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Life Prediction of Thermal Barrier Coating Considering Degradation and Thermal Fatigue

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A thermal barrier coating (TBC) is used to protect gas turbine components from extreme environments. Typically, the TBC system consists of two parts: a ceramic top coat and metallic bond coat. Thus, the TBC system is exposed to thermal fatigue owing to the mismatch between the thermal expansions of the ceramic top coat and metallic bond coat. The durability of the TBC decreases with repeated thermal fatigue and degradation under high-temperature conditions, which can eventually result in failure. Therefore, the life of the TBC should be predicted while considering degradation and thermal fatigue. In this study, TBC specimens were produced under different degradation and thermal fatigue conditions, and the bond test was performed on these specimens. Based on the bond test results, the life of the TBC was predicted according to degradation and thermal fatigue.

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NOMENCLATURE

σ_{15min} = bond strength under a 15 min heating condition
σ_{20min} = bond strength under a 20 min heating condition
σ_{30min} = bond strength under a 30 min heating condition
N = number of thermal fatigue cycles
a = slope of the life prediction equation
a_0 = slope of the life prediction equation without degradation
$f(t)$ = function of the slope and dwell time
t = dwell time (min)
σ = bond strength
σ_0 = bond strength without degradation

1. Introduction

The thermal barrier coating (TBC) is an important technique that is used to protect gas turbine components.[1] TBC failure is usually due to thermal fatigue caused by gas turbine operation and termination under extreme environmental conditions.[2,3] Thermal fatigue is caused by thermal stresses from differences in the thermal expansion coefficients of different materials and can lead to delamination of the TBC.[4,5] Thermally grown oxide (TGO) forms at the interface between the top coat and bond coat when the TBC is exposed to high-temperature conditions.[6-9] TGO grows with the degradation time, which gradually reduces the durability of the TBC.[10,11] Therefore, the life of a TBC should be evaluated by considering the effects of degradation and thermal fatigue.

In general, the life of a TBC is evaluated with a thermal fatigue test that emulates the operating conditions based on repeated operation and termination of the gas turbine.[12-15] However, the thermal fatigue test takes long time to complete, so a life assessment method that can replace the thermal fatigue test is needed. Kim et al.[16] performed a bond strength test according to the damage level of the thermal fatigue and used the results to indirectly evaluate the life of a TBC.

In this study, TBC specimens were fabricated at different damage levels of thermal fatigue and under various heating conditions. Bond strength tests were then performed with these specimens. Finally, the life of the TBC was predicted by considering the effects of the degradation and thermal fatigue based on the bond strength test results.

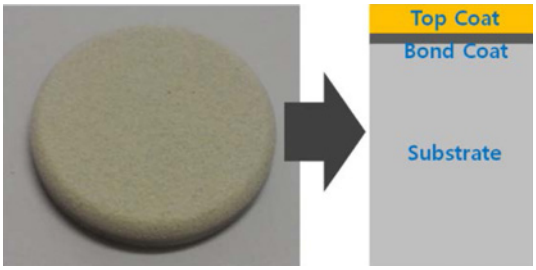

Fig. 1 APS-TBC specimen

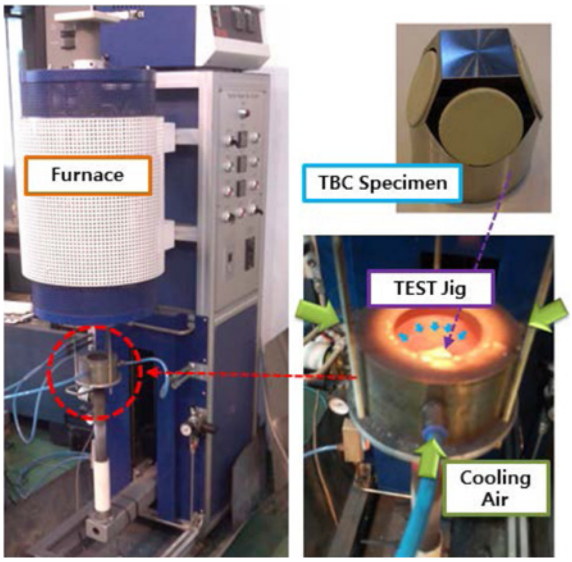

Fig. 2 Equipment used for the thermal fatigue test

Table 1 Materials and thickness of the thermal barrier coating

Layer	Materials	Thickness
Top coat	8% Y2O3-ZrO2	470 ìm
Bond coat	NiCrAlY	250 ìm
Substrate	Ni-based super alloy	3 mm

2. Thermal Fatigue Test

2.1 Features of TBC specimen

In this study, a coin-shaped specimen with a diameter of 25 mm and thickness of 3 mm was fabricated from a Ni-based super alloy. A NiCrAlY bond coat was deposited on the Ni-based super alloy substrate, and a YSZ (Yttria Stabilized Zirconia) top coat was deposited on the bond coat by APS (Air Plasma Spraying) technique as shown in Fig. 1. Table 1 presents the materials and thickness of each layer of the TBC specimen.

