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Automatic detection of a damaged cutting tool during machining I: method to detect damaged bandsaw teeth during sawing

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Abstract This paper presents an on-line method for detecting damaged teeth in the bandsaw using acoustic emission (AE) signal energy. The method is based on an analysis of differences in AE energies generated by normal and damaged teeth during sawing. Because of the difference in the amount of sawing, the AE energy was low for sawing by the damaged tooth and high for sawing by the normal tooth immediately after the damaged tooth. The ratio of AE energy for two successive teeth – a normal tooth immediately following a damaged tooth – was much greater than 1, whereas the ratio of AE energy for two successive normal teeth was close to 1. The results demonstrate that the technique using the AE energy ratio for two successive teeth is effective for on-line detection of damaged bandsaw teeth.

Key words Acoustic emission · Damaged bandsaw teeth · Two successive teeth · AE energy ratio

Introduction

In recent years, more efficient sawing methods have been sought with the objectives of improving sawing accuracy, reducing kerf, and in turn increasing lumber yield. One way to achieve these objectives is to monitor the sawing process automatically. A possible method for automatically monitoring the sawing process is to use acoustic emission (AE) measurements, which have enabled on-line monitoring of the cutting behaviors for various cutting conditions.[1–4] Machining control systems using AE signals have been proposed to produce a desired surface finish by automatic control of the workpiece feed rate for circular sawing and routing.[5,6] Many researchers have used AE measurement techniques for identifying the wood machining process and sensing tool wear. [7–10] However, the use of the technique is limited to tool failure. The detection of tool failure, which includes cracking, chipping, and fracture of the tool during cutting, is more important than sensing tool wear. The reasons are that (1) tool failure is a stochastic process and is more difficult to predict and detect than tool wear, and (2) tool failure is apt to cause fatal damage to the product. Therefore it must be avoided or immediate measures taken once it happens.[11]

During actual production, bandsaw teeth are sometimes damaged by sawing pieces of metal, small stones, and unusually hard knots. A bandsaw with damaged teeth adversely affects the surface roughness, sawing accuracy, and other normal teeth. This study investigates the possibility of detecting damaged teeth on a bandsaw during sawing by using AE signal measurement technology.

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Experimental procedures

Cutting condition

The sawing was conducted using a woodworking bandsaw with 700 mm wheel diameter and a distance between the wheel axles of 1250 mm. The saw blades had a length of 4700 mm, width 75 mm, thickness 0.75 mm, gullet depth 5 mm, tooth pitch 20 mm, and number of teeth 235. Four saw blades were used in this experiment. One of them was the normal tooth, and the others consisted of one, two successive, and three successive damaged teeth. Figure 1 shows the damaged tooth in the bandsaw blade used for the experiment. The sawing velocity and the feed speed were kept at 13.3 m/s and 3 m/min in the experiment. The workpiece for the experiment was yellow poplar (*Liriodendron tulipifera* Linn.) with a moisture content of

