AE Monitoring in Surface Treatment of Materials

Manabu ENOKI
Department of Materials Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan; enoki@mme.mm.t.u-tokyo.ac.jp, tel.+81-3-5841-7126, fax +81-3-5841-7181

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Abstract

Ceramic thermal barrier coatings (TBCs) by atmospheric plasma spraying (APS) process have been widely used to add good heat resistance to metal base materials. It is well known that horizontal delamination cracks and vertical segmentation cracks occur in the coating during the APS process and these cracks affect the reliability of the coating. However, health monitoring of the APS process itself is very difficult because spraying machine emits large noise and high heat.

Shot peening is also one of the surface treatment methods to improve the materials properties such as fatigue strength by shooting of balls on the surface of products in order to generate a compressive stress. However, there are a few researches on quantitative evaluation between shot conditions and mechanical properties of products, and the optimal shot conditions are determined through a try and error process.

In this study, a new AE system was developed to detect the cracks during the APS process. This system realized noncontact and noise resistance by utilization of laser interferometer and our original continuous waveform measurement and analysis equipment. All AE signal was continuously sampled and stored during the whole APS processing time. After that, several types of noise were cut and both delamination and segmentation cracks were detected from the continuous waveform by software signal processing. AE signals were also measured during shot peening and impact energy was evaluated in various shot conditions. AE source location technique was very useful to estimate the impact location of shot balls and the number of impact was constituent with the detected number of AE signals. Quantitative source model for impact was proposed and the energy balance for each impact was analyzed using the inverse analysis of AE signals.

Introduction

Acoustic emission (AE) method is one of the in-situ NDE methods and may be adapted to the detection and evaluation of material processing. However, there are some difficulties to measure effective AE. For example, conventional AE methods which use piezoelectric sensors are difficult to apply because the temperature of the specimen during atmospheric plasma spraying (APS) process often exceeds the Curie temperature of the sensors. Therefore, the non-contact laser AE method which uses laser interferometers as sensors is effective to monitor the APS process. Our research group already reported laser AE monitoring during thermal cycling of ceramic coatings and also applied laser AE method to detect the cracks in ceramic coatings during cooling period after the plasma spraying process. [1-3] However, these previous studies could not monitor the spraying process itself because of large noise from APS system. Therefore, our original AE measurement and analysis system “Continuous Wave Memory” (CWM) was modified for this study to detect damages during APS process. [4] Conventional AE measurement system needs a preset threshold voltage and noise filtering to detect AE events from noisy environment. In contrast, the CWM system can continuously record the signals from sensors to hard disks during a whole experimental time. This recording method enables flexible and thorough analysis of AE characteristics after the experiment as many times as needed. CWM was also implemented with a set of powerful signal processing methods for the continuous waveform such as time-frequency analysis and frequency filter with spectrum subtraction.
Shot-peening is a common procedure to improve the fatigue life of metal components. [5-7] In this process, relatively hard particles are projected to the target surface progressively, and there are indentations on the surface as a result of local plastic deformation. [8-10] This compressively stressed layer is highly effective in preventing premature failure under conditions of cyclic loading since the fatigue failure generally propagates from the free surface of a target and usually starts in a region which is subjected to high tensile stresses. [11, 12] However, there are few quantitative references about processing conditions and the quality of products. It is an issue in which processing conditions of every machine and products are decided by trial and error in manufacturing scene. In this work, we measured and analyzed AE which generates due to particle impact on a metal specimen, and obtained the impact force quantitatively.

**Damage evaluation during air plasma spraying process**

Figure 1 shows the schematics of AE monitoring during the top coating process. For protection of the optical components, two jigs were provided as external and internal, both of which were attached to the shock absorbers at the bottom to protect the specimen from superfluous vibration. The “external jig” held a steel cover plate to guard the internal equipments. The cover plate had a hole in the center with 40 mm in diameter. The position of the external jig was carefully adjusted so that the plasma jet would hit only the specimen through this hole. Meanwhile, the internal jig was a table made of steel and brass, and it held the specimen and the pyramid mirror, which reflects the four channels of laser beams to the bottom surface of the specimen. The specimen was fixed to the internal jig at three points on its side surface not to be shaken by the plasma jet. Alumina powder (K-16T, Showa Denko K.K.) was sprayed as the top coating over the bond coating. The plasma spray gun scanned over the specimen by 80 mm x 90 mm area with 150 mm/s velocity and 5 mm pitch. In the following manuscript, the one time scanning of this area is called “one pass”. The temperature of the specimen was monitored by a type K thermocouple inserted into the hole in the specimens and was recorded by the data logger (NR-1000, Keyence Corp.).

