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Evaluation of Writing Performance for Different Types of Ballpoint Pen Ink by Acoustic Emission Sensing

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Abstract: During contact, deformation, and fracture of surface asperities between the friction surfaces of materials, acoustic emission (AE) waves are generated as the strain energy is released. By detecting the AE waves during friction using an AE sensor, the state of friction, wear, and lubrication between the friction surfaces can be measured and evaluated with high sensitivity. In this study, in order to establish a method for evaluating the writing performance of ballpoint pens by AE sensing, the measurement method was examined, and AE signal waveforms were analyzed. It was found that AE sensing can detect phenomena that do not appear as a change in frictional force during writing. In addition, frequency analysis of the AE signal waveforms revealed that differences in writing performance depending on the ink type of the ballpoint pen can be evaluated and interpreted.

Keywords: tribology; sliding friction; rolling friction; wear; acoustic emission (AE); ballpoint pen; ink; writing instrument; writing performance; frequency analysis

Citation: Hase, A. Evaluation of Writing Performance for Different Types of Ballpoint Pen Ink by Acoustic Emission Sensing. *Lubricants* **2022**, *10*, 44. https://doi.org/10.3390/lubricants10030044

Received: 15 February 2022
Accepted: 14 March 2022
Published: 15 March 2022

1. Introduction

In recent years, ballpoint pens with various features and functions have been commercialized, and many products with features such as good writing performance have been developed [1]. It is considered that the writing performance (writing smoothness) of a ballpoint pen is determined not only by pen design [2,3], but also mainly by the tip (a ball and a ball-receiving seat) and ink components [4]. Writing performance is evaluated by measuring frictional resistance and vibration in addition to human sensitivity [5,6]. However, since microscopic and complicated tribological phenomena are involved in the tip, it is often difficult to make comparisons with conventional measurement methods. In order to develop better products, sensing technology that can measure and evaluate changes in microscopic and complicated phenomena is required.

At the time of contact, deformation, and fracture of surface asperities at the frictional interface of a material, acoustic emission waves (AE waves) are generated as elastic strain energy is released. By measuring the AE waves generated under tribological phenomena, it is possible to measure and evaluate the state of friction, wear, and lubrication at the frictional interface in situ [7–10]. One study on AE waves and writing instruments reported that it is possible to evaluate the tone of drawn lines by measuring the AE waves generated during writing with a mechanical pencil [11]. On the other hand, as far as the author knows, there has been no study on using AE waves to evaluate the writing performance of a ballpoint pen.

The present study aimed to measure and evaluate the state of friction, wear, and lubrication of the tip of a ballpoint pen with high sensitivity by using an AE sensor [12] to measure the AE waves generated during writing, and thus evaluate the writing performance of ballpoint pens. The evaluation method was examined by measuring and analyzing the AE signal, and the features of the AE signal acquired during writing with a ballpoint pen and the findings obtained about the source of the AE waves were analyzed.

2. Experiments

Figure 1 is an overview of the experimental setup and measuring system used in this study. Using a pin-on-flat-type reciprocating friction tester, the refill of the ballpoint pen (pin side) attached to a jig could be slid on the stage (flat side) through a crank mechanism. The test paper was fixed on the stage. For this experiment, the exterior parts of the ballpoint pen were removed, and only the tip and refill were tested. The ball had a diameter of 0.7 mm, and the pen tip and ball were made of stainless steel. The refill was fixed perpendicular to the test paper surface.

