ACOUSTIC EMISSION EVALUATION SYSTEMS OF TOOL LIFE FOR SHEARING OF PIANO AND STAINLESS STEEL WIRES

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Abstract

Shearing is a machining operation that separates the workpiece material by the growth of a crack, which occurs in the narrow region around the tool tip. It is necessary to evaluate the tool life because the product quality is influenced by the wear conditions of the tool. However, the problems for evaluating the condition and the tool life have not been solved yet. In this study, chaos time series analysis, wavelet transform and waveform analysis are applied for recognizing the characteristics of the detected AE signals in the shearing of piano and stainless steel wires. The results are as follow: (1) AE signals have the chaotic property, and the wear condition and the tool life will be evaluated by the largest Liapunov exponent and the correlation dimension; (2) the RA (rise time/amplitude) value of the time fluctuation waveform of the wavelet coefficient is an effective parameter for tool life prediction; (3) the validity of this system for the tool life by the RA value was confirmed by the comparison with the experimental results.

Keywords: Tool life, evaluation system, chaos time series analysis, wavelet transform, shearing

Introduction

Shearing is one of the most important working methods in the manufacturing process. We need to evaluate tool wear conditions for the quality control of products and the improvement of the productivity. Such a system is yet unavailable [1]. In this study, chaos time series analysis, wavelet transform analysis and waveform analysis were applied for evaluating the tool wear conditions in shearing of piano and stainless steel wires, and the extraction of the parameters from detected AE signals for evaluating the tool life was investigated. From the study, it became clear that the RA (rise time/peak amplitude) value of the time fluctuation waveform of the wavelet coefficient is an effective parameter. An evaluation system using the parameter was proposed, and its validity was confirmed by comparing with the experimental results.

Chaos Time Series Analysis and Wavelet Transform

Chaos time series analysis

Chaos time series analysis is one of the effective methods, when the cause of the complexity of the signal is the fluctuations of the nonlinear dynamical system or the internal factors. In the judgment of the chaos property, the recurrence plots that represent the distance Dᵢⱼ between two points (i.e. Xᵢ and Xⱼ) in the phase-space on the two-dimensional coordinate plane (i, j) are used. The plots are evaluated by the texture of the gradation colors for Dᵢⱼ and the
Wavelet Transform

AE signals in shearing arise from the deformation of the wire, the growth of the crack, the tool wear condition, etc. Various such factors may be elucidated by grasping the occurrence time of the frequency components corresponding to each factor. The frequency analysis results with FFT are effective for identification and discrimination of the microscopic fracture factor, and FFT contributes to the solution of the fracture mechanism. However, it is not suitable for the analysis of the signals, whose the statistical properties change with the time [7-11]. Therefore, another method that transforms a signal into a time-frequency domain is needed for analyzing non-stationary or transient signals such as AE. Wavelet transform (WT) is one of the methods for supplementing the shortcoming of FFT. The WT of the signal \( f(x) \) is defined by:

\[
\left[ WT \ f \right](a,b) = \int_{-\infty}^{\infty} \Psi^\ast(x)f(x)dx\\[0.5cm]\nonumber
\]

