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TBC Delamination Life Prediction by Stress-Based Delamination Map

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The thermal barrier coating (TBC) is applied to gas turbine components to protect the hot-section components from extremely high temperature condition. Since metallic substrate cannot endure such severe condition of gas turbines, the delamination of the TBC can cause the failure of the whole system. Thus, the delamination life of the TBC is one of the most important issues for designing the hot-section components which operate at high temperature condition, and thermal stress between the coating layers is known as one of the major causes of the delamination. Especially, growth of thermally grown oxide (TGO) by Al-diffusion from bond coat is known as one of the main reasons to increase thermal stress between coating layers. Thus, in this study, the TGO growth behavior in the TBC is investigated, using the isothermally aged TBC specimens at high temperature conditions (900 - 1100°C), and thermal stress on TGO layer is investigated by finite element analysis, considering the TGO growth in the TBC. Finally, the test and FEA results are concluded as the TGO delamination map which can predict the delamination life time of TBC under isothermal condition.

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NOMENCLATURE

d_{TFO} = Thickness of TGO
t = Aging time
T = Aging temperature
a = Variable for Eq. (1)
b = Variable for Eq. (1)
S^{TGO}_{Max} = Maximum stress parallel to the interface (σ_{11}) between TGO and top coat
Y, A, R = Variables for Eq. (4)

1. Introduction

Due to the regulatory policy on carbon footprint in Europe and North America, interest in combined cycle power plant (CCPP) has been increasing in recent years.[1-4] High energy efficiency and the use of natural gas with relatively low carbon content are the advantages of combined cycle power plant which includes gas turbine as the first generator.[1]

The thermal barrier coating (TBC)s are applied to gas turbines to protect the hot-section components from extremely high temperature condition and lower the surface temperature of the components.[5-10] Due to such protection by TBCs as thermal barrier, turbine inlet temperature can be increased. In other words, higher efficiency of gas turbine can be obtained by thermal protection of TBCs. TBCs usually consist of superalloy substrate, MCrAlY (where M is Ni, Co, or both) bond coat, ceramic (7 - 8 wt.% ZrO_2-Y_2O_3) top coat, and thermally grown oxide (TGO) which is formed between top and bond coat by Al-diffusion from bond coat.[5,11] Ceramic top coat plays a role as thermal barrier with relatively low thermal transfer coefficient, and bond coat increases the adhesive strength between metallic materials and ceramic top coat. TGO layer protects metallic substrate from high temperature oxidation.

Since metallic substrate cannot endure such severe condition of gas turbines, the delamination of TBCs can cause failure of a component, and due to the high speed rotation of gas turbine, failure of a component can cause the failure of the turbine system. Thus, the delamination life of the TBC is one of the most important issues for designing hot-section components that operate under high temperature condition. One of the major failure mechanisms of TBC is thermal stress that is caused by thermal expansion mismatch between coating layers.[5] Especially, the growth of TGO by the Al-diffusion from bond coat is known as one of the main reasons to increase thermal stress between coating layers. In addition, the interface between ceramic top coat and TGO layer has been reported as the place where the delamination occurs due to the induced stress by TGO.[5,12,13]

Kim et al.[12] arranged isothermal test results on air plasma sprayed(APS) TBC as delamination map which can predict the delamination life. However, the delamination map from previous research[5] can be used only at tested area (tested temperature). In this study, the TGO growth behavior in the TBC is investigated using isothermally aged TBC specimens at high temperature conditions, and thermal stress on TGO layer is investigated by finite element analysis considering the TGO growth of the TBC. Finally, the test and FEA results are concluded as the stress-based TGO delamination map which can predict the delamination life time not only a tested area but also at untested area.

2. Isothermal Aging of TBC

2.1 Isothermal Aging on TBC Specimen

Coin type TBC specimens were prepared according to previous researches.[5,12,14] IN738LC which is widely used material for 1st stage turbine blades was chosen as substrate and MCrAlY bond coat (200 μm) was deposited on the substrate by low vacuum plasma spray (LVPS) method. On the top of the bond coat, ceramic top coat (500 μm, 7 - 8 wt.% ZrO_2-Y_2O_3) was deposited by air plasma spray (APS) method. During the coating process, coating thickness was controlled by optical measurement on height of the surface.