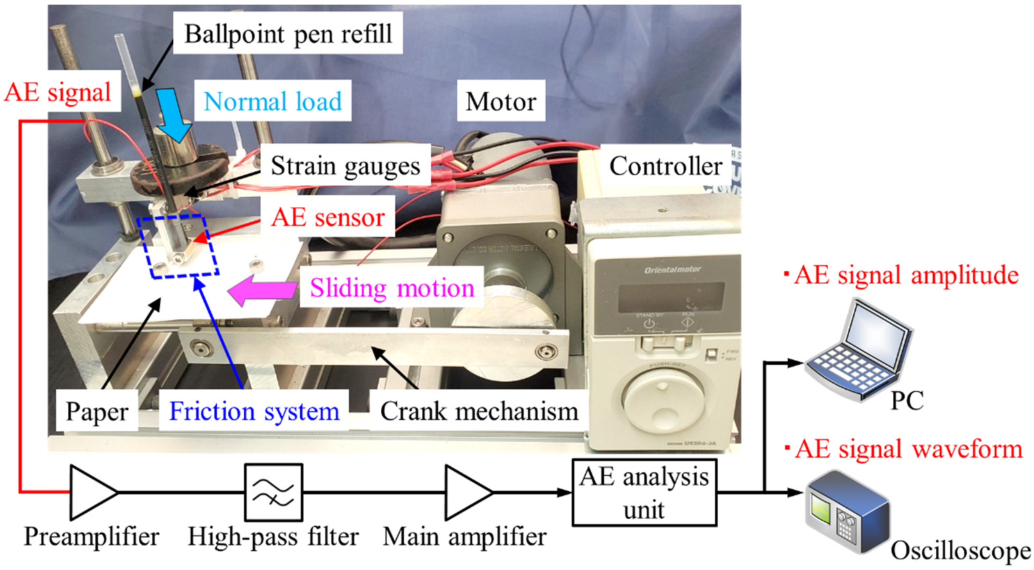

Figure 1. Experimental setup and measuring system for evaluating the writing performance of a ballpoint pen by AE sensing.

It is thought that the writing performance of ballpoint pens is mainly determined by the tribological phenomena between the ball and the ball-receiving seat in the tip. If the AE sensor is attached on the paper and table side, it is considered that the writing performance cannot be evaluated correctly because the AE waves are greatly attenuated and also the positional relationship between the AE sensor and the AE source changes. Therefore, the AE sensor was attached to the ballpoint pen side to measure the AE waves. After examining the installation position in a preliminary experiment, the AE sensor was installed on the side face of the jig near the tip, as shown in Figure 2. The distance and interface were considered so that the AE waves would not be attenuated: the distance between the wave receiving surface of the AE sensor and the ballpoint pen tip was 2 mm. In addition, strain gauges were attached to the leaf spring of the pin test specimen fixing part, and the writing resistance (frictional resistance) was measured.

The writing conditions were a writing pressure (normal load) of 1.0 to 1.5 N and a writing speed (average frictional speed) of 15 mm/s. In the experiment, a 30 mm straight line was drawn only once in one direction, and this process was repeated at room temperature. The test paper used was high-quality paper with a thickness of 0.12 mm. For the ballpoint pen ink, a comparative experiment was performed using a common oil-based ink and a special oil-based ink with excellent writing performance. Furthermore, comparative experiments with not only the oil-based inks but also a water-based ink and a gel ink were performed.

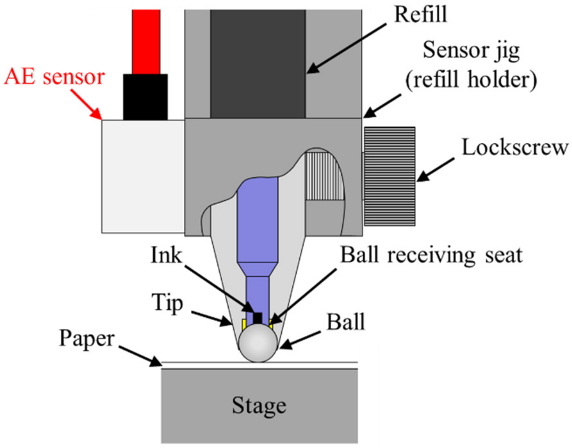

Figure 2. Schematic diagram of the friction system in a ballpoint pen and the AE sensor position.

The output signal from the AE sensor was amplified by a preamplifier and a main amplifier, then filtered for noise rejection. Table 1 shows the AE measuring conditions. The amplification factor was 100 dB, and a 50 kHz high-pass filter was used. The AE signal amplitude and the AE signal waveform (source signal) were measured and analyzed to evaluate the AE signal during writing. The AE signal waveform was continuously measured and analyzed with the time window of one waveform set to 200 µs.

