to 0.2 MHz, and the emissions originate from rolling and collision of wear particles between the sliding surfaces. Also, frequency peak for sliding friction (slip event) also occurs at 0.1 MHz, and the emissions originate from collision of surface asperities.

Finally, we can confidently state that the mechanisms of wear can be recognized from the features of the AE frequency spectrum, particularly as the frequency domains for adhesive wear are clearly separate from those for abrasive wear. However, it is important to analyze the AE frequency after examination of the resonance frequencies of the AE sensor and of the experimental

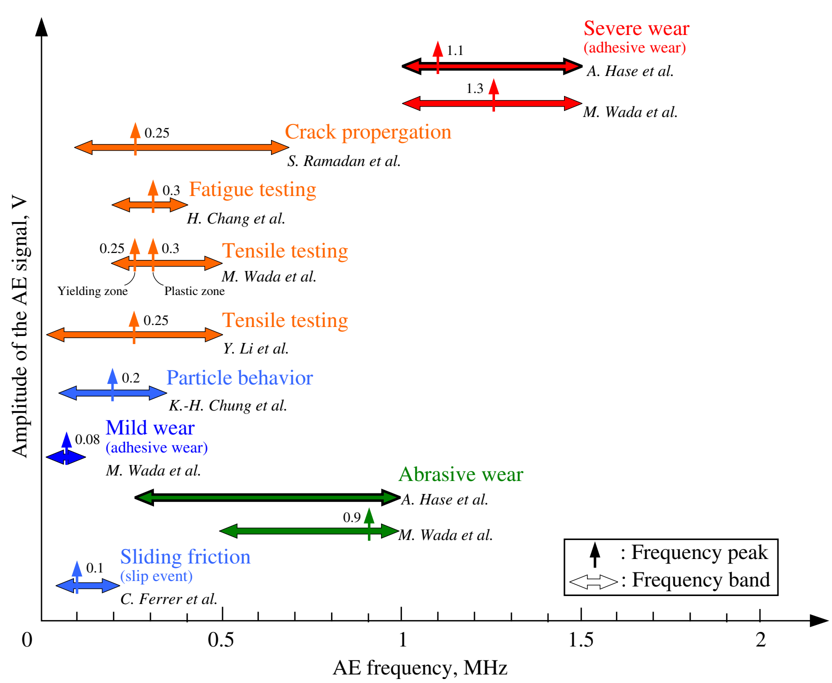

Fig. 9. Correlation map of AE frequency spectra for phenomena involving deformation and fracture (⇔: frequency band, ↑: frequency peak).

system, and when the AE characteristics of the material are clearly understood. Moreover, it should be possible to discriminate AE signals that correspond to particular wear mechanisms from the frequency distribution of the AE.

5. Conclusions

We measured and examined the AE signals generated during the two main types of mechanical wear (adhesive wear and abrasive wear), and we reached the following conclusions:

1. In adhesive wear, burst-type AE signals are produced as a result of the generation of wear elements and transfer particles. The amount of transfer influences the amplitude of the detected AE signals. The frequency peak of the AE signals occurs at around 1.1 MHz.
2. In abrasive wear, burst-type AE signals are generated by cutting and plowing of material. The removal capability of the abrasive grains influences the amplitude of the detected AE signals. The frequency peaks are distributed in the region from 0.25 to 1 MHz.
3. The mechanisms of wear can be recognized from the features of the AE frequency spectrum. Also, the AE signals that correspond to particular wear mechanisms can be discriminated.

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