where \( \Psi^\ast \) is the complex conjugate of the wavelet function \( \Psi_{a,b}(x) \). The function \( \Psi_{a,b}(x) \) is defined by \( |a|^{-1/2} \Psi((x-b)/a) \). The function \( \Psi(x) \) is the mother wavelet (e.g., Gabor wavelet) with the scale parameter \( a \) and the shift parameter \( b \) and provides a set of the localized functions in both frequency and time. The scale parameter \( a \) gives the width of window and consequently the frequency as the mother wavelet is expanded or compressed in time. The shift parameter \( b \) determines the position of the window in time and thus defines the analysis part of the signal \( f(x) \). Therefore, it is possible to make the optional wavelet of the angular frequency \( \omega_a/a \) in time \( b \) by changing both parameters, and the signal \( f(x) \) is represented by putting the various optional wavelets together. The wavelet coefficient and its fluctuation enlarge respectively, if the wavelet \( \Psi((x-b)/a) \) that was deformed by the parameter \( a \) and \( b \) resembles a part of the signal \( f(x) \). The intensity of the coefficient is correspondent to the amplitude of the signal \( f(x) \) [7-11]. Therefore, the fluctuation of the coefficient shows the activity of the component with the frequency \( \omega_a/a \) in time \( b \). WT becomes effective for the analysis of AE signals, in which sudden fluctuations and many phenomena are mixed, when the transform result was represented on the plane of \( b \) and \( 1/a \). Therefore, it is possible to contribute to the grasp of the fracture phenomena, if the features of the time fluctuation waveform of the wavelet coefficient in each frequency component are extracted. This feature of WT is very important for grasping each factor of fracture by the features of the analysis result.
Experimental Method

The piano wire SWP-B and stainless steel wire SUS304-WPB were used as the workpiece material. The tensile strength was 2.5 GPa for piano wire and 1.9 GPa for stainless steel wire, respectively, and the diameters of both wires are 0.7 mm. The high-speed tool steel SKH-51 was employed as the materials of a shearing tool and a mandrel.

Figure 1 is the schematic drawing that shows the experimental equipment and the processing order of the detected AE signals. The signals from shearing in a coiling machine are detected by an AE sensor of the wide-band type and are recorded in a digital oscilloscope. The distance to the center of an AE sensor from the AE source (i.e., the tip of the cutting tool) is fixed at approximately 58 mm. The features of the signals for evaluating the wear condition and tool life are extracted by the chaos analysis, the wavelet transform and the waveform analysis. On the other hand, the shearing stress is calculated from the detected strain by the semiconductor strain gauge attached on the tool. Here, the initial clearance between a tool and a mandrel was set at 0 mm in order to give priority to the quality of the shear plane, and the burr length is measured every 100 shearing. In the criterion of the machining field, it is judged that the tool reached its life when the burr length became 10~15% of the diameter of the wire. Therefore, the limit was set at 70~100 µm.

In order to extract the features for evaluating the tool life, the following operations are done: (1) the wear conditions are decided by the features of the obtained information (i.e., the behavior of the burr length and the shearing stress, and the conditions of the shear plane and the tool tip, etc.); (2) the property for the determinism of the detected signals is examined by observing the results of chaos time series analysis; (3) the frequency components, which characterize the tool life are specified by the wavelet transform results, and the features (i.e. the

Fig. 1 Experimental device and conceptual scheme in this study.
Fig. 2 Examples of experimental results for piano wire.

Fig. 3 Examples of experimental results for stainless steel wire.
maximum amplitude, the energy and the RA value, etc.) of the time fluctuation waveform of the wavelet coefficient in the components are extracted.

**Experimental Results and Considerations**

*Shearing stress and burr length*

Figures 2 and 3 show the experimental results of the piano and stainless steel wires against the number of shearing. In each, the burr length, the shearing stress, the photographs of the shear plane, the cutting tool and the mandrel are shown. From the results shown in the figures, the wear conditions of both wires were classified into the initial wear area, the steady wear area, the sign of tool life area and the tool life area. The features in each wear condition of the piano wire are as follows (cf. Fig. 2): the burr length rapidly increases and the shearing stress sharply decreases in the initial wear area; the length slowly increases and the stress slowly decreases in the steady wear area; the length rapidly increases and the stress very slowly decreases in the sign of tool life area; the length reaches at 100 µm in the tool life area. On the other hand, the features in each wear condition of the stainless steel wire are as follows (cf. Fig. 3): the fluctuations of the burr length and the shearing stress are extreme in the initial wear area; the fluctuations become moderate in the steady wear area; the length increases in the sign of tool life area; the length rapidly increases and reaches 70 µm in the tool life area. From these results, it is difficult to evaluate the tool wear conditions after the steady wear area by only observing the behavior of the shearing stress. Especially, in case of the stainless steel wire, which is more ductile than the piano wire, the evaluation of the condition is difficult because the fluctuation of the stress is extreme and the large burr easily occurs by the extrusion action that was caused by the wear of the tool tip. Therefore, it is important that the features capable of evaluating the conditions and the tool life are extracted from the AE signals. For extracting the features, it is necessary to grasp the relationships between the conditions and the crack initiation modes. Then, the relations between the RA value [12] and the average frequency [12] were examined for discriminating the modes. In the relationships, the signals of the tensile mode crack have the features, of which the RA value is small and the frequency is high, and the signals of the shear mode crack have the features, of which the RA value is large and the frequency is low [12]. Here, the discrimination criterion of each crack initiation mode is determined by considering the distribution conditions of the plots in the phase-space of the two-dimensional coordinate plane by both parameters.