Table 1. Summary of the AE measuring conditions.

AE Sensor (Frequency Band)	Wideband-type (0.5–4.0 MHz)
AE Amplification Factor	100 dB
AE Band-Pass Filter	High-pass filter: 50 kHz Low-pass filter: through

3. Results and Discussion

3.1. Change in AE Signal Amplitude during Writing with a Ballpoint Pen

First, the results of a comparative experiment between a common oil-based ink that has varying performance depending on the conditions and an oil-based ink that has excellent writing performance are described. Figure 3 shows the observation results of a line written after the experiment using (a) the common oil-based ink and (b) the special oil-based ink. Both lines were drawn without interruption.

(**a**) (**b**)

Figure 3. Observations of a straight line drawn on the paper using the ballpoint pen with different ink types: (**a**) common oil-based ink and (**b**) special oil-based ink.

Figures 4 and 5 compare the frictional resistance and AE signal amplitude when writing using each ink. In Figure 5, the graph on the right is an enlargement in the range of 0 to 1 V of the graph on the left. It can be seen that the magnitude of the frictional resistance is almost constant, although there is a difference in ink performance. On the other hand, the AE signal amplitude differs not only in magnitude (mean value) but also in the occurrence timing of the burst-type AE during writing. This is because the amount of ink exudation is related and the microscopic friction phenomenon in the tip, which will be described later, is captured.

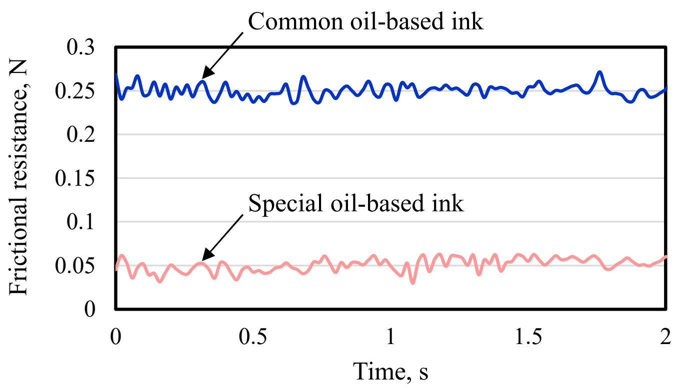

Figure 4. Changes in frictional resistance for different ink types.

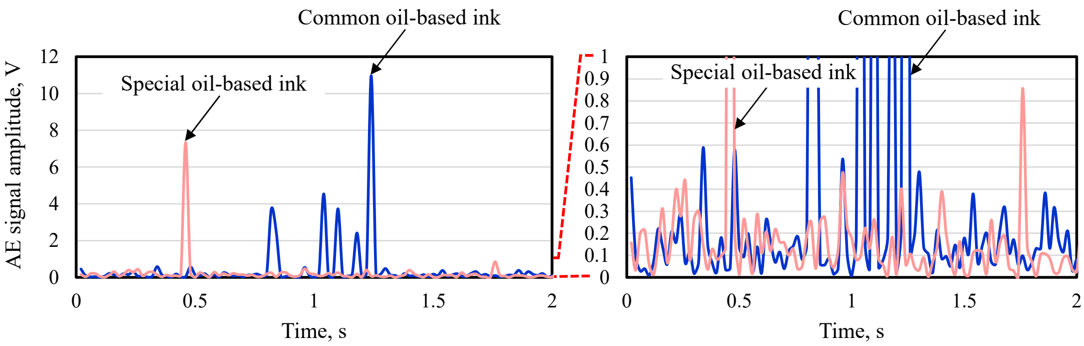

Figure 5. Changes in AE signal amplitude for different ink types.

