

Automatic Event Detection in Noisy Environment for Material Process Monitoring by Laser AE Method

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Abstract. Laser acoustic emission (AE) method is a unique *in-situ* and non-contact non-destructive evaluation (NDE) method. It has a capability to detect signals generated from crack generation and propagation, friction and other physical phenomena in materials even in high temperature environment. However, laser AE system has lower signal-to-noise ratio compared to the conventional AE system using PZT sensors, so it is difficult to apply this method in noisy environment. A novel AE measurement system to detect events in such difficult environments was developed. This system could continuously record all AE waveforms and enable unrestricted post-analyses. Noise reduction filters in frequency domain coupling with a new AE event extraction using multiple threshold values showed a good potential for AE signal processing. This system was successfully applied for crack monitoring of plasma spray deposition process of ceramic coating.

1. Introduction

Non-destructive evaluation (NDE) methods for process monitoring have many advantages, such as precise controlling of processes and detection of accidental failures, *etc.* In this field, AE method is one of important candidates because it provides *in-situ* monitoring, which can detect various physical events in solid materials *e.g.* crack generation and propagation. Piezoelectric zirconate titanate (PZT) sensors are generally used as AE sensors, however they have applicable temperature limit up to their Curie point. Laser AE method is one choice for high-temperature monitoring. Since laser interferometers are used as AE sensors, non-contact measurement becomes available. However, there still has a problem about signal-to-noise ratio due to noises generated during process monitoring. Their sources and intensities change frequently along a progress of processes. Recently, a novel system called, “Continuous Wave Memory” (CWM), has been developed for detection and analysis of AE waveforms. The CWM system has a capability to continuously record all AE waveforms during the whole measurement time and this makes post-analysis of AE waveforms flexible such as re-configuration of noise filters and threshold voltages.

Thermal barrier coatings (TBCs) with yttria-stabilized zirconia (YSZ) top coat deposited by atmospheric plasma spraying (APS) have been widely used to protect metal substrate from heat and wear damages. In this top coat, vertical cracks were induced during deposition process to improve performance and durability of TBCs [1]. For the sake of process controlling, it is important to monitor the crack generation during APS deposition, however, there are few methods applicable for *in-situ*



monitoring. Our previous study has shown that the deposition of Al_2O_3 top coat was successfully monitored by laser AE method [2]. However, AE monitoring during deposition of YSZ top coat was more difficult because AE events generated in YSZ top coat are less numbers and smaller amplitudes than those in Al_2O_3 top coat due to higher toughness values of YSZ. In this study, we applied laser AE method to investigate crack generation during APS of YSZ top coat. An improvement of signal processing based on multiple-threshold method for AE event extraction was carried out and the potential of these methods were discussed.

2. Experimental Setup

Figure 1 shows the experimental setup of a specimen and experimental equipment. The substrate of the specimen was an Inconel® 601 (Nilaco Corp.) disk with a diameter and a thickness of 30 and 5 mm, respectively. The top surface of the substrate was grid blasted to increase the adhesion between the substrate and the bond coat while the bottom surface was mirror-finished polished to improve the reflectance of a laser beam for better detectability of laser AE. CoNiCrAlY particles (AMDRY 9954, Sulzer Metco Ltd.) were preliminary deposited as a bond coat by the high velocity oxygen fuel (HVOF) spray method. Then, the prepared specimen was fixed to the internal jig as shown in figure 1(b). The external and internal jigs were separated and vibration insulator was attached. The jigs were carefully installed to avoid superfluous vibration and laser scattering by suspended particles. A plasma torch (SG-100, Praxair, Inc.) scanned over the specimen with a speed of 50 mm/s (figure 1(c)). YSZ particles (K-90, Showa Denko K. K.) were sprayed through a hole on the external jig with a diameter of 40 mm just over the specimen. Temperatures were also measured by type K thermocouples with a frequency of 100 SPS (samples/s).