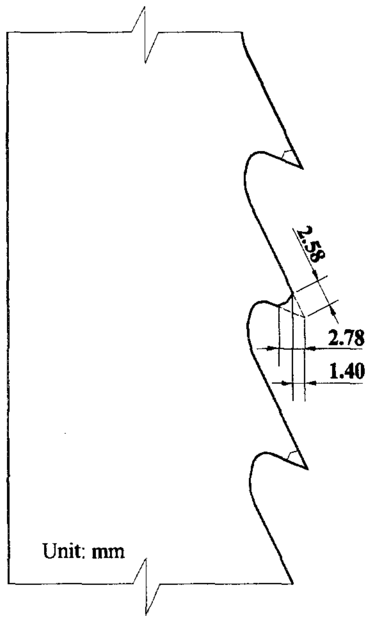

Fig. 1. Damaged tooth in the bandsaw blade

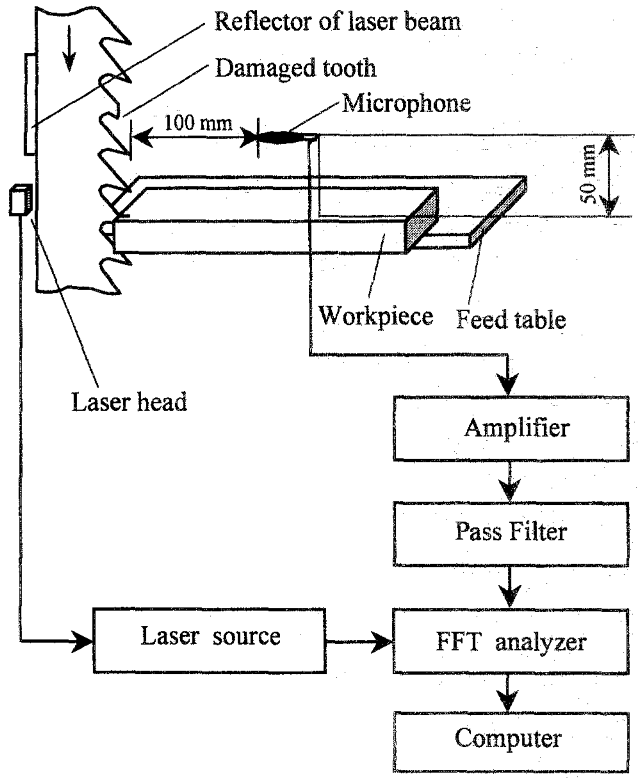

Fig. 2. Experimental setup used for acoustic emission (AE) signal acquisition, digitization, and processing. FFT, fast Fourier transform

12%–14%, specific gravity 0.51, thickness 20mm, and length 300mm.

AE signal measurement method

A microphone, amplifier, high-pass filter, fast Fourier transform (FFT) analyzer, and a personal computer were used to measure the AE signal, as shown in Fig. 2. The microphone was used as the AE sensor, which was positioned at a height of 50mm from the top of the workpiece and 100mm away in the front of the sawteeth. The microphone responded up to 100kHz with uniform sensitivity. The AE signal was measured on the frequency range between 35 and 100kHz through the pass filter. The FFT analyzer recorded data at a rate of 256 sample points per millisecond. The AE signal data recorded in the FFT analyzer were transmitted to the personal computer. The AE signal was measured for two cases. One was the AE signal for sawing by several teeth including the damaged teeth. The other was the AE signal for the whole sawing process.

A laser beam was used to recognize the AE signal for sawing by the damaged teeth. A reflector for the laser beam was attached on the back edge of the saw blade in line with the damaged tooth positions as shown in Fig. 2. This allowed measurement of the AE signal for sawing by the damaged teeth. The input laser intensity signal was connected to the trigger of the FFT analyzer to record the AE signal for sawing by the reflector portion of the saw blade. The laser beam was continuously energized during sawing. As soon as the laser beam hit the reflector, the size of the laser reflection signal suddenly reached a set level and automatically triggered the recording of the AE signal for sawing by the damaged teeth.

Results and discussion

Figure 3 shows the AE signal, AE energy, and AE energy ratio of two successive teeth from sawing by several teeth including a damaged tooth. A workpiece of 20mm thickness, which was equal to the tooth pitch of the bandsaw, was used to identify the AE signal generation per tooth. It was observed that the amplitudes of the AE signals for normal teeth (T_1, T_2, T_3, T_7) were almost equal. As tooth T_4 was missing its tip, it did not saw like a normal tooth. Therefore, the amplitude of the AE signal for T_4 was smaller than that for T_1, T_2, T_3, and T_7. As a result, the following normal tooth (T_5) had to cut an increased amount of wood to make up for the damaged tooth (T_4). Therefore, the amplitude of the AE signal from sawing by tooth T_5 was the largest. The amplitude of the AE signal for tooth T_6 was larger than that for teeth T_1, T_2, T_3, and T_7 because of the influence of the attenuated AE signal of tooth T_5.