With AE sensing, it is possible to identify and discriminate deformation and fracture phenomena by analyzing the frequency of the AE signal waveform [13]. Therefore, the frequency of the AE signal waveforms detected during writing in Figure 5 when it was stable (when small-amplitude AE signals occurred) and when it was unstable (when large-amplitude AE signals occurred) were analyzed. Figures 6 and 7 show the results for (a) the common oil-based ink and (b) the special oil-based ink, respectively. In the stable state (i), a frequency peak was confirmed around 0.1 to 0.2 MHz (low-frequency range). On the other hand, in the unstable state (ii), a large frequency peak was confirmed not only in the vicinity of 0.1 to 0.2 MHz but also in the vicinity of 0.2 to 0.4 MHz (medium-frequency region).

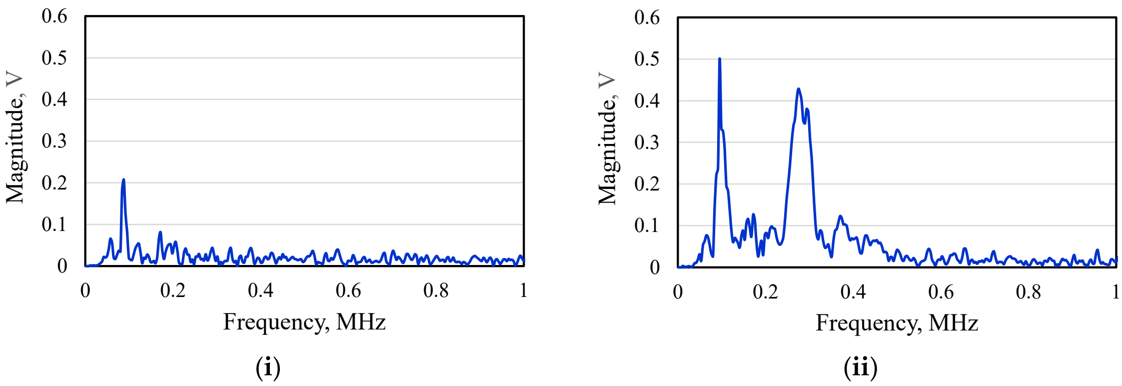

Figure 6. Typical frequency spectra of the AE signal waveforms for common oil-based ink: (**i**) stable state and (**ii**) unstable state.

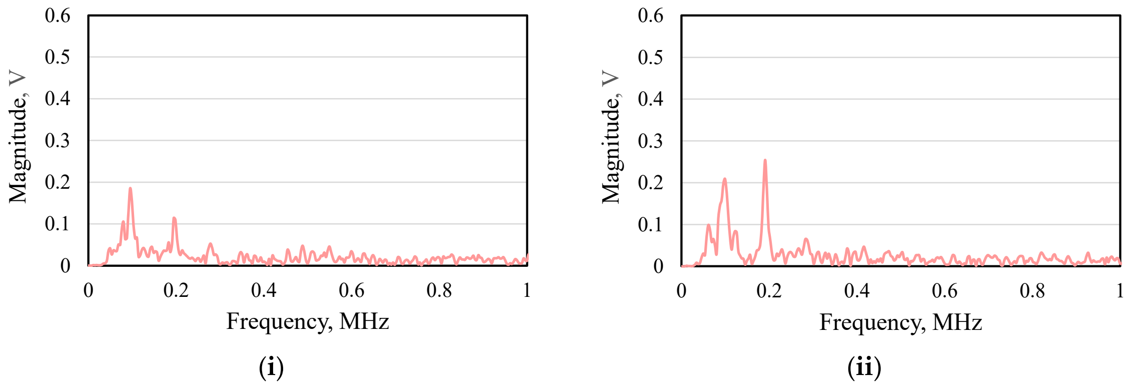

Figure 7. Typical frequency spectra of the AE signal waveforms for special oil-based ink: (**i**) stable state and (**ii**) unstable state.

From the results of analyzing the frequency of the AE signal waveform measured under tribological phenomena, it is known that the low-frequency AE signal is caused by the friction phenomenon and the medium-frequency AE signal is caused by the deformation and fracture of the surface asperities. Therefore, it is considered that the friction and lubrication between the ball and the ball-receiving seat are poor with the common oil-based ink, and the magnitude of the low and medium frequencies of the AE signal due to deformation and fracture due to sliding friction increases.