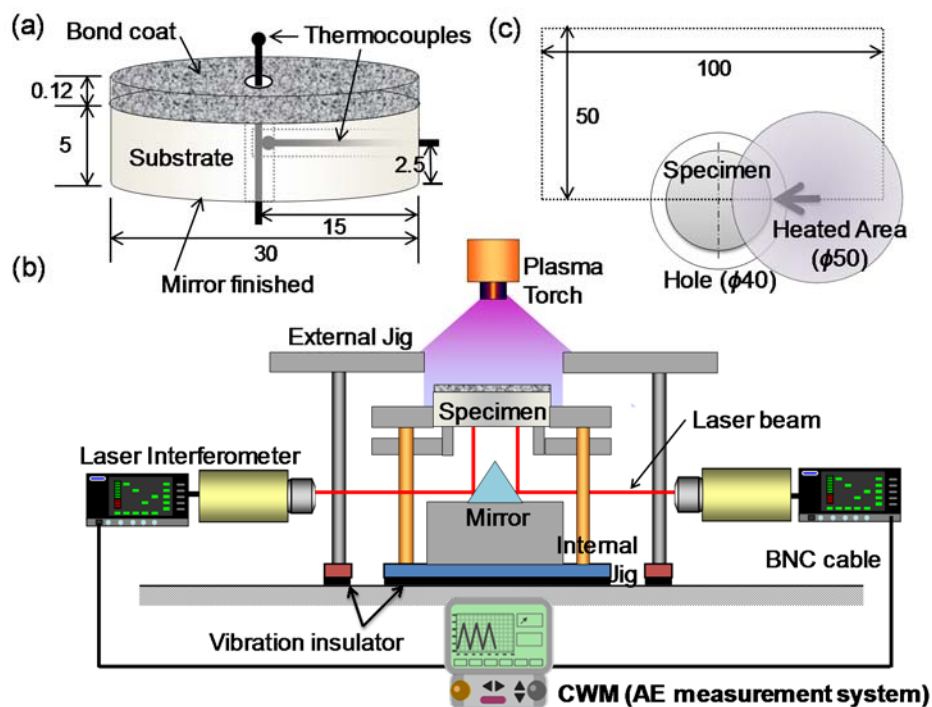


Figure 1. Experimental setup for laser AE monitoring of APS process.
(a) Specimen, (b) Equipments, (c) Scanning path of the plasma torch.

Four laser interferometer units (AT3600S and AT0022, Graphtec Corp.) were used as AE sensors. All laser beams were focused on the bottom surface of the specimen to monitor the speed of out-of-plane vibration (figure 1(b)). The output signals of the laser interferometers were continuously recorded by CWM with a frequency of 10 MSPS. Sampling resolution and range were 12 bit and ± 5

V, respectively. Synchronized analog-to-digital converter boards (PCI-3525, Interface Corp.) and parallelized hard disk drives (HDDs) were used in CWM for this sampling.

3. Results and Discussion

Figure 2(a) show an example of short time Fourier transform (STFT) of detected signal. It was evident that STFT is helpful method to separate valid signals from noise by their frequency characteristics. The noise filter was applied by following equation [3, 4]

$$I_1(t, f) = \max\{0, I_0(t, f) - \lambda(f)\} \quad (1)$$

where t is time, f is frequency, I_0 and I_1 are the intensity matrix before and after the filtering and $\lambda(f)$ is a subtraction value for noise reduction (NR). When $\lambda(f)$ is sufficiently large in some frequency band, the above equation behaves as a frequency filter. It also behaves as a background noise filter when $\lambda(f)$ is an appropriate value in entire frequency band. By apply this filter with $\lambda(f) = \infty$ for $f < 100$ kHz and $\lambda(f) = 3000$ a.u. for $f \geq 100$ kHz, the noise as shown in figure 2(a) could be removed and the result is shown in figure 2(b). Since noises fluctuated over the monitoring period, continuous recording enabled post-configuration for optimization of NR filter based on confirmation of frequency characteristic of actual waveform. After NR, the intensity matrix was converted into the waveform for further analysis by inverse STFT method.

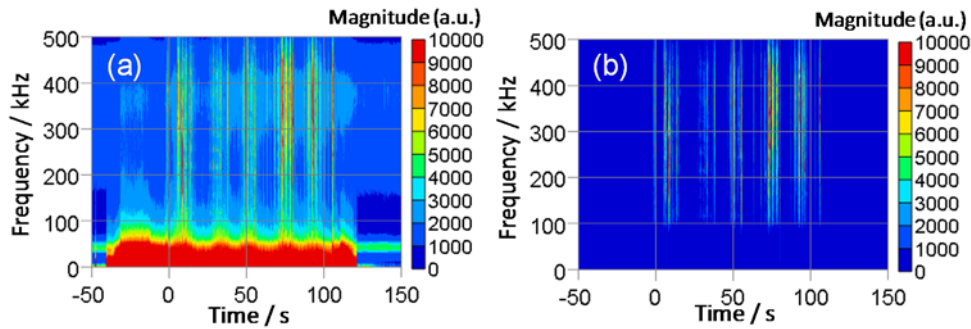


Figure 2. Time-frequency-intensity matrix (a) before and (b) after the NR filter.