2.2 Conditions of thermal fatigue test

The thermal fatigue test was performed with testing equipment that automatically transferred specimens into and out of the furnace, as shown in Fig. 2. The thermal fatigue test was organized as a repeating sequence of two processes: heating at 1150°C in a furnace and cooling

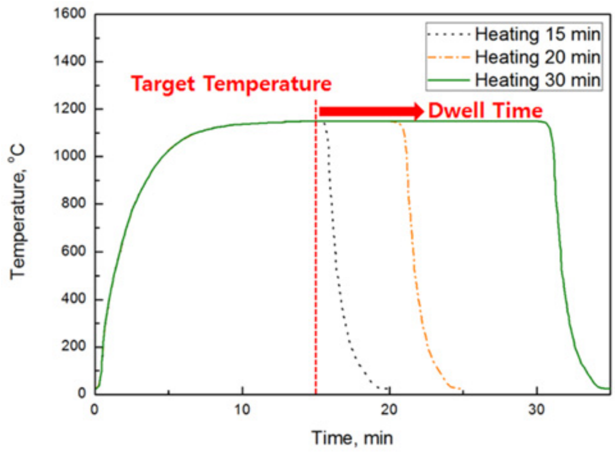

Fig. 3 Temperature measurement during the thermal fatigue test

Table 2 Results of thermal fatigue test according to heating time

Heating time	15 min		20 min		30 min	
Cooling time	5 min					
Life of TBC (cycles)	214	243	176	195	146	167

Table 3 TBC specimens at different damage levels

Heating time (min)	Dwell time (min)	Damage level (%)	Number of cycles (cycles)
15	0	25	57
		50	114
		75	171
20	5	25	46
		50	90
		75	136
30	15	25	39
		50	78
		75	117

at room temperature using air spraying. The temperature was measured at the coating interface to confirm the time to reach the target temperature, as shown in Fig. 3. The heating time is the total time of the heating process, and the dwell time is the degradation time after the target temperature is reached. Based on the temperature measurements, the specimen reached 1150°C after a heating process of 15 min and reached room temperature after a cooling process of 5 min. Thermal fatigue tests were carried out with heating steps of various times (e.g., 15, 20, and 30 min) followed by 5 min of constant cooling in every case in order to evaluate the influence of the heating time on the thermal fatigue life.

2.3 Results of thermal fatigue test

Thermal fatigue tests were performed twice with heating times of 15, 20, and 30 min. Each thermal fatigue test was conducted until spallation of the TBC occurred. Thus, the life of TBC was defined as the number of thermal fatigue cycles. Table 2 present the results of the thermal fatigue test under each heating condition. The life of the TBC decreased as the heating time increased because of the TGO growth from TBC degradation.

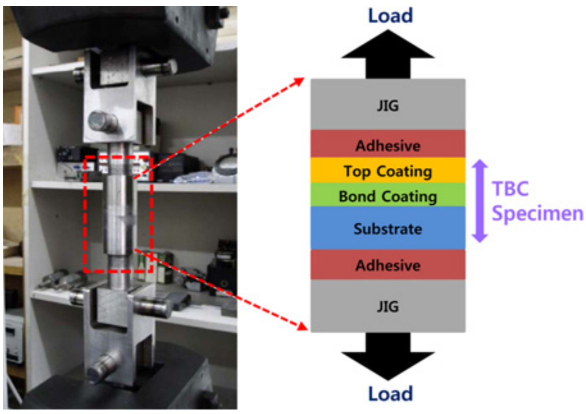

Fig. 4 Equipment used for the bond strength test

3. Bond Strength Test

3.1 Feature of TBC specimen

Different levels of damage were inflicted on TBC specimens to evaluate the life of the TBC indirectly, as presented previously by Kim et al.[16] After the average life was calculated under each condition of the thermal fatigue test, TBC specimens were prepared with different damage levels by performing the thermal fatigue test at 25%, 50%, and 75% of the mean life of the TBC. Table 3 lists the heating time, dwell time, number of cycles, and damage level.

