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Classification of Defects in a Thermal Barrier Coating Layer using the Fuzzy C-means Algorithm

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A thermally grown oxide (TGO) layer of Al_2O_3 is formed between a CoNiCrAlY bond coating and a zirconia top coating of a thermal barrier coating (TBC) system on an Inconel 738 substrate during exposure at 1050°C. Thick TGO is vulnerable to damage in terms of cracking and spallation. In order to estimate the TBC failure, fundamental damage data of TGO that is induced by compressed air are monitored to determine the failure mode and the state of damage by using a nondestructive acoustic emission (AE) system. The defects of the TGO are detected and evaluated by means of AE signal analysis with the root mean squared value in the frequency range of 100 kHz to 400 kHz. The thickness of the TGO increased with the oxidation time. The RMS (Root Mean Square) value decreased almost linearly as the TGO thickness increased up to the failure of the TBC. The amplitude of the AE signal decreased dramatically when the TGO was delaminated. The AE signals for pattern classification were evaluated in accordance with the TBC layer. It is conceivable that the center value represents the damage state of the TBC coating.

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NOMENCLATURE

M = Ni, Fe, Co or their combination

1. Introduction

Thermal barrier coatings (TBCs) have been considered as the method of choice for high-temperature applications, such as jet engines, gas turbines, and blades, because of their excellent thermal, mechanical, and chemical properties.[1-5] Intermediate MCrAlY bond coatings (M=Ni, Fe, Co or their combination) are employed to alleviate the thermal mismatch between yttria-stabilized zirconia (YSZ) and metallic substrates.[1,2,6] Our previous studies revealed that tangential cracks form first; then, lateral cracks are developed.[1] Both cracks propagate and then intersect with each other, resulting in the failure of the coatings by spallation. In addition, an in-situ non-destructive test technique (acoustic emission, viz., AE) combined with a fracture mechanics measurement or cyclic thermal test at 1050°C was performed to qualitatively characterize the failure mechanisms of sprayed coatings.[2] Reductions in the AE in terms of amplitude and energy were observed for TBCs that were fatigued for 2000 cycles, implying that adherence between the coatings and the substrate was significantly lowered due to the formation of micro-cracking, spallation, and plastic deformation caused by thermal fatigue. It is suggested that AE signal analyzes can be effectively for the indirect determination of damage in plasma-sprayed coatings.[2]

Most solid materials generate AE when they are stressed because AE is the generation of stress waves by a material undergoing abrupt structural rearrangement.[7-9] A thermally grown oxide (TGO) layer of Al_2O_3 is formed between a CoNiCrAlY bond coating and a zirconia top coating of a TBC on an Inconel 738 substrate. Thick TGO is vulnerable to damage in terms of cracking and spallation. In order to analyze TBC failure, lifetime assessment technology and criteria for the replacement of TBCs should be developed and established. Fundamental damage data on TGOs generated by compressed air are monitored to determine the failure mode and the state of damage by using an AE system. The defects of the TGO are detected and evaluated by means of AE signal analysis with the mean square and frequency analysis. The AE

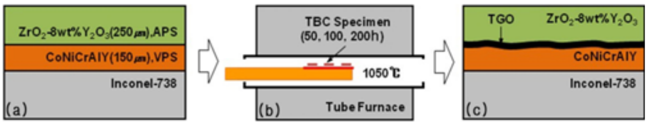


Fig. 1 Schematic diagram of: (a) TBC specimen, (b) thermal oxidation process, and (c) formation of TGO

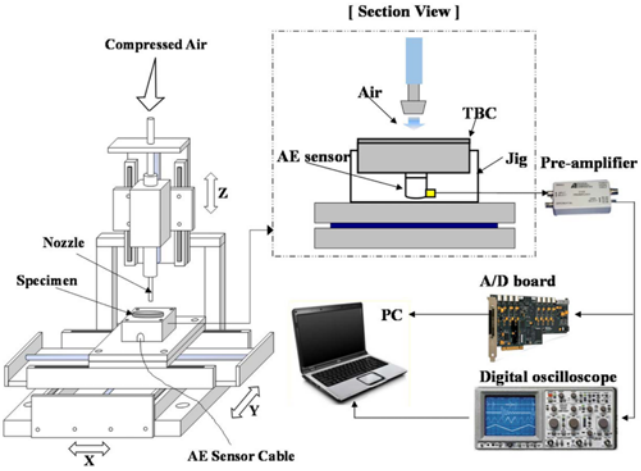


Fig. 2 Experimental setup for the AE monitoring system

parameters are further classified into five clusters by using the fuzzy C-means algorithm (FCM) to elucidate the relationship between the AE signals and damage in the TBCs.[9,10]