![Fig. 1. Four channel laser AE monitoring equipments of APS process.](image)
Fig. 2. Temperature history during 30 passes heating without powder feeding.

Fig. 3. Typical temperature history and AE events during APS process (Gun speed: 150 mm/s).

Four channels of heterodyne laser Doppler interferometers were used as AE sensors in this study. One channel of AE sensor consisted of a class 3B He-Ne laser head unit (AT0022, Graphtec Corp.) and a demodulation unit (AT3600S, Graphtec Corp.). The laser beam was continuous wave with 2 mW power. Sensitivity of the demodulation units was 1 mm/s/V. Detectable frequency range of the laser interferometer was up to 400 kHz. Emitted laser beams were reflected by the pyramid mirror, focused on the bottom surface of the specimen and reflected back onto the same paths. Output waveforms from the laser interferometers were continuously sampled by the CWM system with 10 MHz frequency, bipolar 5 V range and 12 bit resolution and stored into hard disk drives. The recorded waveforms were analyzed by the internal software of the CWM system. At first, the recorded continuous waveforms were analyzed by short time Fourier transform (STFT) method to obtain the spectrograms, i.e. time-frequency characteristics. Since STFT is a quicker calculation method than other time-frequency
Fig. 4. Another example of temperature history and AE events during APS process.

analysis methods, such as wavelet transform method, it should be adaptive for analysis of long waveforms. In this study, the continuous waveform was split into short parts with 1024 samples length and each part was processed by the fast Fourier transform (FFT) method. Consequently, the frequency resolution of this STFT processing became about 10 kHz because the sampling frequency was 10 MHz.

Figure 2 shows the temperature history of a test without powder feeding. No AE event was detected from three times of tests with 28 passes of heating. Therefore, it was confirmed that 1) there was no false detection of noise as AE events, 2) no AE was detected from the bond coating and 3) AE event which was detected during spraying with powder should be assumed due to cracking inside of the top coating or at its interface with the bond coating. Figure 3 shows the temperature history and AE events with the standard condition, i.e. 150 mm/s of gun speed, 20 passes spraying and 800 A of plasma output. Each bubble mark shows one AE event with its occurrence time, maximum amplitude and peak frequency which was calculated by the Gabor wavelet transform. In this case, the temperature of the specimen went down after the largest AE event at 151 s even during spraying. Furthermore, it was visually observed that a large part of the top coating was already delaminated immediately after the end of spraying. Therefore, the AE event at 151 s should be caused by a large delamination of the top coating. Interruption of the heat conduction from the top coating to the substrate by this delamination is considered to be the cause of the temperature decrease. Figure 4 shows another result of a test with the same standard condition as the previous one. Delamination of the top coating was not observed visually at the end of spraying in this test. However, AE events were detected during spraying. Therefore, these AE events might be due to subsurface cracks during spraying. In the cooling period after that, large AE events were detected and finally all of the top coating was delaminated. Figure 5 and 6 show the result of tests with different gun speeds from the case of figure 4. The numbers of passes in these tests were adjusted to make the top coating with the same thickness in the all tests. Then, the activity of AE was higher when the gun speed was slower. It was considered that a slower gun speed made large temperature fluctuations during spraying, which provided a more severe environment for the top coating and induced delamination events in the top coating. These results clearly indicate that AE measurement during plasma spraying is essential for understanding and control of the cracks in the ceramic coatings because AE events can be detected both during the spraying and the cooling period thereafter and analyzed to provide detailed information of each event such as its timing, location, amplitude and peak frequency.
Fig. 5. Temperature history and AE events (Gun speed: 75 mm/s, 10 passes of spraying).

Fig. 6. Temperature history and AE events (Gun speed: 300 mm/s, 40 passes of spraying).