The greatest problem encountered with application of AE is the analysis or interpretation of the emission signals obtained owing to the randomness of the AE process. An emission signal is nonperiodic, contains many frequencies, and cannot be described by an explicit mathematical relation.[12] Most current applications of AE in nondestructive testing use the ring-down count or count rate method of signal analysis. Although this type of analysis is both useful and easy to perform, it is subject to three criticisms: (1) The count is a function of signal frequency; (2) the count

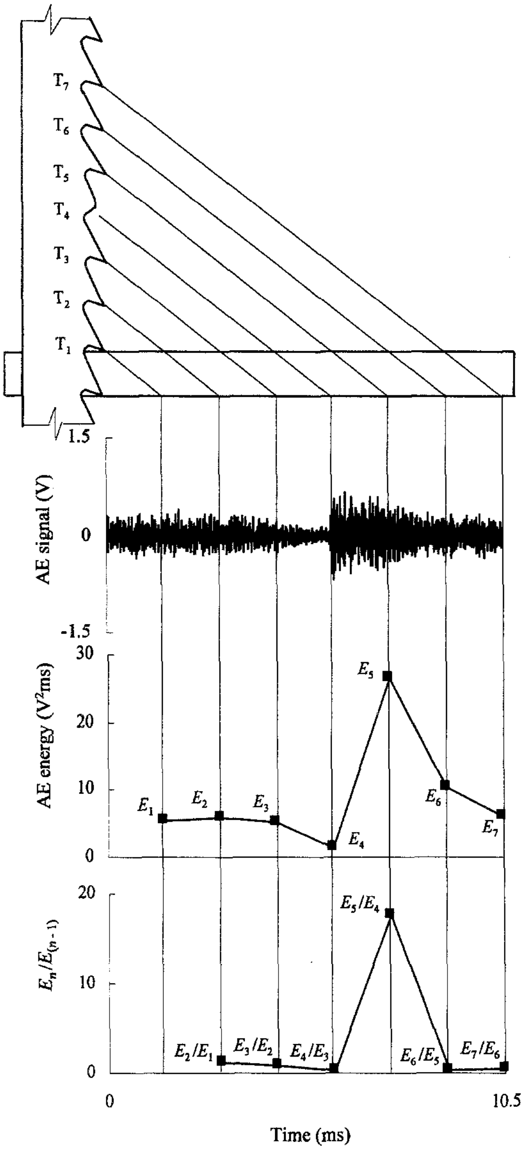

Fig. 3. AE signal, AE energy, and AE energy ratio of two successive teeth for several teeth including a damaged tooth. T_1–T_3 and T_5–T_7 are normal teeth; T_4 is the damaged tooth. E_1–E_7 are AE energy values for teeth T_1–T_7

considers signal amplitude only indirectly in that a large-amplitude signal often lasts longer than a low-amplitude signal; and (3) there is no direct relation between the count and a physically meaningful parameter. One of the primary methods for quantitatively presenting acoustic emission data is by measuring the energy of the AE signal.[13] In this study, the method of AE energy analysis was used.

The energy of a transient signal can be defined as[13]

$$D = \frac{1}{R}\int_0^{\infty} V^2(t)dt \tag{1}$$

where D is AE energy of a transient AE signal, $V(t)$ is the instantaneous voltage, and R is the input impedance of the voltage measuring circuit. In discrete form, which is suitable for digital processing, Eq. (1) becomes

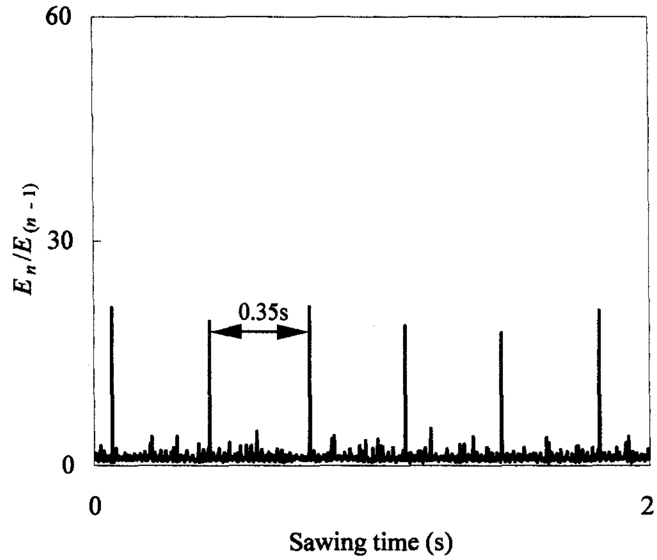

Fig. 4. AE energy ratio of two successive teeth during the sawing process by the bandsaw with a damaged tooth