Isothermal aging on TBC specimens were conducted with electric furnace. 900, 1000, and 1100 °C were chosen as aging temperature according to operating condition of industrial gas turbines and previous researches.[5,12,14] TBC delamination occurs on isothermally aged specimens of 800 hours at 1100 °C and 3200 hours at 1000 °C. In case of isothermal aged specimens at 900 °C, TBC delamination did not occur until 3200 hours.

2.2 TGO Thickness Growth Prediction Model

After the isothermal aging on TBC specimens, the specimens were cut in half by a diamond cutter, and TGO thickness of selected specimens were measured with scanning electron microscope. Fig. 1 shows an example of TGO formed at isothermal aging condition, and the results of the measurement were arranged as Table 1.

According to the previous research[12] and TGO growth behavior at 1100°C (Fig. 2) which has the smallest scatter, TGO growth behavior can be defined by Eq. (1), and two variables (a and b) in Eq. (1) are dependent on aging temperature as shown in Fig. 3. Thus, those two variables, a and b, can be defined by aging temperature, as arranged

Table 1 TGO thickness of isothermal aged TBC

Aging time (hour)	Aging temperature		
	900°C (μm)	1000°C (μm)	1100°C (μm)
0	0	0	0
25	not measured	not measured	2.88
50	1.44	1.94	3.94
75	not measured	not measured	4.56
100	1.49	3.29	5.14
200	1.35	3.06	not measured
400	1.95	4.72	not measured
800	2.84	5.21	delaminated
1600	not measured	not measured	-
3200	not measured	delaminated	-