Fig. 7. (a) Shape of specimen for shot peening and (b) position of sensors and projection region.
Impact force evaluation during shot peening process

Three types of steel balls with different diameters were used as shot particle. They were projected by a centrifugal shot peening machine. SCM440 was selected to target for projected particles. Four sensors were used to measure AE. The shape of the specimen, sensors position and projection region are shown in Fig. 7. Particles through the cover impact the upside of the specimen, and bounce to fall in the receiver. The number of impacted particles (not projected) was estimated by measuring the weight of receiver. Sensors caught the elastic wave which comes from the impact of the specimen and particles as an AE event, and the rubber shuts out the noise waves which come from the impact of the cover and particles. Continuous Wave Memory (CWM) was also used to detect and analyze AE waveforms. All AE waveforms were recorded continuously at a sampling rate of 10MHz. Two kinds of experiment were conducted. First, it was checked whether AE waveforms change or not before and after shot peening process. One million of SB-6 particles were projected at a velocity of 50 m/s. Second, the difference of AE waveforms with different particle size and projection velocity was observed. The projection condition is following, particle size is 3 levels, SB-10, SB-6 and SB-3, velocity is 6 levels, 30, 40, 50, 60, 70 and 80 m/s with each particle size. Ten thousand of particles were projected for each condition.

Figure 8 shows the projected surface before and during and after shot peening process. Rough surface area increased as more particles projected. The coverage rose above the 100% when 700 thousand particles projected. Figure 9 shows the first peak amplitude and WT peak frequency as a function of number of projected particle, respectively. Both are around uniform value through the process, in spite of the plastic deformation of the surface. The difference of AE waveform is thought to be hidden, because the effect of elastic impact is highly larger than plastic deformation. So, we can measure the effect of projection condition without regard to surface deformation. In this experiment, one million of particles were projected in total, about 29255 particles impacted on the specimen; the number was calculated by measuring the weight of the receiver. Meanwhile, the number of the detected AE events was 29984. The two values are very near. With AE method, we can estimate the number of the impact of particles.

A waveform $V$ detected by sensors is the convolution of input force function $F_j$, propagation function in the specimen $G_{ij}$ and response function of sensor $S_i$, as expressed in equation (1).

$$V(x', t) = S_i(x', t) * G_{ij}(x', x, t) * F_j(x, t)$$

(1)

Therefore, input force function can be derived from detected AE signal by deconvolving the propagation function and the response function. [13] The propagation function was derived by calculating with FEM model, and the response function of the sensors was derived by
Fig. 8. The projection region of the specimen, (a) before projected, (b) after 10 thousand of particles projected, (c) 30 thousand, (d) 100 thousand, (e) 300 thousand and (f) one million.

Fig. 9. The first peak amplitude change and WT peak frequency change during shot peening.

Fig. 10. Detected waveforms and inverse analysis result for impact force.

Fig. 11. Relation between impact duration time and WT peak frequency (left), and the first peak amplitude of the waveform data and kinetic energy plot (right).
deconvolution of lead broken experiment and simulation. Four detected events from different project conditions were chosen to analyze the impact force. Figure 10 shows the detected waveform and deconvoluted result due to an impact force by the impingement of a particle and the specimen. The validity of these results is confirmed in following two ways. Fig. 11 is the graph of the duration time of the impact force and WT peak frequency of the waveform. The impact time is in inverse proportion to the WT peak frequency. For deriving the kinetic energy of each data, the velocity is known, but the mass of each particle is not known. So, in order to estimate the value of mass, the mass from the impact forces in Fig. 11 was calculated by applying momentum conservation law. The first peak amplitude of waveform data and kinetic energy were plotted in Fig. 11. These four points exist around the approximate curve, and they are consistent with the mean experimental value. These comparisons demonstrated that the impact force results seem to be valid, and the impact force could be derived by this analysis.

Conclusions

AE method was applied to two types of material processes such as thermal spray coating and shot peening. Non-contact AE measurement with laser interferometer could detect AE due to delamination and cracking in ceramic coatings, and it was concluded that process condition could strongly affect to damage process. Impact force of particle could be quantitatively evaluated by inverse analysis of AE waveform. This result will be applied to obtain the optimal peening condition. It was demonstrated that AE was very promising to condition monitoring for materials processing.

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References