$$E_R = \frac{\Delta t}{R}\sum_{i=1}^{m} V_i^2 \tag{2}$$

where E_R is AE energy during an interval time, V_i is the voltage at each sample point, and Δt is a time interval between samples. In this study, the time interval (Δt) for calculating AE energy is defined as the sawing time per tooth. That is, as the bandsaw velocity was 13.3 m/s and tooth pitch was 20 mm, Δt was 1.5 ms. Therefore, the number of sample points of the voltage was 384. Because the AE signal passed through the same circuit for the same period of time, the impedance R was not considered. The AE energy per tooth can be calculated by

$$E_n = 1.5 \times \sum_{j=1}^{384} V_j^2 \tag{3}$$

where E_n is the AE energy from sawing by the n^{th} tooth, and V_j is the voltage point in the n^{th} tooth sawing time. The ratio of AE energy (ΔC) due to sawing by two successive teeth, that is, by the n^{th} tooth and the $(n\text{-}1)^{th}$ tooth, can be calculated by the equation

$$\Delta C = \frac{E_n}{E_{n-1}} \tag{4}$$

In Fig. 3, E_1 to E_7 show the AE energy for teeth T_1–T_7. The AE energy showed the same tendency as the amplitude of the AE signal. That is, the AE energy was the smallest for tooth T_4 and largest for tooth T_5. The AE energy for the other normal teeth (T_1, T_2, T_3, T_6, T_7) was an intermediate value. The E_2/E_1, and E_3/E_2 ratios were approximately 1. The E_4/E_3, E_6/E_5, and E_7/E_6 ratios were less than 1. The E_5/E_4 ratio was about 18. This demonstrates that the AE energy ratio for two successive teeth can easily distinguish a damaged tooth, the normal tooth immediately after the damaged tooth, and other normal teeth.

Figure 4 shows the AE energy ratio of two successive teeth during the sawing process by the bandsaw with a

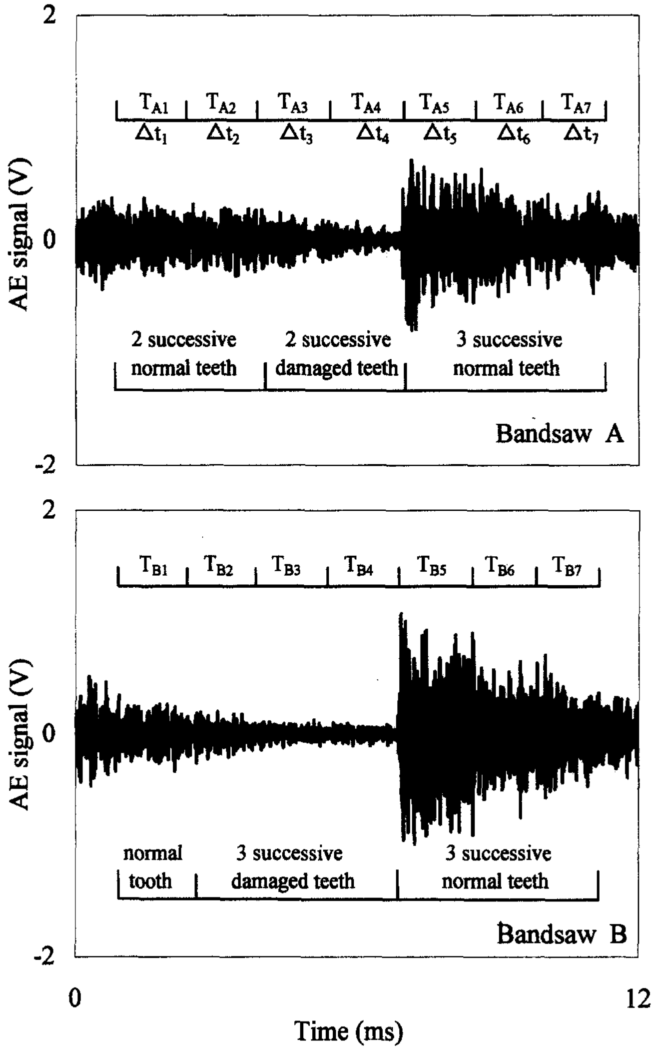

Fig. 5. AE signal due to sawing by several teeth including two (bandsaw A) and three (bandsaw B) successive damaged teeth. T_{A1}, T_{A2}, and T_{A5}–T_{A7} are normal teeth; T_{A3} and T_{A4} are damaged teeth; T_{B1} and T_{B5}–T_{B7} are normal teeth; T_{B2}–T_{B4} are damaged teeth. Δt_i, sawing time by tooth T_{Ai}, and T_{Bi} (i = 1–7)