2. Experimental Procedure

2.1 Materials

Prior to the experiment, an Inconel 738 substrate with 25.4 mm diameter and 5 mm thickness was grit-blasted using 46 mesh alumina and then the surface of specimen was washed by an ultrasonic cleaner and the distilled water. CoNiCrAlY (Amdry, USA) and 8 wt% YSZ (Metco, USA) were used as the starting powders whose average particle sizes were 45 μm and 80 μm, respectively. An intermediate CoNiCrAlY bond coating with a thickness of 150 μm was prepared on the 738 Inconel substrate by vacuum plasma spraying (VPSing). A top-coat YSZ with a thickness of 250 μm was atmospheric plasma-sprayed (APSed) onto the CoNiCrAlY alloy, as shown in Fig. 1(a). High-temperature oxidation experiments (Fig. 1(b)) were performed at 1050°C for up to 200 h in air to generate the TGO (Fig. 1(c)).

2.2 AE system

Fig. 2 shows that compressed air with a pressure of 5 bar was fired on the surface of TBCs through a nozzle of 0.7 mm diameter. Each specimen was positioned at the center of the stage by means of 3-axis micro-stages. The distance between the nozzle and the specimen was 7 mm. The AE monitoring system, as shown in Fig. 2, was composed of resonant-type sensors (PICO, PAC), a wide band preamplifier (1220A, PAC), an AE-DSP 32/16 board, a digital oscilloscope (9374L, Lecroy), and a personal computer. The AE sensors were triggered at the onset of a crack; then, AE waveforms (rise time, ringdown count, and energy) were monitored, preamplified, and analyzed.[2]

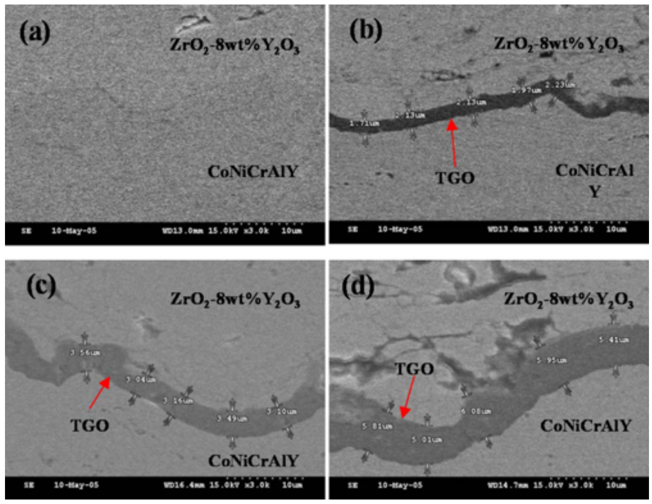


Fig. 3 Scanning electron images of cross-sections of the specimens. (a): Before oxidation. (b)-(d): After oxidation for 50 h, 100 h, and 200 h, respectively, at 1050°C

2.3 Fuzzy C-means algorithm

It is difficult to distinguish quantitatively the TGO layer defects depending on growth time by only in-situ AE signals during experiments. Therefore, an approach to fuzzy clustering is introduced to classify the defects of TBO layer. The Fuzzy C-means clustering algorithm is a method that is frequently used in pattern recognition, allowing one piece of data to belong to two or more clusters.[9,10] The suggested classification algorithm can classify the membership grade in a group by dividing each dataset into several groups and classify more quantitatively cluster as similar group.

