Detection of AE Events due to Cracks in TBC during Spraying Process

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Cracks may occur inside a top coating or at an interface between the top and bond coating of the thermal barrier coating (TBC) during atmospheric plasma spraying (APS) process. The acoustic emission (AE) method is suitable for detection of the generation and propagation of these cracks because it is an in-situ non-destructive evaluation technique. However, AE monitoring of APS process is prevented by large acoustic noise at elevated temperature on a specimen due to heating by the plasma jet. Therefore, a non-contact laser AE method with a newly developed measurement and analysis system was used for monitoring of the top coating process. Several types of noise reduction processes such as soft-thresholding were applied to continuously recorded AE waveform. Experiments were conducted with various preheating temperatures and scanning speeds of the plasma torch. AE events due to cracking were detected only during spraying, on the other hand no events were detected after spraying. The effect of preheating temperature and scanning speed of the plasma torch on the development of cracks were estimated. A correlation was observed between the density of delamination cracks and the number of AE events.

1. Introduction

Thermal barrier coatings (TBC) are one of the most widely used heat shields on the structural components which are used in high temperature environments such as turbine blades. TBC generally consists of an oxide top coating for thermal insulation and a bond coating beneath the top coating for oxidation resistance. Even though atmospheric plasma spraying (APS) is often used in industry to fabricate the top ceramic coating, cracks may occur inside the top coating or at the interface between the top and bond coating during plasma spraying. Already several non-destructive evaluation (NDE) methods such as ultrasonic testing and X-ray testing have been applied to find cracks in ceramic coatings.\(^{1,2}\) However, since those ex-situ NDE methods can find only existing cracks, an in-situ NDE method such as acoustic emission (AE) method is needed for process monitoring to detect occurrence and propagation of cracks.

However, high temperature of a specimen and the large acoustic noise which are generated by the plasma jet prevents such AE monitoring of APS process. Surface temperature of the specimen can easily exceed the Curie point of piezoelectric transducers (PZT) during spraying, which is the upper limit of working temperature of conventional AE sensors. The non-contact laser AE method,\(^{3,4}\) which utilizes a laser interferometer as a sensor is one of the solution to overcome this problem. Nishinori et al. and Taniguchi et al. applied this laser AE method for detection of delamination in alumina coatings during cooling period just after APS process.\(^{5,6}\) However, these previous studies could not monitor the whole spraying process because of extremely large noise during spraying.

Therefore, a novel AE measurement system called Continuous Wave Memory (CWM)\(^3\) was developed in our group. In a conventional AE measurement system, a threshold voltage for detection of AE events and some parameters for noise reduction must be set before experiments and hence cannot be changed after the measurements. This procedure makes difficult to analyze AE waveforms with low signal-to-noise ratio. In contrast, the PC-based CWM system can continuously record the signals from sensors to hard disks throughout the whole experiment time. Post analyses of the recorded waveforms with various parameters were enabled. In our previous study, alumina top coating process was successfully monitored by the laser AE method with a CWM system.\(^{8,9}\) However, AE events could not be detected from yttria-stabilized zirconia (YSZ) top coating process of TBC using the same experimental setup because of weak signal amplitudes due to smaller thermal expansion coefficient mismatches among the top coating, bond coating and substrate, and higher strength of the YSZ top coating than that of the alumina coating.

In the present study, further improved noise reduction process and AE event detection method were applied to monitor the damage of the YSZ coating process of TBC.

2. Experimental Procedure

Substrate was a disk of Inconel\(^\text{®} \) 601 with 30 mm in diameter and 5 mm in thickness. The bottom surface of the substrate was mirror finished to reflect laser beams. The top surface of the substrate was grid blasted by abrasive powder (alumina, #36, JIS R6001 compliant) to increase the adhesion between the substrate and the bond coating. Two holes with 1.8 mm in diameter were drilled into the specimen for temperature monitoring by type K thermocouples during the top coating process. One is from the side to the center and the other is a through hole from the top to the bottom.