damaged tooth. The ratio of AE energy for two successive teeth was calculated by Eq. (4). It was found that the ratio increased abruptly after every 0.35 s. This sawing time interval corresponded to the time for one revolution of the bandsaw. This behavior was caused by the fact that the ratio of AE energy for two successive normal teeth was almost 1, and that the ratio of AE energy for the damaged tooth and the normal tooth immediately following, was much greater than 1. Therefore, the periodically increased ratio is considered to be caused by the damaged tooth. This result indicates that the method to investigate the ΔC described above (ΔC method) is effective for on-line detection of a damaged tooth.

Figure 5 shows the AE signal for several teeth including two (bandsaw A) and three (bandsaw B) successive damaged teeth. T_{A3} and T_{A4} were two successive damaged teeth. T_{B2}, T_{B3}, and T_{B4} were three successive damaged teeth. Because all the damaged teeth did not saw like normal teeth, the amplitude of the AE signal for successive damaged

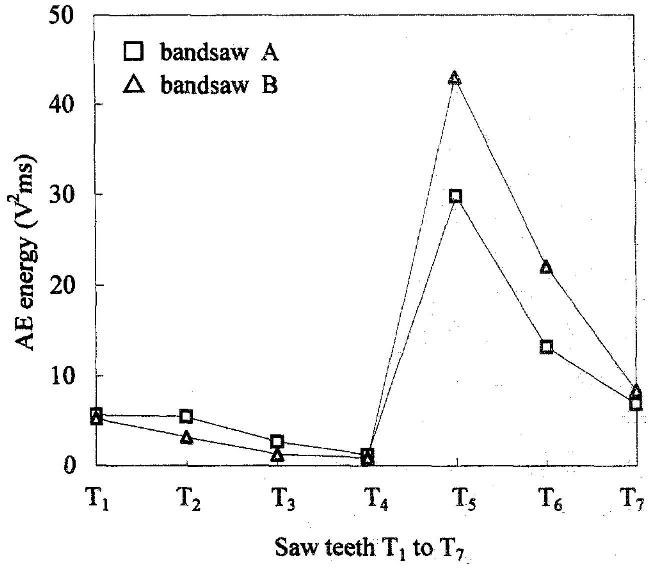

Fig. 6. AE energy for teeth T_1–T_7 of bandsaws A and B. T_1, T_2, and T_5–T_7 are normal teeth; T_3 and T_4 are damaged teeth in bandsaw A. T_1 and T_5–T_7 are normal teeth; T_2–T_4 are damaged teeth in bandsaw B

teeth decreased. The amplitude of the AE signal for tooth T_{B5} was larger than that for tooth T_{A5} because of the increased amount of sawing by tooth T_{B5}. Figure 6 shows the AE energy for teeth T_1–T_7 of bandsaws A and B. The AE energy was smallest for the sawing by the last damaged tooth, and the energy was almost the same for T_{A4} and T_{B4}. Among the normal teeth, the AE energy was largest for the normal tooth immediately after the damaged tooth, and the energy was larger for T_{B5} than for T_{A5}. Therefore, the AE energy ratio of E_{B5}/E_{B4} was larger than that of E_{A5}/E_{A4}. The ratio of AE energy for the damaged tooth and the following normal tooth increased with increasing numbers of successive damaged teeth for the number of damaged teeth investigated. Using this method may be difficult, however, for detecting the successive damaged teeth of the specific bandsaw with irregular tooth pitch. This problem will be discussed in further studies.