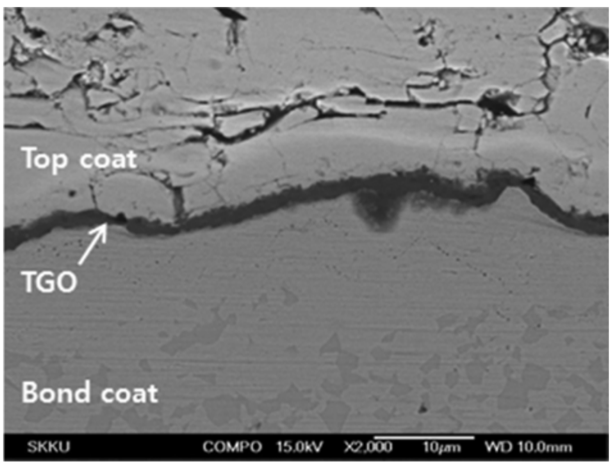

Fig. 1 TGO growth at 1000°C for100 hours

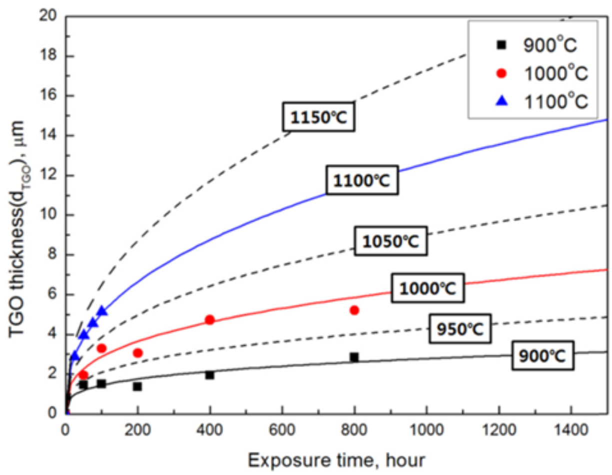

Fig. 2 TGO growth behavior of the TBC

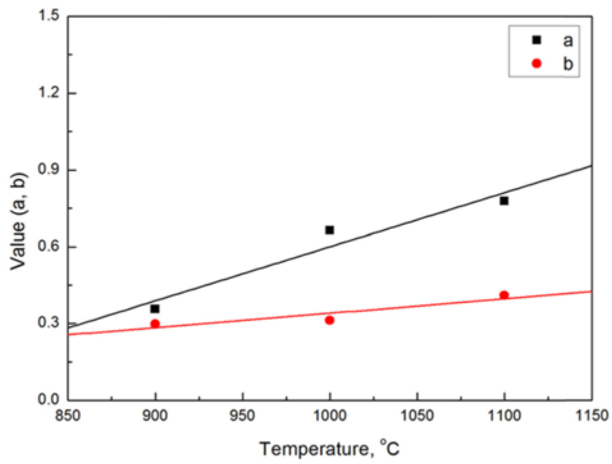

Fig. 3 Dependence of the variables (a and b) on temperature for Eq. (1)

in Eqs. (2) and (3). Finally, TGO thickness can be predicted by Eqs. (1)-(3) according to its temperature and exposure time. Fig. 4 shows test results(dots) and predicted TGO thickness(lines) by Eqs. (1)-(3).

$$d_{TGO} = a \cdot t^b \quad (1)$$

$$a = 0.00211 \cdot T - 1.51 \quad (2)$$

$$b = 0.000562 \cdot T - 0.221 \quad (3)$$

In addition, hot-section parts of gas turbines are exposed to not only isothermal condition which occurs during steady-temperature operation, but also thermal fatigue condition which occurs during start up and shut down. Therefore, TGO thickness at thermal fatigue and combined condition (isothemal aging+thermal fatigue) should be also investigated. According to previous researches,[5,14] thermal fatigue tests on coin-type specimens were conducted, and TGO thickness at thermal fatigue condition and combined condition (isothemal aging + thermal fatigue) can be predicted by Eqs. (1)-(3) based on exposure time at high temperature. Predicted TGO thickness was verified by the results of thermal fatigue and pre-aged thermal fatigue. Thermal fatigue tests for the verification were conducted at the temperatures of 1150ºC and 25ºC. Heating for 15 minutes by electric furnace and air cooling for 5 minutes by air spray were applied for thermal fatigue. Before the thermal fatigue tests, pre-isothermal aging (50, 200, 400 hours) was conducted on sellected TBC specimens to simulate the combined condition (isothemal aging + thermal fatigue). Both tests were conducted twice for the reliability of the test results. As shown in Fig. 4, TGO thickness at thermal fatigue condition was successfully predicted only within 5% error, and TGO thickness at the combined condition was predicted within 24% error. Considering large scatter of the TGO thickness from the test results (Fig. 2), 24% error of predicted values (vs. test results) seems as acceptable scatter. Therefore, TGO thickness prediction by Eqs. (1)-(3) can be used not only for isothermal condition but also for thermal fatigue and conbined condition (isothermal aging + thermal fatigue).

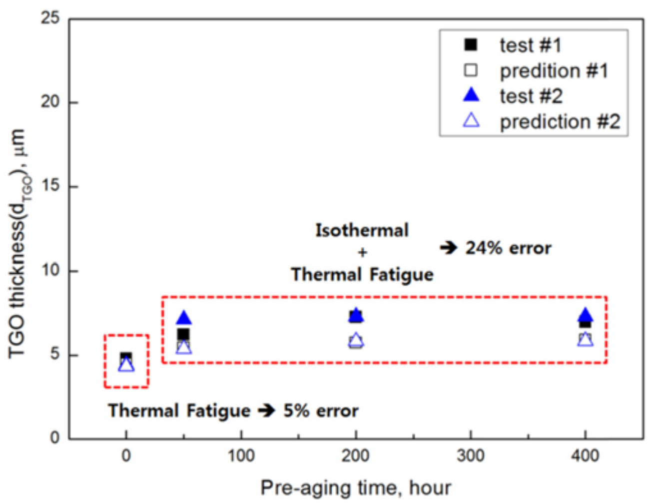

Fig. 4 TGO thickness prediction results for thermal fatigue and thermal fatigue with pre-isotheral aging

