During the experiment, acoustic emission signals were collected as a noninvasive means to detect possible fracture types and to reveal subtle changes in the soldered structure under different soldering conditions. AE signals were detected by a Model R-30 sensor (Physical Acoustic Corp., Princeton, NJ, USA). To minimize the thermal damage while preserving the integrity of the signals of interest, a wave-guide made of high carbon iron was used between the acoustic sensor and specimen. Before each measurement, the surface of the upper part of the wave-guide was coated with vacuum grease (Dow Corning, Midland, MI, USA) to decrease the acoustic impedance before sensor attachment. The lower part of the wave-guide was then placed in contact with the specimen in a similar way. Signals from the acoustic sensor were amplified by a 40-dB preamplifier (type 1220A) along with a high-pass filter with the cut-off frequency set at 100 kHz. After digitization, the signal was processed by a MISTRA 2001 system (Physical Acoustic Corp.) for further analysis. The AE amplitude threshold was set at 50 dB; also the digital band-pass filter range was set at 100-400 kHz with a magnification factor of 20 dB (Fig. 1). To produce artificial soldering cracks, the specimen was soldered with pure flux powder. The AE amplitude threshold was set at 43 dB, with the band-pass filter range set at 10-400 kHz, and the sampling rate set at 4 MHz. In each experimental setting, acoustic signals recorded by MISTRA system were analyzed for counts/hits and energy/hits. Matlab version 5.0 (Mathworks, Natick, MA, USA) was used to analyze the spectra of AE signals.

The initial stage consisted of background AE collection for 10 s before heating the sample. During soldering, for all 3 flux concentrations (67%, 75%, or pure flux powder) and both soldering temperatures (1150 °C or 1200 °C), the temperature of the specimen was raised from room temperature to the preset temperature in about 2 s and was kept constant for another 5 s. After the power of the heat source was switched off, the specimen was then cooled to room temperature undisturbed. There were 3 distinct phases of AE signals observed, which corresponded to various heating stages during soldering: the heating period, the isothermal period, and the cooling period, which came to a total of

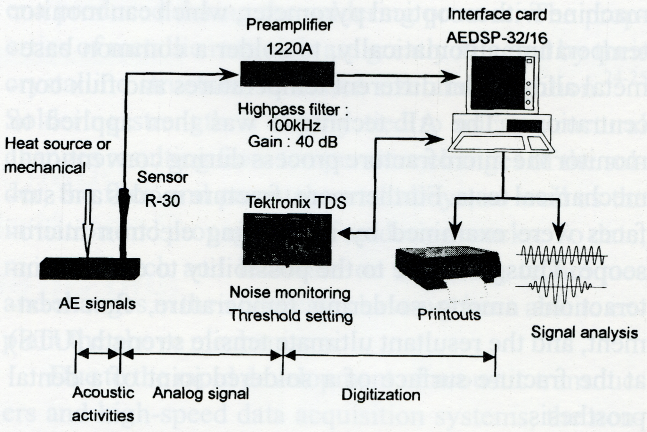

Fig. 1. Diagram of the acoustic emission detection system.

120 s for all 3 experimental periods.

Tensile test and SEM examination

After soldering, the specimen was ground to remove the residual flux and the oxidized layer on the soldered surface. Ultimate tensile strength (UTS) was evaluated by a load-testing machine (858 Mini Bionix, MTS System, Eden Prairie, MN, USA) with a crosshead speed of 0.05 mm/min. For all samples with visible fracture sites, the fracture mode and the fractured surfaces were examined under a scanning electronic microscope (S-2400, Hitachi, Tokyo, Japan).

For each experimental condition with 7 specimens, the mean and standard deviation of the UTS were calculated, and then analyzed using two-way ANOVA (CCS Statistica, Statsoft, Tulsa, OK, USA) to evaluate the experimental conditions of soldering temperature and solder flux concentration. Tukey's HSD test with significance set at the $p < 0.05$ level was chosen as the post-hoc test for further differentiation of the sub-levels of these main effects.

RESULTS

Acoustic emissions during soldering

During the heating period, AE signals with high counts and energy values were detected in the time domain, with the amplitude threshold of acoustic emis-