In the workpiece variables including earlywood and latewood, the number of growth rings, the density of the wood, and the knot size and distribution are believed to affect the amplitude of the AE signal. Therefore, application of the ΔC method was directed to a workpiece including knots. Figure 7 shows the AE signal, AE energy, and AE energy ratio of two successive teeth from sawing a workpiece with a knot by normal teeth T_1 to T_{50}. The knot appeared to have a great influence on the AE signal based on the experimental observation. The amplitude of the AE signal increased rapidly after sawing by the 24^{th} tooth, which began to saw the hard knot, because of its high density and the disorder of the fiber direction around the knot.[14] E_1–E_{50} represent the AE energy for teeth T_1–T_{50}. The AE energy showed the same tendency as the amplitude of the AE signal; that is, the AE energy was low for sawing the normal part and high for sawing the knot part. The AE energy for teeth after the 24^{th} tooth was often more than 10 times that for earlier teeth.

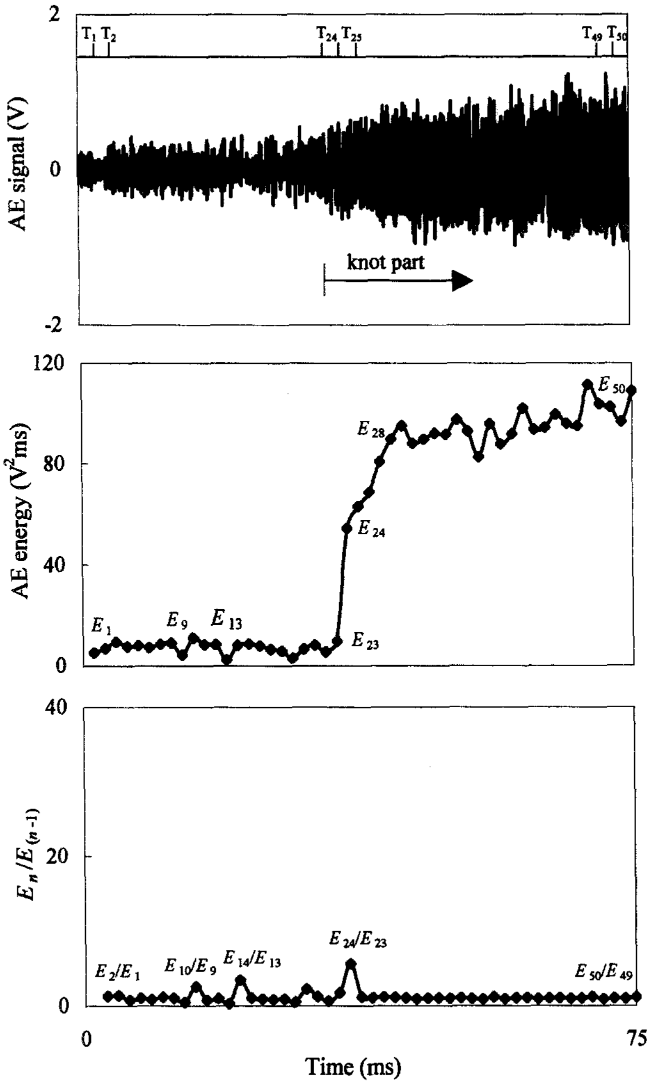

Fig. 7. AE signal, AE energy, and AE energy ratio of two successive teeth from sawing a workpiece with a knot by normal teeth T_1–T_{50}. E_1–E_{50} are AE energy values for teeth T_1–T_{50}

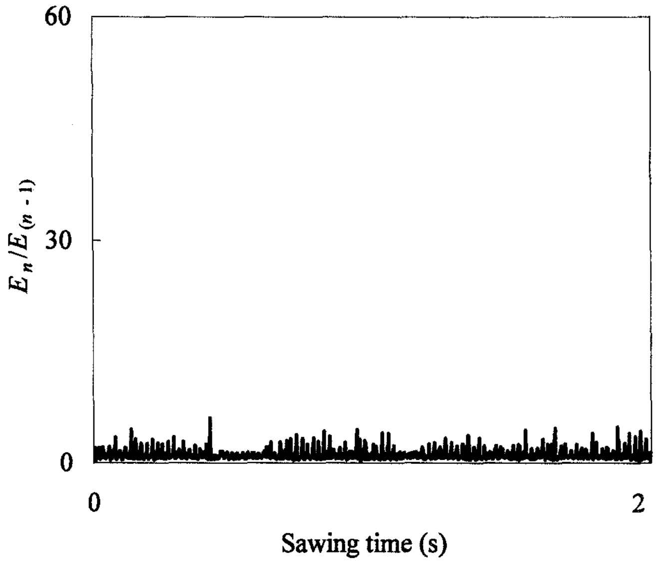

Fig. 8. AE energy ratio of two successive teeth during sawing of the part of the workpiece with a knot by the bandsaw with normal teeth

During sawing the normal part, the AE energy ratios of E_{10}/E_9 and E_{14}/E_{13} were between 1 and 5, respectively. This can be explained by the fact that the wood was not homogeneous in structure.