Figure 3 shows a schematic of hit detection method in this study. In general, start and end time of an AE hit are decided by AE count, *i.e.* threshold crossing. However, decision of the last count is difficult if the waveform is noisy or hits occur frequently. Therefore, false recognitions might be occurred, *e.g.* a long duration hit is recognized as multiple hits and/or a series of short duration hits are recognized as one unified hit. To overcome this problem, the end of an AE hit is determined as

$$\Delta t_s \geq a \cdot \min\{\Delta t_{\text{Max}}, \max(\Delta t_{\text{Min}}, \Delta t_d)\} \quad (2)$$

where Δt_s is silent time (time from the end of the last count), a is a pre-set ratio, Δt_d is duration of a hit (time between the first and the last count), Δt_{Min} and Δt_{Max} are limiters of Δt_s . When the last AE count is identified after Δt_d period the first count, the end of this hit will be decided if there is no AE count until $a\Delta t_d$ period from the last count. If an AE count is detected in this time, Δt_d is extended to the new last AE count and the judge will be restarted. The value of Δt_d increases with lower threshold voltage (V_{th}). However, when V_{th} is lower than the noise level, inequality (2) is not satisfied and no AE hit will be detected (figure 3(b)). In this study, the default values of a , Δt_{Min} and Δt_{Max} were set as 0.5, 100 μs and 10 ms, respectively. The selection of suitable V_{th} is very important for AE extraction. Generally, a low fixed value of V_{th} is preferred when the noise level is sufficiently low and stable, however, this is not practicable for fluctuated-noise environment. In this study, multiple-threshold method was used for AE hit and event detection

Figure 4 showed an example of AE events detection during some part of an experiment by multiple-threshold method (50, 80, 100 and 150 mV). It is noted that events shown in this figure were simultaneously detected from at least three channels. No events were detected with $V_{\text{th}} = 50$ mV

because this V_{th} was always lower than the noise level. The numbers of events with V_{th} of 80, 100 and 150 mV were two, three and seven, respectively. The V_{th} of 80 mV was available only when the noise level was relatively low. In contrast, AE events with small amplitudes were discarded with V_{th} of 150 mV even if the noise level was sufficiently low. It is clear that the number of detectable AE events decreased by using one fixed V_{th} . The multiple-threshold method showed a potential to extract more detectable AE events by summation of all detected events from each V_{th} . This method also provided an automatic AE event detection without manual adjustment of V_{th} .

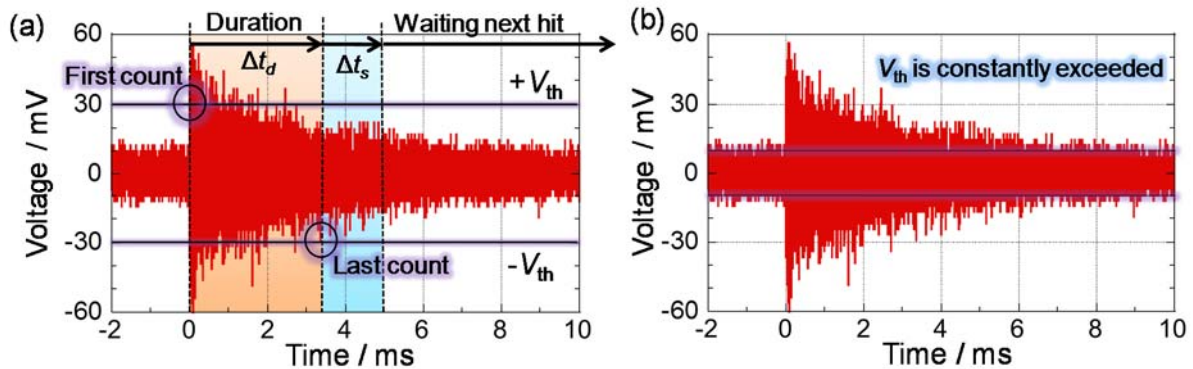


Figure 3. Schematic of AE hit detection with (a) high and (b) low threshold voltages.

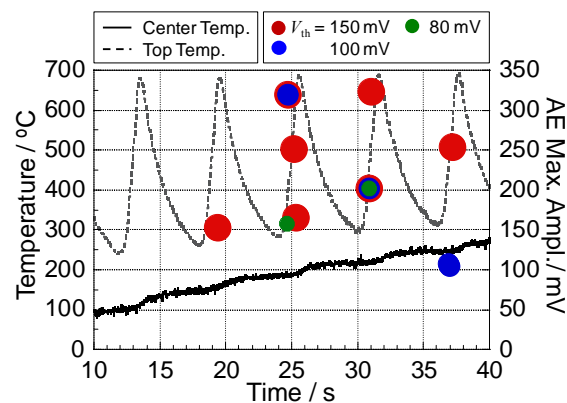


Figure 4. Temperature history during APS and AE events which were detected by multiple-threshold method.

4. Conclusions

Continuous waveform recording enabled the flexible and strong filters for NR in frequency domain. A combination of frequency filter and background noise filter was effective to improve the signal-to-noise ratio. Multiple-threshold method for AE hit and event detection made it possible to follow fluctuating noise level during a noisy manufacturing process of materials such as plasma spray.

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