At first, CoNiCrAlY powder (AMDRY 9954, Sulzer Metco Ltd.) was sprayed to the blasted surface of the substrate as a bond coating with 0.12 mm thickness by high velocity oxygen fuel thermal spraying process. Then, YSZ powder (K-90, Showa Denko K.K.) was sprayed over the bond coating as top coating. Type 3600 APS system with a SG-100 plasma spray gun (Praxair, Inc.) and an industrial robot arm (YR-UP 20-A00, Yaskawa electric corp.) were
used in this process. The plasma torch scanned over the specimen by 80 mm × 90 mm area with 5 mm pitch. Experiments were conducted with varied conditions of preheating temperature and scanning speed of the plasma torch as shown in Table 1.

Figure 1 shows the schematics of AE monitoring during deposition of the YSZ top coating. The “external jig” was used to hold a stainless steel cover plate as shown in Fig. 1(b), and the “internal jig” was used to hold a specimen. The position of the external jig was carefully adjusted so that the plasma jet would hit only the specimen through the center hole with 40 mm in diameter. The external jig was separated from the internal jig and a shock absorber was placed at the bottom of them to suppress superfluous vibration. The specimen was fixed to the internal jig at three points on its side in order not to be shaken by the plasma jet.

AE waveforms were monitored by four sets of laser Doppler interferometers. A pair of a He–Ne laser head unit (AT-0022, Graphtec corp.) and a demodulation unit (AT-3600S, Graphtec corp.) composed one channel of the AE sensor. The demodulation unit was remodeled from the commercial model AT-3600 to improve the sensitivity from 10 to 1 mm/s/V. The laser beams from the laser interferometers were reflected by a pyramid shape mirror, focused on the mirror finished bottom surface of the specimen and reflected back to each laser interferometer on the same paths. Figure 1(c) shows the positions of the laser focuses. The detectable frequency range of the laser interferometer was DC to 400 kHz. The output signals of the laser interferometers corresponding to the out-of-plane velocities were continuously recorded at 10 MHz frequency with bipolar 5 V range and 12 bit resolution and stored into the hard disk drives by the CWM system.

Type K thermocouples were inserted into the two holes in the specimens. The temperatures at the top surface and the center of the substrate were also measured by the CWM system at 100 Hz frequency.

The obtained continuous AE waveforms were analyzed and denoised by the internal software of the CWM system. A recorded waveform was converted to a spectrogram by the short-time Fourier transform method. In the spectrogram the low frequency and relatively strong noise component due to mechanical vibration of the specimen by the plasma jet was eliminated by a pruning high pass filter (HPF) with 100 kHz of cut-off frequency. At the same time, high frequency and relatively weak background noise of the laser interferometer was reduced by the soft-thresholding method. Therefore, noise reduction is conducted by the following formula,

\[ a_2(f, t) = \begin{cases} 0 & f < f_c, f \geq f_c \text{ and } a_1(f, t) \leq \lambda \\ a_1(f, t) - \lambda & f \geq f_c \text{ and } a_1(f, t) > \lambda \end{cases} \]

where \( a_1 \) is intensity of the original spectrogram, \( a_2 \) is intensity of the filtered spectrogram, \( f \) is frequency, \( t \) is time, \( f_c \) is a cut-off frequency and \( \lambda \) is a value of soft-threshold. The detail of the signal processing can be found elsewhere.

AE events were detected after the noise reduction process. At least three of four channels had to hit within 15 µs time lag to be regarded as an AE event. The signal from one channel which did not synchronize can be ignored in this process because suspended YSZ particle often scattered one laser beam and made large temporal noise on this channel. Multiple threshold voltages as 150, 100, 80 and 50 mV were applied to detect more AE events under fluctuating noise. Low threshold voltage is appropriate when the noise level is sufficiently low. On the other hand, high threshold voltage is needed when the noise level is high and the waveform constantly exceeds the low threshold voltage. One AE event set was obtained by one threshold voltage and all AE events were calculated from four different threshold voltages. Then, when the trigger time difference among the AE events from the analyses with the different threshold voltages is within 100 µs or shorter, those AE events were recognized as the same one AE event.

3. Results and Discussion

Figure 2 shows the denoised waveform with and without soft-thresholding process from the same as-recorded signal. Both waveforms were already applied the same pruning HPF process with 100 kHz of cut-off frequency. In the previous study about alumina top coating, only pruning HPF process was enough to detect AE events. On the other hand in the current case of YSZ top coating, few AE events were detected from waveform without soft-thresholding process. Therefore soft-thresholding process is necessary to find AE events during YSZ top coating process.