At the transition period from normal wood to the knot portion, the AE energy for successive normal teeth increased gradually. AE energy E_{23}–E_{28} for teeth T_{23}–T_{28} showed this phenomenon. The E_{24}/E_{23} ratio was about 5. This ratio was small comparing with the AE energy ratio for the damaged tooth and the normal tooth immediately following, as shown in Fig. 3. However, because of the complex wood structure in this part, the ratio for two successive normal teeth may be large, like that for a damaged tooth and the normal tooth immediately following, although this situation was not found in this experiment. If this situation occurs, the damaged tooth still can be detected by observing the periodically increased ratio due to the damaged tooth in sawing normal wood, as shown in Fig. 4.

While sawing the knot, the AE energy ratios from E_{28}/E_{27} to E_{50}/E_{49} for two successive teeth were nearly 1. This occurs because the AE energy for each tooth was high, however the difference in AE energy between two adjacent teeth was relative small.

During the transition period from knot to normal wood, the AE energy for successive teeth decreases. If the damaged tooth happens to saw this part, the ratio of AE energy for the damaged tooth and the normal tooth immediately following, may not be easily distinguished from that for two successive normal teeth. However, as described above, by observing the periodically increased ratio caused by the damaged tooth when sawing the normal part, as shown in Fig. 4, the damaged tooth still can be detected.

Figure 8 shows an example of the AE energy ratio of two successive teeth while partially sawing the part of the workpiece with a knot by the bandsaw with normal teeth. A periodic large value was not observed in the AE energy ratios (ΔC), though the AE energy for each normal tooth was high, as shown in Fig. 7. This phenomenon proves that knots do not influence use of the ΔC method for detecting a damaged tooth. The AE signal, AE energy, and AE energy ratio of two successive teeth when a knot was sawn by several teeth including a damaged tooth are shown in Fig. 9. T_1–T_7 were the same teeth as in the situation shown in Fig. 3. E_1–E_7 were the AE energies for teeth T_1–T_7. It was observed that the amplitude of the AE signal, AE energy, and AE energy ratios for T_1–T_7 showed the same tendency as described in Fig. 3. That is, the amplitude of the AE signal and AE energy for the damaged tooth (T_4) were the smallest, and those for the normal tooth immediately after the damaged tooth T_5 were the largest. The E_2/E_1 and E_3/E_2 ratios were approximately 1. The E_4/E_3, E_6/E_5, and E_7/E_6 ratios were less than 1; the E_5/E_4 ratio was about 14. Therefore, while sawing the knot, the AE energy ratios for two successive normal teeth and for the damaged tooth and the following normal tooth, can be distinguished.