3. Results and Discussion

TBCs composed of a 150 μm CoNiCrAlY bond coating prepared by VPS and a 250 μm YSZ top coating layer through APS were prepared on an Inconel 738 substrate. The specimens were thermally oxidized for 50 h, 100 h, and 200 h, respectively, at 1050°C. Scanning electron images of the cross-sections of the TBCs before and after oxidation are shown in Fig. 3. TGO is known to be generated by the reaction of Al and oxygen.[11] No TGO layer was observed for the TBCs without oxidation, as depicted in Fig. 3(a). The TGO layer was visible after high-temperature oxidation due to the formation of Al_2O_3 at the interface between the top and bond coatings.[1,11] The thickness of the TGO determined by SEM increased with the oxidation time. Chen et al.[11] reported that the stable Al_2O_3 layer suppressed TGO growth in the VPS-generated bond coat since Al atoms have to travel farther as thermal exposure continues. The TGO with stable Al_2O_3 exhibited favorable crack resistance by suppressing incoming oxygen from the outside effectively, resulting in improved TBC durability. The relationship between the critical crack size (a) for initiating TBC

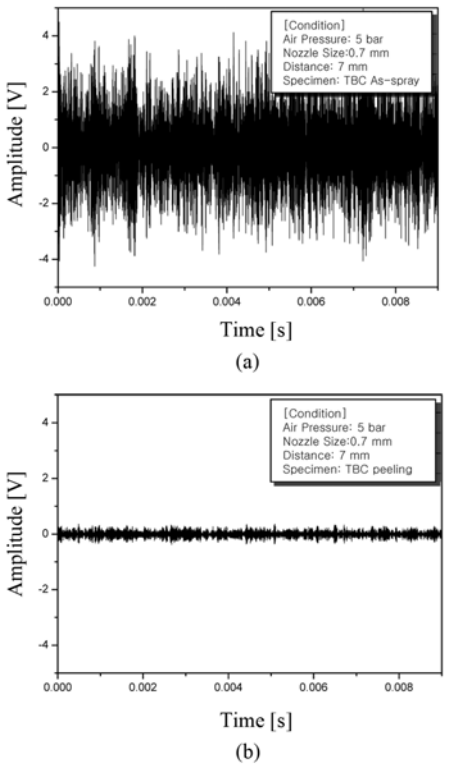


Fig. 4 Raw AE signals obtained from TBCs: (a) without cracks and (b) with cracks

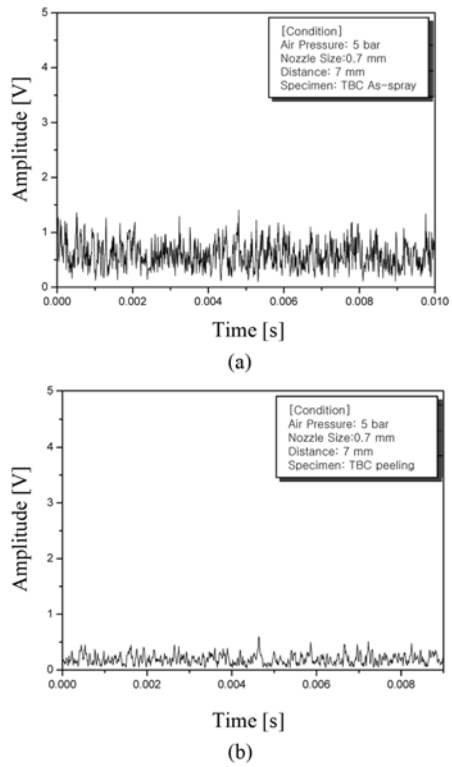


Fig. 5 AE RMS obtained from TBCs: (a) without cracks and (b) with cracks

spallation and the TGO thickness (h), which is expressed as a=kh2/3 (k=constant), may be helpful in predicting the TBC lifetime,[11] but it warrants further research.

After compressed air was applied onto the surface of TBCs to generate defects in the TBCs, the raw AE signal was monitored.[9,10] The raw AE signals obtained from the original TBCs without (Fig. 4(a)) and with cracks (Fig. 4(b)) are examined. The root mean square signal (RMS) is also shown in Fig. 5. A lower AE amplitude may represent cracking with a large crack volume, as demonstrated in Figs. 4(b) and 5(b). Experimental results revealed that the amplitude of AE signals decreased as defects formed. The variation of the AE RMS with the TGO thickness is shown in Fig. 6. The RMS value started to decrease almost linearly as the TGO thickness increased up to the failure (delamination or peeling-off) of TBCs. An inverse linear relationship between the AE signals and defects inside the TBCs was qualitatively found in this study.