3. Thermal Stress Analysis

3.1 TGO Model for Finite Element Analysis

To obtain thermal stress in TBC, finite element analysis was performed. The shape of TBC was modeled according to the previous research by J. Schwarzer et al.[15] The model consisted of four layers: a top coat, a bond coat, TGO, and a substrate. The thickness of each layer is listed in Table 2. TGO was modeled as a sine form at the interface between the top coat and the bond coat, and it was assumed to have a period of 100 μm and amplitude of 10 μm.[15] The half period of the model was constructed, and then, symmetric and coupling conditions were applied to the model, as shown in Fig. 5.[15] Total 37 cases of analysis (7 cases of temperature conditions from 900 to 1200ºC, 7 cases of TGO thickness condition from 0.1 to 6 μm) were performed, as shown in Table 3.

3.2 Conditions of Finite Element Analysis

The material was assumed to be elastic and plastic, and the elastic and plastic properties used in the finite element analysis are described in Table 4.[16-19]

Table 2 Materials and thickness of finite element analysis model[11]

	Top coat	Bond coat	Substrate
Thickness	500 μm	200 μm	3 mm
Materials	7-8% Y_2O_3-ZrO_2	NiCrAlY	IN738LC

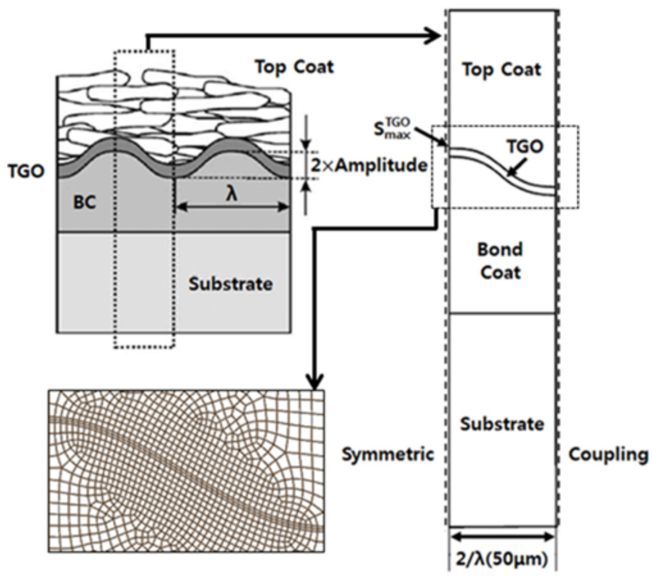

Fig. 5 Scheme of TBC model for finite element analysis[8]

Table 3 Cases of FEA

Aging temperature	TGO thickness, μm						
	0.1	1	2	3	4	5	6
900ºC	O	O	O	O	O	O	O
950ºC	O	O	O	O	O	O	O
1000ºC	O	O	O	O	O	O	O
1050ºC	-	O	-	-	-	-	-
1100ºC	O	O	O	O	O	O	O
1150ºC	-	O	-	-	-	-	-
1200ºC	O	O	O	O	O	O	O

To obtain the thermal distribution in TBC, heat transfer analysis was performed. The surface of top coat was heated to the goal temperatures (900, 950, 1000, 1050, 1100, 1150, 1200°C) until whole specimens reach the goal temperature. After the heat transfer analysis, the thermal stress analysis was performed with the temperature distribution obtained from the heat transfer analysis. The finite element analysis model consisted of about 92,000 elements. DC2D4-type elements were used for the heat transfer analysis, and CPE4R-type elements, for the thermal stress analysis. Whole process of FEA was conducted by ABAQUS.