3.2. Changes in AE Signal Frequency Depending on the Type of Ink

Next, in order to evaluate the writing performance by ink type, the features of the change in frequency of the AE signal waveforms (AE signal frequency) detected during writing with oil-based inks (common ink and special ink), water-based ink, and gel ink with a ballpoint pen are described.

Figure 8 shows the change in frequency of the AE signal waveforms at various times in each experiment. The seventeen spectra of the AE signal waveforms detected during writing are arranged in chronological order. It can be seen that the AE signal amplitude increases in the order of (c) water-based ink, (d) gel ink, and (a) oil-based ink. This is consistent with the order of good writing performance by general ink type. From the AE signal measurement in the sliding friction experiment under the lubricated condition, it is known that the change in friction state due to the film thickness ratio can be detected with high sensitivity [14]. For instance, immediately after large-amplitude AE signals occurred (as seen at 0.5 s for special oil-based ink in Figure 5), the thickness of the line tended to be slightly thinner from the magnified observation of the writing line. Therefore, the frictional state between the ball and the ball-receiving seat due to changes in viscosity and the amount of exudation of the ink is captured.

As mentioned earlier, large frequency peaks were confirmed around 0.1 to 0.2 MHz (low-frequency region) when writing was stable, and around 0.2 to 0.4 MHz (medium-frequency region) when writing was unstable. This trend was the same even for different ink types, and was confirmed for the water-based ink and the gel ink with low AE signal amplitude. With the gel ink, the lines tended to be slightly thinner at the end of writing. It is presumed that this was due to the fact that the friction between the ball and the ball-receiving seat increased due to the decrease in the amount of ink exudation, and the microscopic damage progressed. After the experiment, the appearance of the surface of each ball was observed, but no major damage was confirmed. Since the writing distance was short, it is considered that there was minor damage to the ball-receiving seat and other contact parts. However, since detailed surface observation using a scanning electron microscope, etc., was not possible in this study, it is necessary to clarify the relationship with microscopic damage in future studies.