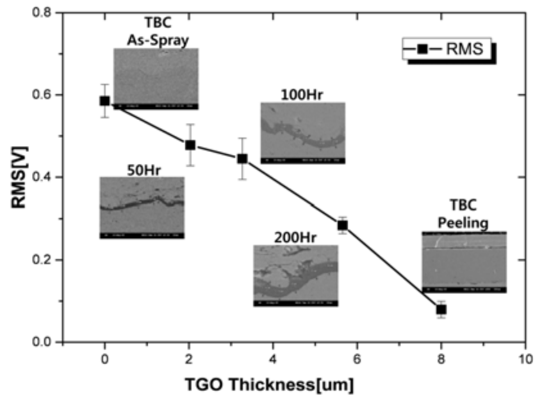
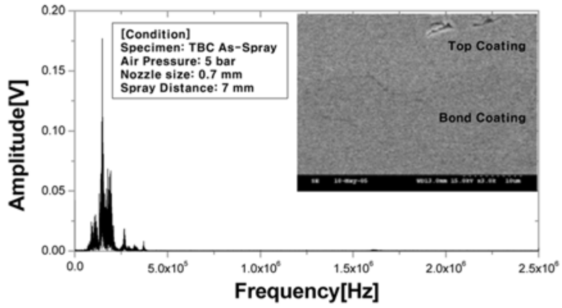


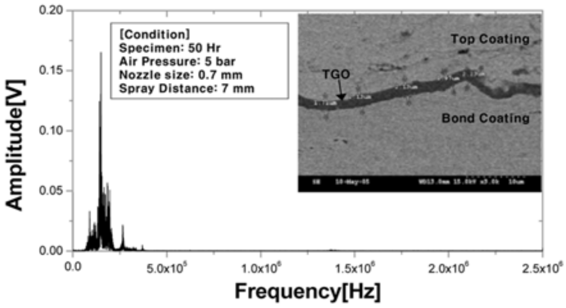
Fig. 6 Variation of the AE RMS with the TGO thickness

The frequency outputs of TBCs with various TGO thicknesses, as displayed in Fig. 7, were examined to quantitatively evaluate the characteristics of defects. Peaks were clearly observed at frequencies in the range of 100~150 kHz. No peak variation in the frequency patterns of the TBCs was found regardless of the TGO thickness. A reduction in the AE intensity with increasing TGO thickness is likely due to the dissipation of the AE signal along the cracks. An increase in the net crack paths caused by an increase in the crack density with prolonged thermal oxidation may be responsible for the reduction in the AE signal intensity. The defects (cracks) became dominant in the TBCs due to stress concentrations caused by prolonged thermal oxidation as the TGOs became thicker. The AE signal amplitude decreased dramatically when the specimen was delaminated, as shown in Fig. 7(e).

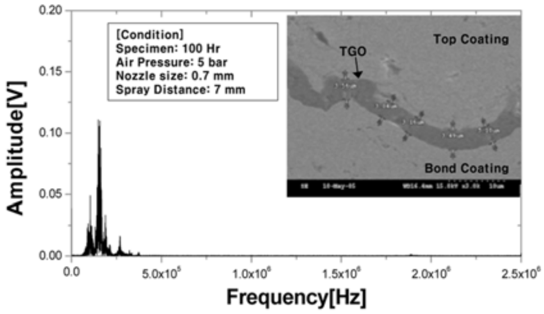
FCM is a method of clustering to improve the performance toward some optimal AE signal. Pattern recognition aims to classify patterns based on statistical information extracted from the patterns. The patterns to be classified are usually groups of measurements, defining points in appropriate AE signals and frequency outputs as functions of the TGO thickness. The subtractive clustering method assumes that each data point is a potential cluster center and calculates a measure of the likelihood that each data-point would define the cluster center, based on the density of surrounding data-points. Pattern recognition containing five clusters were evaluated for the as-sprayed TBCs, the TBCs oxidized for 50 hr, 100 hr, and 200 hr, respectively, at 1050°C,