3.3 Results of Finite Element Analysis

It is known that delamination of the TBC occurs at the interface between TGO and the top coat[14,20] and the stress parallel to the interface (σ_{11}) is known as the main cause of delamination.[17] Corresponding to the previous researches,[14,20,21] in this study, the stress, parallel to the interface between top and TGO, has the highest stress value, as shown in Fig. 6. Especially, the maximum stress(S^{TGO}_{Max}), parallel to the interface, occurred on the peak of TGO which is the interface between the top coat and the TGO. Fig. 5 shows the location where the maximum stress occurs.

Each maximum stress on TGO(S^{TGO}_{Max}) - TGO thickness relation can be expressed as an exponential equation, as shown in Eq. (4). The variables of the Eq. (4), Y, A, and R, are temperature-dependent values as shown in Fig. 7. The relations of the variables for Eq. (4) and temperature are arranged in Eqs. (5)-(8) by curve fitting as shown in Fig. 7. Finally, maximum thermal stress in TBC can be predicted by Eqs. (4)-(8) and Fig. 8 compares the stress values from FEA and predicted values by Eqs. (4)-(8).

$$S^{TGO}_{Max} = Y + A \cdot \exp(R \cdot d_{TGO}) \tag{4}$$

$$Y = -273.1 + 0.7176 \cdot T \tag{5}$$

$$A = 125.2 - 0.192 \cdot T \tag{6}$$

$$R = 0.04155 - 0.0002970 \cdot \mathrm{T}(\text{temperature} \leq 1000^{o}\mathrm{C}) \tag{7}$$

$$R = -0.1839 - 0.00007141 \cdot \mathrm{T}(\text{temperature} > 1000^{o}\mathrm{C}) \tag{8}$$

Table 4 Material properties[12-15]

	Top coat	TGO	Bond coat	Substrate
Young's Modulus (GPa)	53	364 - 416	138 - 209	141 - 206
Poisson's ratio	0.25	0.23 - 0.25	0.27	0.28 - 0.3
Density (kg/m^3)	6037	3984 - 3868	7711	7860
Specific heat (J/kg°C)	500	755 - 1285	628	456
Thermal expansion coefficient (10^{-6}/°C)	7.6 - 12.7	4.6 - 8.3	12 - 19.3	11.6 - 15.9
Thermal conductivity (W/mK)	1 - 2.3	6.7 - 33	11.6 - 25	11.8 - 25.4
Yield strength (MPa)	-	300	114 - 426	345 - 950

4. Stress-Based Delamination Map

According to the isothermal test data in section 2, the TBC delamination occurs between 1600 and 3200 hours in the case of

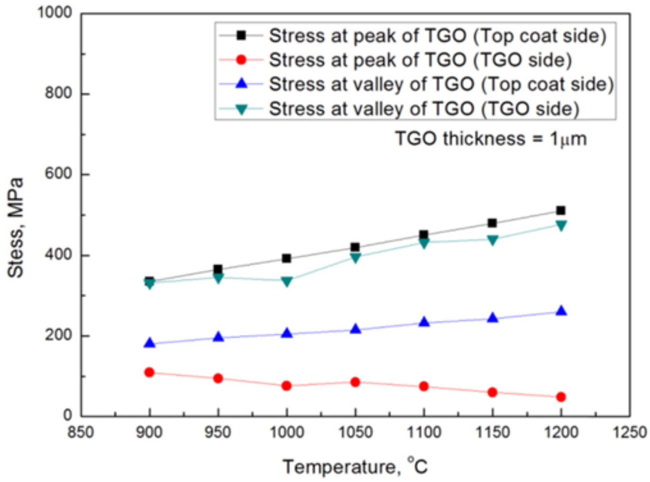

Fig. 6 An example of thermal stress distribution at the interface between TGO and top coat (TGO thickness = 1 μm)