3.2 Conditions of bond strength test

The TBC system was fixed on the jig with epoxy adhesive. It was then kept in the furnace at a temperature of 177°C for approximately 2 h to improve adhesion. The test machine (INSTRON, 8820) was used in the bond strength test at a speed of 1 mm/min as per ASTM C633-13. After the load-displacement diagram was obtained through experiments, the bond strength was calculated by dividing the fracture load by the cross-sectional area.

3.3 Results of bond strength test

The bond strength test was performed by using TBC specimens with different damage levels of thermal fatigue; Table 4 presents the test result. The bond strength decreased as the number of thermal fatigue cycles increased. This tendency correspond to the bond strength test results which conducted by Kim et al.[16] The TGO growth caused by the repetitive thermal fatigue reduces the durability of the TBC. According to observations of the fractured surface, the TBC failed at the interface between the top coat and bond coat in the bond strength tests, as shown in Fig. 5.

4. Life Prediction of TBC

4.1 Life prediction according to changes under thermal fatigue conditions

The bond strength-thermal fatigue cycle diagram was obtained for heating times of 10, 20, and 30 min, as shown in Fig. 6. The life prediction equation for each heating condition was derived from the bond strength-thermal fatigue cycle diagram and is given by Eqs. (1)-(3). The TBC specimen was not damaged under the initial condition, so the bond strength at the 0^{th} cycle was constant regardless of the heating condition. Therefore, the bond strength under the initial condition was assumed to be the same in each life prediction equation. The thermal fatigue life was predicted in accordance to the number of cycles when the bond strength was zero, similar to Kim et al.[16] The predicted thermal fatigue life under each heating condition was compared to the results of the thermal fatigue test, as presented in Section 2. Table 5 presents the predicted life values. The predicted thermal fatigue life of the TBC had an error of 12-27%, compared to the results of the thermal fatigue test. Zhang et al.[17] reported that the degradation of TBC occurs during heating step before TBC reaches the target temperature. However, in this study, it was assumed that the effect of dwell time is more effective than that of heating step before TBC reaches the target

Table 4 Bond strength test results

Dwell time (min)	Damage level (%)	Bond strength (MPa)
0	25	52.3
	50	33.7
	75	27.8
5	25	47.8
	50	34.4
	75	28.4
15	25	46.9
	50	32.9
	75	22.5

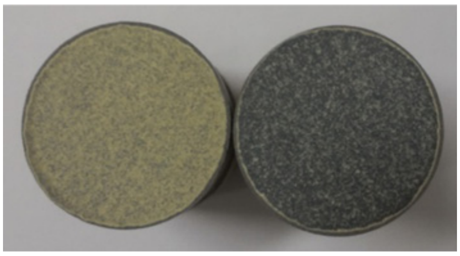

Fig. 5 Fracture surface of a specimen with 50% damage (heating period of 30 min)

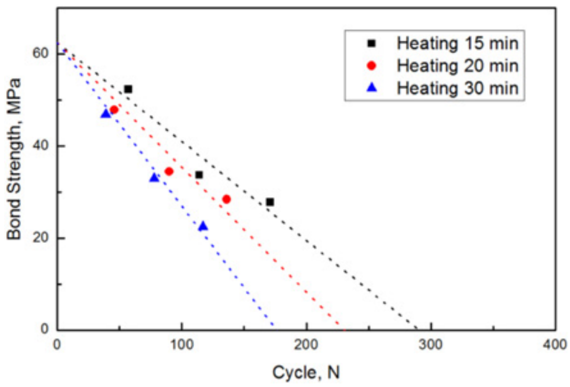

Fig. 6 Bond strength-thermal fatigue cycle diagram

Table 5 Predicted life results

Heating time (min)	Evaluated by thermal fatigue test (cycles)	Predicted by bond test (cycles)	Error (%)
15	228.5	290.7	27.2
20	185.5	230.6	24.3
30	156.5	176.1	12.5

temperature on degradation and the effects were ignored. And then, it is thought that the life prediction error occurs and the error increases as the number of thermal fatigue cycle increases. However, a life of the TBC is known to exhibit a wide variation.[13,18] Therefore, the life of a TBC can be predicted by using these equations under each heating condition.