Figure 4 shows the discrimination criteria of the crack initiation modes (i.e., discriminated by the RA value and average frequency) and the distributions of each crack mode occurrence every 500 shearing. From the results, the AE signals of the composite mode crack that combined the features of the tensile and the shear mode crack were observed as follow.

*Piano wire:* The occurrence rates of the crack initiation modes before the tool life show large values in the order of the tensile, the composite and the shear mode crack. On the other hand, the rates after the tool life show large values in the order of the composite, the shear and the tensile mode crack. After the tool life, the occurrence conditions of the modes changed to the shear or the composite mode crack from the tensile mode crack. This means that worn tools resulted in the occurrences of the composite and the shear mode crack. Finally, the occurrence of the composite mode crack rapidly increases from the sign of tool life area.

*Stainless steel wire:* The shear mode crack is mainly detected right after the experiment start. After that, the occurrence of the tensile mode crack becomes predominant. The occurrence of the composite mode crack begins to increase from the sign of tool life area.
Fig. 4 Discrimination standard and event counts of each crack mode for piano and stainless steel wire.

Fig. 5 Chaos time series analysis results of each crack mode for piano wire.
Therefore, the growth of the wear also affected the occurrence conditions of the crack initiation modes. The above results indicate that the occurrence conditions of the crack initiation modes are influenced by the growth conditions of the tool wear caused by the difference of the mechanical properties of the work piece materials.

Fig. 6 Chaos time series analysis results of each crack mode for stainless steel wire.

Results of chaos time series analysis

Figures 5 and 6 show the results of the chaos time series analysis of each crack initiation mode. The signs of the exponents in the Liapunov spectrum of three dimensions to the modes show a plus, nearly zero and a minus, respectively. Also it is possible to obtain the correlation dimension because the dimension of each mode converges to a constant value. Therefore, it is judged that the detected AE signals have the chaotic property.

Figures 7 and 8 show examples of the recurrence plots of the crack initiation modes. In these figures, the recurrence plots that were represented by the gradation and the monochrome colors, the iso-direction recurrence and the iso-direction neighbors plots are shown. Here, the recurrence plot is evaluated by the texture of the gradation colors and the comparison of the plotting densities of the plot and the iso-directional neighbors plot. In Fig. 7(a) and Fig. 8(a), it is clear that the space patterns are aperiodic and the textures are non-uniform. These show that the signals have the property of the unsteady behavior. From the results of Fig. 7(b)(d) and Fig. 8(b)(d), one finds that the detected signals have the property of the deterministic chaos, because the densities of the recurrence and the iso-directional neighbors plot were similar.
Therefore, it is concluded that the detected signals are not stochastically caused and are arising deterministically along some rules. From the above results, it was found that the extraction of the features of the signals and the observation of the behaviors of the features are effective.

Figure 9 shows the relationships between the largest Liapunov exponents and the correlation dimensions of both wires to the number of shearing. From the results, we find the following.