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<th>Table 1 Condition parameters of APS.</th>
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<td>Chemical Composition</td>
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Fig. 1 Experimental equipments of laser AE measurement of plasma spraying process. (a) whole system, (b) scanning area of the plasma torch, (c) positions of AE measurement.
The counted AE events and temperature history curves of the specimen are shown in Fig. 3. Events were observed in all experimental conditions. It is noteworthy that all events were detected during spraying and no events were detected during cooling period. It is remarkably different from the case of alumina top coating where many AE events were detected both during and cooling as shown in Fig. 3(d).\(^8,9\)

Figure 4 is the cross section SEM photographs of the specimens after the APS process. Both segmentation cracks and delamination cracks were developed in the top coating layer. “Segmentation crack density” and “delamination crack ratio” parameters are used to estimate the development levels of these two types of cracks. The former one is defined like following formula and widely used.\(^12\)

\[
c_s = \frac{n_s}{w}
\]

where \(c_s\) is “segmentation crack density”, \(n_s\) is the number of segmentation cracks in the observation area and \(w\) is width of the observation area. Segmentation cracks are defined as cracks running perpendicular to the coating surface and penetrating at least half coating thickness.\(^12\) However, delamination cracks cannot be counted simply by their number because each of them has very different length. So in this study a parameter by following formula is defined,

\[
c_d = \frac{l_d}{w}
\]

where \(c_d\) is “delamination crack ratio”, \(l_d\) is the total length of delamination cracks in the observation area and \(w\) is width of the observation area. Figure 5 shows the result of these two

\[\text{Fig. 2 Sample of denoised AE waveform with HPF process and (a) without soft-thresholding process, (b) with soft-thresholding process.}\]

\[\text{Fig. 3 AE events and temperature history curves of the specimen. (a) 75 mm/s and no-preheating, (b) 75 mm/s and 500°C preheating, (c) 150 mm/s and no-preheating, (d) (For reference) Alumina coating, 75 mm/s and no-preheating.}\]
parameters. The spray conditions with preheating and fast scanning resulted in lower delamination crack density which is shown in Fig. 5(a). This is very reasonable because preheating reduces the temperature difference between the top coating and the substrate and also faster scanning can reduce the temperature fluctuation around the top coating. On the other hand, the segmentation crack density which is shown in Fig. 5(b) exhibits almost no variation among these spraying conditions. The relationship between the number of AE events, the segmentation crack density and the delamination crack ratio are plotted in Fig. 6. The effect of preheating and fast scanning on the number of delamination cracks was clearly recognized by the decreasing of the number of AE events. However, further improvement of the measurement and analysis of AE is needed because individual AE events which are originated from delamination cracks and segmentation cracks could not be separated in this study.

It is also indicated that most of the delamination cracks occurred during spraying because all AE events were detected in the spraying period. Although not all cracks can be detected in the present system and analyses, it is concluded that the possibility of cracking during cooling is substantially low because no events were detected during the period when the noise level is quite lower than the spraying period.

Fig. 4 Cross section SEM photographs of the top coating after the top coating process. (a) 75 mm/s and no-preheating, (b) 75 mm/s and 500°C preheating, (c) 150 mm/s and no-preheating.

Fig. 5 Development level of cracks in the top coating of TBC, (a) Segmentation crack density, (b) Delamination crack ratio.

Fig. 6 Relationship between number of AE events and development level of cracks.
4. Conclusions

(1) TBC top coating deposition process was monitored by non-contact and non-destructive laser AE method. Newly developed AE measurement system and signal processing method enabled to detect AE events during plasma spraying process.

(2) Preheating and fast scanning of the plasma torch can reduce the delamination crackings during spraying, which were indicated by the reduction of AE events.

(3) All AE events due to cracking were detected during spraying and no AE events were detected after spraying. It is revealed that cracks in the TBC top coating layer mainly formed during spraying process.

Acknowledgement

We thank Mr. Masayuki Komatsu, Mr. Toshio Hiraoka, Mr. Hiroshi Araki and Ms. Akiko Takenouchi for supporting fabrication of our equipments, operation of the APS system and observation of the specimen.

REFERENCES