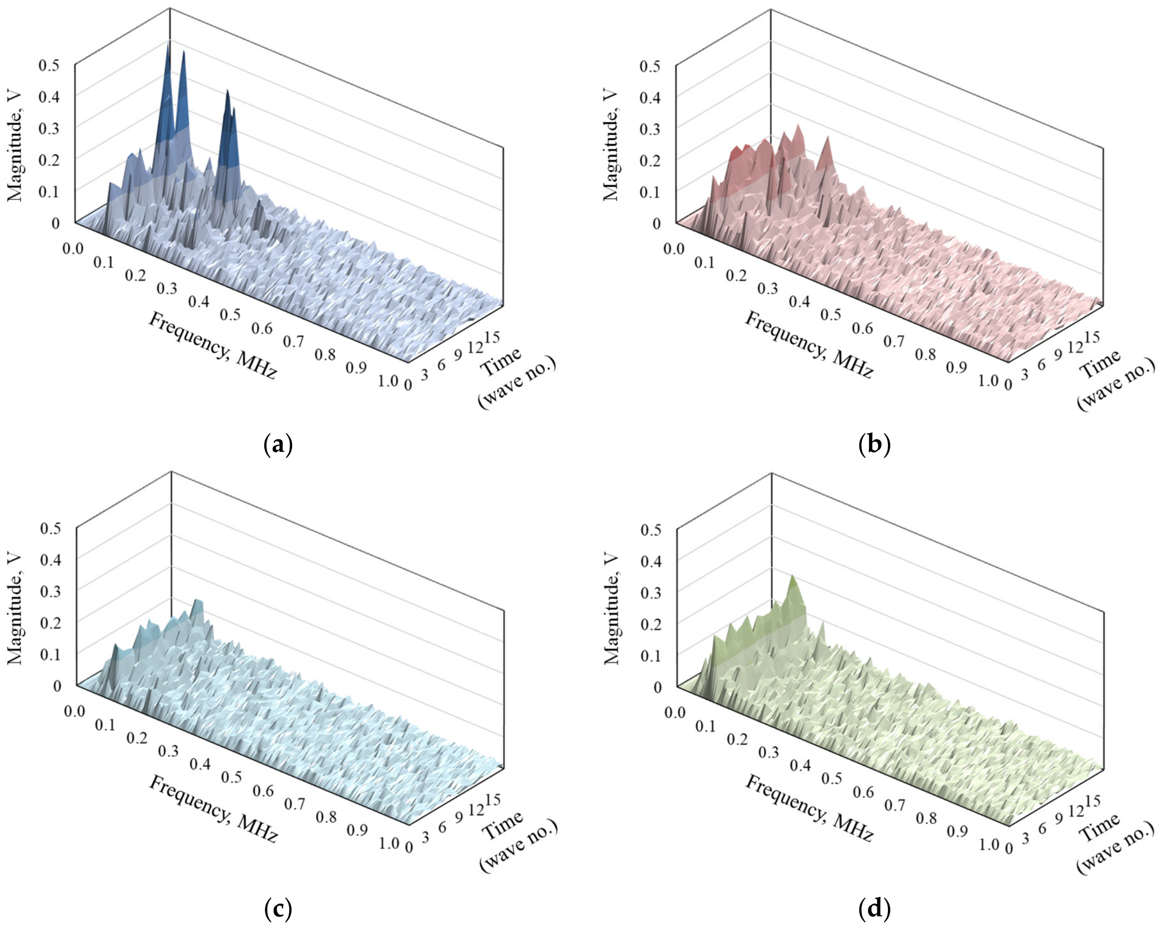

Figure 8. Changes in frequencies of the AE signal waveforms at various times during writing: (**a**) common oil-based ink, (**b**) special oil-based ink, (**c**) water-based ink, and (**d**) gel ink.

3.3. Evaluation of Writing Performance of Ballpoint Pens by AE Sensing

Figure 9 shows the relationship between the coefficient of friction obtained in the experiments using ballpoint pens with different ink types and the AE mean value, which is the average value of the AE signal amplitude. This coefficient of friction, which involves not only sliding friction but also rolling friction between the ball and the paper, was obtained by dividing the average value of writing resistance by the writing pressure. The error bars in the coefficient of friction and the AE mean value represent the standard deviation, $\pm\sigma$ and $+\sigma$, for the signal change during the experiment, respectively. The results show a linear relationship between the AE mean value and the coefficient of friction. The correlation coefficient for the regression line was 0.99. Although it is necessary to clarify the effects of writing pressure and writing speed on this relationship, the results suggest that the writing performance of a ballpoint pen can be quantitatively evaluated by AE sensing.

In order to investigate the factors that affect the writing performance of ballpoint pens, frequency analysis of AE signal waveforms could be utilized. Accordingly, the signal ratio for each frequency component was calculated from the frequency spectrum average in Figure 8. Based on the findings obtained in previous studies [13,15], the frequency components were classified as follows: 0 to 0.2 MHz relates to a friction phenomenon, 0.2 to 0.5 MHz relates to plastic deformation of surface asperities and crack growth under the friction surface, 0.5 to 1.0 MHz relates to abrasive wear, and 1.0 to 1.5 MHz relates to adhesive wear. Figure 10 shows the results of arranging the AE mean value by the signal ratio for each classified frequency component. The bar graph on the left shows the ratio of the frequency components for each amplitude. The bar graph on the right shows the ratio of only the frequency components by standardizing the magnitude of the amplitude. These figures reveal that the frequency component ratio related to the wear of the water-based ink and the gel ink was larger than that of the oil-based inks. This result agrees with the measured amount of wear of the ball-receiving seat according to the ink type [16]. Therefore, this method can be used to identify the factors that affect the writing performance and lifetime of a ballpoint pen. Since the ratio of the AE signal frequency component may change depending on the tip structure, ink viscosity, ball hardness, etc., it can be used for optimization during product development.