**Piano wire:** The largest Liapunov exponents of the crack initiation modes in the steady wear area show comparatively large values. However, the exponents decrease from the sign of tool life area and converge to constant values in the tool life area. This indicates that the chaotic property becomes strong in the first half of the steady wear where the multiple factors were mixed. Then, it becomes weak from the first half of the tool life area. The correlation dimensions of the crack initiation modes do not cross, and the dimensions show high values in the order of the tensile, the composite and the shear mode crack. Especially, the dimension of the shear mode crack reaches the maximum value near the tool life area. On the other hand, the dimensions of the tensile and the composite mode crack reach the maximum value in the steady wear area.
Fig. 8 Recurrence plots of AE signals on each crack mode for stainless steel wire.

**Stainless steel wire:** The largest Liapunov exponents of the crack initiation modes show relatively large values in the initial wear area. The exponents then converge to near 0.4 in the tool life area. Therefore, the chaotic property becomes weak when the wear grew and the tool was nearing its life. As in the piano wire, the correlation dimensions show high values in the order of the tensile, the composite and the shear mode crack. Therefore, it is possible to discriminate each mode by observing the dimensions. The dimensions of the tensile and the composite mode crack become the highest in the tool life area and exceed two. The dimensions are generally higher than the dimensions of the piano wire. It is believed that this phenomenon was caused by more ductile mechanical property of the stainless steel wire.

From the above results, it was proven that the chaotic property of the AE signals becomes weak regardless of the mechanical property of the workpiece materials when the tool is coming near a tool life.

**Evaluation by wavelet transform and waveform analysis**

It has been reported that a close relation exists between the fracture surface condition and the fracture energy. In short, the energy becomes smaller when the surface is smooth, and the
Fig. 9 Parameters of evaluating wear conditions with chaos time series analysis method.

Fig. 10 Features of detected AE signals and wavelet transform results of each crack mode for piano wire.

energy becomes larger when the surface is rough [13]. The relationships between the crack initiation modes and the AE signals’ features were investigated. As the features, the energy and the RA values for the time fluctuation waveforms of the wavelet coefficient from 50 to 500 kHz were employed. Figures 10 and 11 show the examples of the results, which show the following.

**Piano wire**: The energy of the time fluctuation waveforms of the wavelet coefficient of each crack initiation mode from 400 to 450 kHz shows large values in the order of the tensile, the composite and the shear mode crack. On the other hand, the RA values of the waveforms of each mode in the frequency range show large values in the order of the shear,
Fig. 11 Features of detected AE signals and wavelet transform results of each crack mode for stainless steel wire.

the composite and the tensile mode crack.

**Stainless steel wire:** The energy of the time fluctuation waveforms of the wavelet coefficient of each crack initiation mode from 350 to 400 kHz shows large values in the order of the tensile, the shear and the composite mode crack. On the other hand, the RA values of the waveforms of each mode in the frequency range show large values in the order of the composite, the shear and the tensile mode crack.

Figure 12 shows the relationships between the RA value and the energy to the number of the shearing. In this figure, the red circle shows a point, at which the RA value went beyond its maximum value (cf. white circle) in the initial wear area. The number of the shearing at the point belongs to the sign of tool life area.

**Piano wire:** The energy decreases with the growth of the tool wear. This is because the occurrence of the AE signal of the tensile mode crack that has the high energy decreased (cf. Fig. 4(a) and Fig. 10). Especially, the rapid decrease of the energy from the sign of tool life area is explained by the decrease of the tensile mode crack and the increases of the shear and the composite mode crack. The behaviors of the RA value and the burr length are similar (cf. Fig. 2). The RA value and the burr length rapidly increase in the two ranges. One of the ranges is from the initial wear area to the steady wear area and the other is from the sign of tool life area to the tool life area. The difference in both areas is that the former decreases after the increase while the latter converges on the maximum value after the increase. This is because the occurrence conditions of the crack initiation modes in both areas were different (cf. Fig. 4(a)). The wear of the side edge of the tool was the main cause on the increase of the clearance between the tool and the work piece in the initial wear area. This is because the wear of the tool tip greatly affects the burr length.