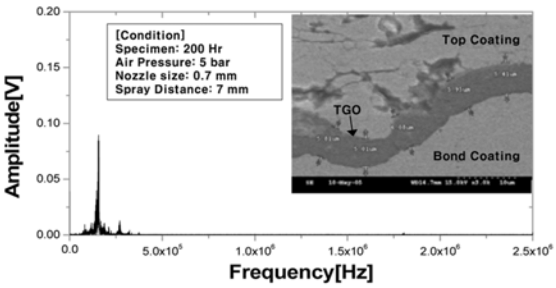
(a) as-sprayed



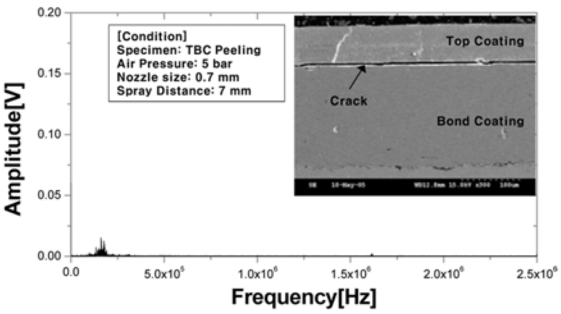
(b) after thermal oxidation for 50 Hr



(c) after thermal oxidation for 100 Hr



(d) after thermal oxi ation for 200 Hr



(e) delaminated TBCs

Fig. 7 Variation of the AE frequency with the TGO thickness

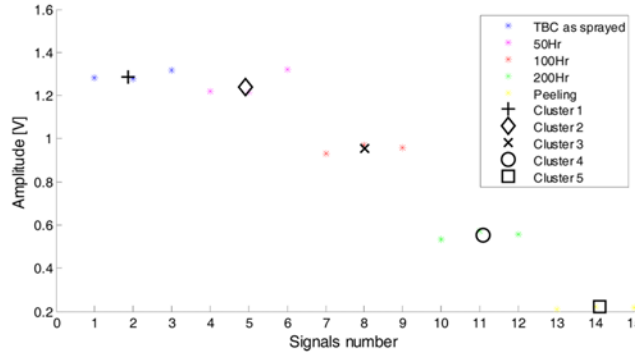


Fig. 8 Result of pattern classification using the fuzzy C-means algorithm

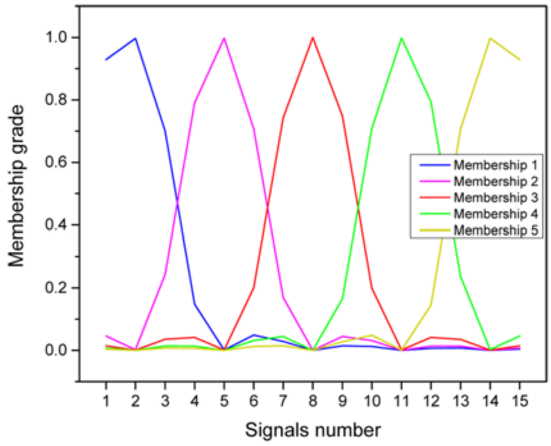


Fig. 9 Result of membership function using the fuzzy C-means algorithm

and the delaminated TBCs.

Fig. 8 is a pattern classification graph of the AE signal measured by the growth of the TGO about TBC coating layer. Pattern classification methods were calculated by screening for the valid frequency bands measured by the AE using FFT. For the pattern classification process, FCM count value were carried out by setting of Cluster number = 5, Max Iteration = 100, Exponent = 2.0 in the calculation. Results of the pattern classification of AE signal was recognized similar pattern on the TBC as spray and TGO 50Hr. TGO 100Hr, 200Hr, Peeling was recognized each pattern.

Fig. 9 is the result of membership function using the fuzzy C-means algorithm. It shows that membership grade is similar value compared to cluster center shown in Fig. 8. Therefore, It is conformed that pattern between AE signals and damages in the TBO growth can be classified by fuzzy C-means clustering algorithm.

4. Conclusions

A top-coat YSZ with a thickness of 250 μm was APS-overlaid onto a CoNiCrAlY bond coating (150 μm in thickness) on an Inconel 738 substrate. High -temperature oxidation was performed at 1050°C for up to 200 hr in air to generate the TGO layer of Al_2O_3. Fundamental damage data of the TGO were obtained by firing compressed air with a pressure of 5 bar on the surface of the TBCs. The defects of the TGO were evaluated by means of AE signal analysis with RMS in the frequency range of 100~400 kHz. The thickness of the TGO increased with the oxidation time. The RMS value decreased almost linearly as the TGO thickness increased up to the failure of the TBCs. The amplitude of the AE signal decreased dramatically when the TGO was delaminated. The AE signals for pattern classification in accordance with the TBC layer were evaluated. It is conceivable that the center value represents the damage state of TBC coatings.

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