$$\sigma_{15min} = -0.215 \times N + 62.5 \quad (1)$$

$$\sigma_{20min} = -0.271 \times N + 62.5 \quad (2)$$

$$\sigma_{30min} = -0.355 \times N + 62.5 \quad (3)$$

$$\sigma = a \times N + \sigma_0 \quad (4)$$

$$a = a_0 \times f(t) = -0.215(1 + 0.0442t) \quad (5)$$

$$\sigma = -0.215(1. + 0.0442t) \times N + 62.5 \quad (6)$$

$$N = \frac{-\sigma_0}{a_0 \times f(t)} = \frac{290.70}{1 + 0.0442t} \quad (7)$$

4.2 Generalized life prediction equation considering dwell time and thermal fatigue

The TBC life can be indirectly predicted by using the derived Eqs. (1)-(3). However, these equations are limited because they are only valid under the specific conditions at which the thermal fatigue test was performed. Based on Eqs. (1)-(3), a generalized relationship between the bond strength and life can be derived as given in Eq. (4). Fig. 7 show that the slope of the life prediction equation decreases as the dwell time increases. The relation of the slope of the life prediction equation can be derived by using Eqs. (4) and (5) and is expressed in Eq. (6).

4.3 Prediction of TBC life with degradation

The thermal fatigue life can be predicted from the number of cycles when the bond strength is zero with Eq. (6), as given in Eq. (7). The thermal fatigue life depends on the dwell time at a temperature of 1150°C and can be predicted by using this equation. The isothermal degradation life can be predicted from the dwell time t in Eq. (7) when the life N is equal to 1 cycle because thermal fatigue can be considered as isothermal degradation when failure occurs during 1 cycle. The isothermal degradation life of 109.2 h at 1150°C was predicted from this equation. Kim et al.[19] performed an isothermal degradation test according to the degradation temperature, and the results are shown in Fig. 8. The TBC life was determined to be 117.5 h at 1150 °C through regression analysis on the isothermal degradation test results. The test results for isothermal degradation from Kim et al.[19] correspond to the

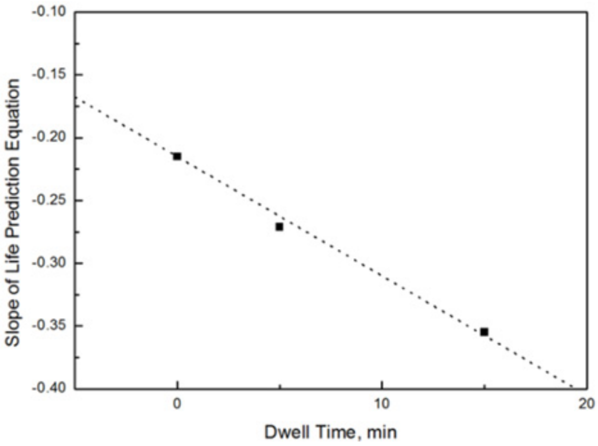

Fig. 7 Slope of the life prediction equation according to the dwell time

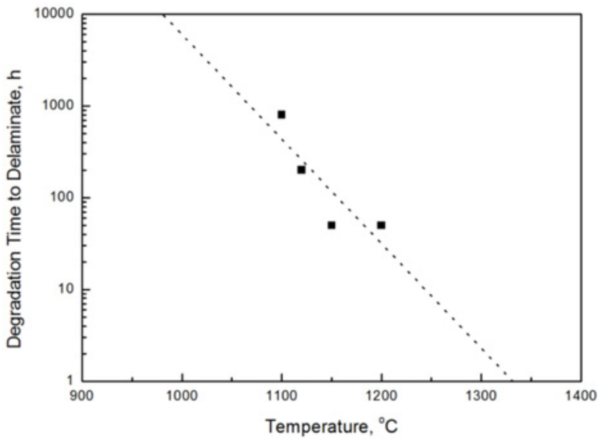

Fig. 8 Degradation time until delamination under isothermal conditions[19]

prediction results of this study. Therefore, this life prediction equation can be applied to isothermal degradation and thermal fatigue problems.

5. Conclusions

This study focused on the predicting the fatigue life of a TBC by using the relation between the bond strength and the number of cycles of the thermal fatigue test. The main results are as follows:

i. A bond strength test was performed with different levels of damage to the TBC, and a life prediction equation under each heating condition was derived based on these test results.
ii. The thermal fatigue life was predicted by using this equation, and the results were consistent with the results of the thermal fatigue test.
iii. A generalized life prediction equation was derived by considering the dwell time and thermal fatigue using the life prediction equation under each heating condition.
iv. The isothermal degradation life was predicted to be 109.2 h with the generalized life prediction equation, which is consistent with the results of Kim et al.[19]

Therefore, this life prediction equation can be applied to isothermal degradation and thermal fatigue problems.

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