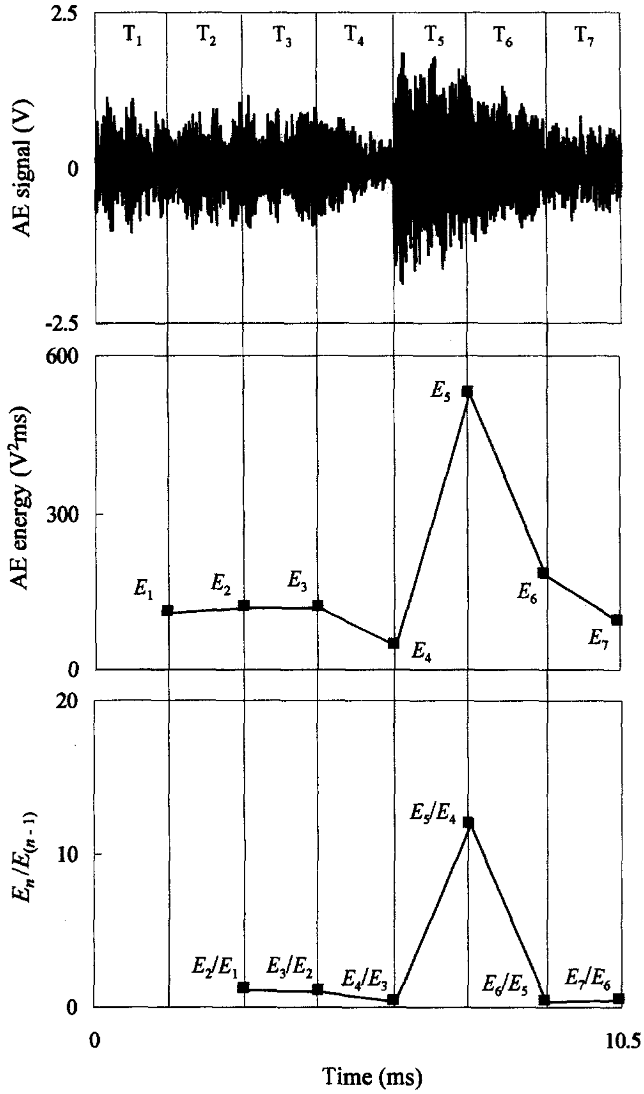

Fig. 9. AE signal, AE energy, and AE energy ratio of two successive teeth while sawing a knot by several teeth including a damaged tooth. T_1–T_7 are the same as those in Fig. 3. E_1–E_7 are AE energy values for teeth T_1–T_7

Figure 10 shows an example of the AE energy ratio of two successive teeth while partially sawing the part of the workpiece with a knot by the bandsaw with a damaged tooth. It was found that the ratio increased abruptly every 0.35 s. This time interval corresponded to the time for one revolution of the bandsaw. This means that the periodically increased ratio was caused by the damaged tooth. Therefore, this method, using the AE energy ratio for two successive teeth, is considered effective for on-line detection of a damaged tooth when sawing workpieces with and without knots.

Conclusions

The conclusions obtained in this study are summarized as follows.

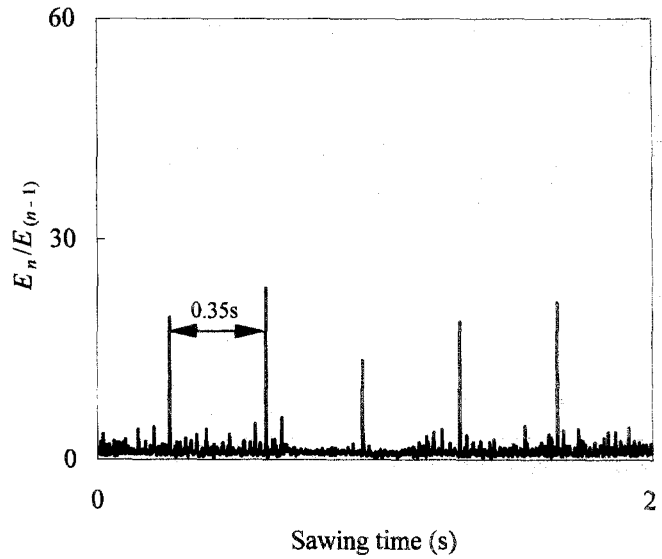

Fig. 10. AE energy ratio of two successive teeth during sawing of the part of the workpiece with a knot by the bandsaw with a damaged tooth. The length of the knot was about 25 mm

1. Because of the difference in the amount of sawing, AE energy was low for sawing by the damaged tooth and high for sawing by the normal tooth immediately after the damaged tooth. The AE energy ratio for the damaged tooth and the normal tooth immediately following, was much greater than 1. However, the AE energy ratio for two successive normal teeth was almost 1.
2. The AE energy ratio for the damaged tooth and the normal tooth immediately following, increased with increasing numbers of successive damaged teeth for the number of damaged teeth investigated.
3. The AE energy from sawing a hard knot was larger than that for normal wood. The AE energy ratio in a workpiece with a knot sawn by a bandsaw with a damaged tooth increased abruptly after a constant time interval, corresponding to the time for one revolution of the bandsaw.
4. It is possible to detect damaged bandsaw teeth automatically using the AE energy ratio for two successive teeth.

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