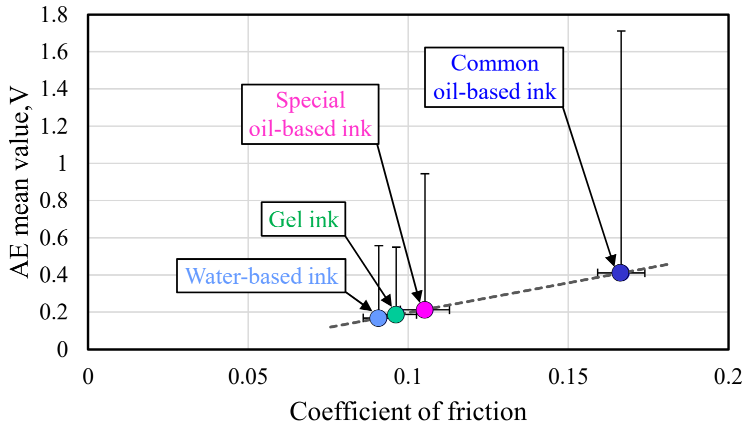

Figure 9. Relationship between the coefficient of friction and the AE mean value.

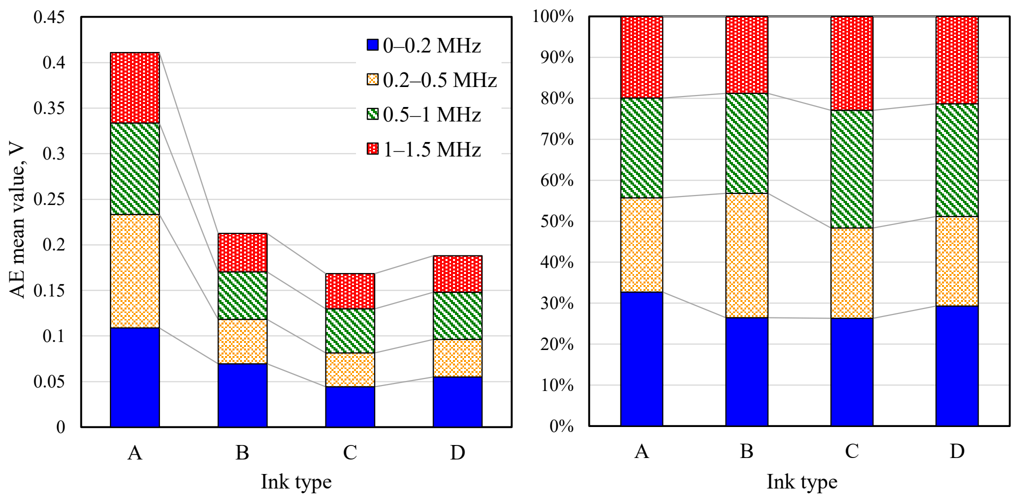

Figure 10. Comparison of the AE mean value for different ink types: (**A**) common oil-based ink, (**B**) special oil-based ink, (**C**) water-based ink, and (**D**) gel ink.

4. Conclusions

In this study, experiments and studies were conducted to evaluate the changes in writing performance due to ink type by using the AE signal acquired during writing with a ballpoint pen by AE sensing. The following conclusions were obtained:

(1) AE sensing can capture the tribological phenomena that occur in the tip of a ballpoint pen during writing with higher sensitivity than by measuring the frictional resistance.
(2) Large frequency peaks were confirmed around 0.1 to 0.2 MHz (low-frequency region) when writing was stable, and around 0.2 to 0.4 MHz (medium-frequency region) when writing was unstable.
(3) A correlation between the AE signal amplitude and the coefficient of friction, which involves both sliding friction and rolling friction between the ball and the paper, was found.

(4) It is possible to evaluate and interpret the differences in writing performance depending on the ink type of a ballpoint pen from not only the changes in the AE signal amplitude but also the ratio of the AE signal frequency component.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The author thanks Ryouta Shimamura, who was a student at Saitama Institute of Technology when the experiments were performed, for his assistance.

Conflicts of Interest: The author declares no conflict of interest.

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