**Stainless steel wire:** The energy decreases with the growth of the tool wear. This is because the occurrence of the AE signal of the tensile mode crack that has the high energy decreased rapidly, and the occurrence of the signal of the composite mode crack that has the low energy increased rapidly (cf. Fig. 4(b) and Fig. 11). As in the piano wire, the behaviors of the RA value and the burr length are similar (cf. Fig. 3). In short, the
fluctuation of the RA value is severe in the initial wear area, becomes stable in the steady wear area and rapidly increases from the sign of tool life area to the tool life area. This is because more ductile wire is susceptible to extrusion.

From the above experimental results on the two kinds of the workpiece materials, we show the existence of a close relationship between the behavior of the RA value of the time fluctuation waveform of the wavelet coefficient and the growth of the tool wear.

**Evaluation System for Tool Life**

We constructed a tool life evaluation system, based on the RA value mentioned previously. Figure 13 shows the flow diagram of this system. Here, we propose to use the parameter $L_{wear}$.

$$L_{wear} = \left( \frac{RA_{MA}}{RA_{max}} \right) \times W$$

(2)

Here, the $RA_{MA}$ is the moving average of the RA value for a set of 500 shearing, the $RA_{max}$ is a maximum value of the $RA_{MA}$ in the last set, $W$ is the coefficient for representing the degree of the cumulative wear and its initial value was set at 3.5. The following sequences are done when the $RA_{max}$ was renewed: the cumulative index $w$ is added to $W$ and its initial value is 0.001; the increment value of 0.001 is added to $w$. The initial and increment values of $w$ were determined by the experimental results, of which there was the change in the tool wear condition at a shearing number of 1000 or more. The parameter $N$ in the execution part of the tool change shown in Fig. 13 is the number, of which the evaluation result was judged to be "Warning", and the tool is checked if the "Warning" continued 1000 times. The criteria shown in Table 1 were established so that several of the evaluations by $L_{wear}$ in the initial wear range become "Warning", because the wear condition in this range gives a large influence in tool life.

Figure 14 shows the evaluation results of the tool life by this system. In this figure, the relationships between the RA value and $L_{wear}$ to the number of the shearing are shown, and the wear conditions that were evaluated by the observation information (i.e., the burr length, the shearing stress and the shear plane condition, etc.) are shown on the top of the figure. In the
results, the execution part of the tool change shown in Fig. 13 was not carried out, and the shearing was continued until the tool life. The results indicate that the evaluation by Lwear is appropriate, because the evaluation results are similar to the judgments of the wear conditions, for which we used the following in each wear region: the evaluations in the initial and the steady wear region are "Safety" and "Warning"; the evaluations from the sign of tool life change to "Danger" from the "Warning" and to the "Tool life" from the "Danger". This system correctly evaluated the wear conditions for two kinds of wires having different mechanical properties.
Conclusions

For evaluating the tool wear conditions and the tool life, the feature extraction of the detected AE signals in the shearing of two kinds of wires was examined. We constructed the system that evaluates the tool life by the features based on RA values.

(1) The detected AE signals have the chaotic property. The wear conditions and the tool life can be evaluated by the largest Liapunov exponent and the correlation dimension, because the behaviors of both parameters in each condition (i.e., the initial wear, the steady wear, the
sign of tool life and the tool life area) have the expected features.

(2) The RA value of the time fluctuation waveform of the wavelet coefficient becomes larger in the range where the burr length rapidly increases. Therefore, RA value is one of the effective parameters for evaluating the tool wear conditions and the tool life. Here, the frequency ranges that should be used in the piano and the stainless steel wire are 400–450 kHz and 350–400 kHz, respectively.

(3) The system that evaluates the tool life by the RA value was constructed, and its validity was confirmed by the comparison with the experimental results.

References