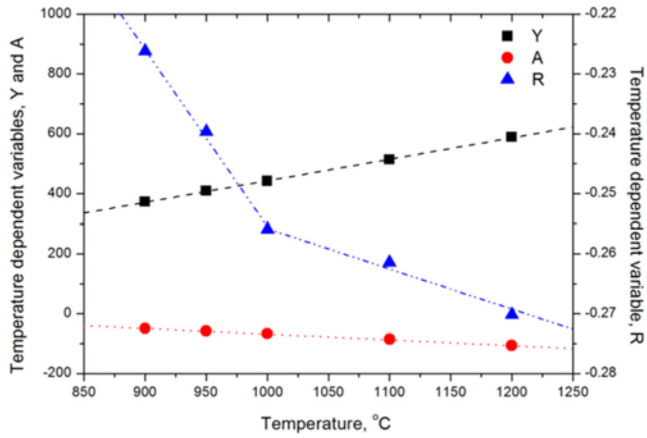

Fig. 7 Temperature dependent variables (Y, A, and R) for Eq. (4)

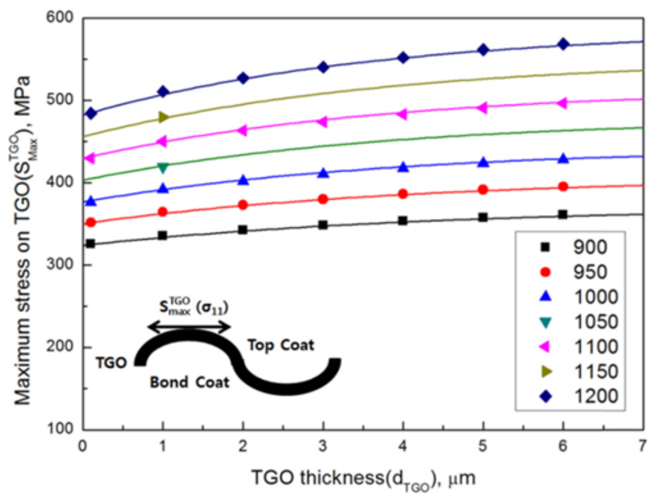

Fig. 8 Stress-TGO thickness relation

1000°C. TGO thicknesses that is calculated by Eqs. (1)-(3) for 1600 and 3200 hours are 8.21 and 10.39 μm, respectively. The maximum thermal stress(S^{TGO}_{Max}) of TBC for those TGO thickness (8.21 and 10.39 μm) can be calculated by Eqs. (4)-(8). The calculated stresses are 435.2 and 438.7 MPa for TGO thickness of 8.21 and 10.39 μm, respectively. Therefore, we can assume that the TBC delamination occurs between 435.2 and 438.7 MPa. These two stresses mean the stress limits (smaller one is conservative limit) to cause TBC delamination. Then, according to the two stress limits (435.2 and 438.7 MPa), two TGO thickness limits for the TBC delamination at each temperature (900 - 1200°C, interval of 5°C) were calculated by Eqs. (4)-(8). Finally, predicted isothermal delamination life time can be calculated by Eqs. (1)-(3) using those two TGO thickness limits calculated above for each temperature. Calculated (Predicted) isothermal delamination life time for each temperature (900 - 1200°C, interval of 5°C) were arranged into the delamination map as shown in Fig. 9.

Delamination map has 3 parts. The first part is the safe zone (under the conservative delamination line) where the TBC delamination does not occur. The second zone is the conservative delamination zone (the area between conservative delamination line and delamination line). There is a possibility that the TBC delamination occurs at the conservative delamination zone. The last area is the delamination zone (the area above delamination line). The TBC delamination is expected at the delamination zone. Fig. 9 also compares the delamination map with real test data.

Since this delamination map is based on both test results and FEA analysis results, the delamination map in this paper can be used to predict the delamination life time not only at tested area but also at untested area. In other words, by Eqs. (1)-(8), aging time and temperature to cause TBC delamination can be simply calculated using stress limits (435.2 and 438.7 MPa).

Commercialized coatings for gas turbines has equivalent operating hours (EOH) of 20,000 - 100,000. It means TBC delamination must not occur at their operating temperature condition. From the suggested delamination map, the maximum operating temperature (990°C) where TBC delamination does not occur can be obtained. From the suggested delamination map, delamination line and conservative delamination line converge on certain temperature, as the exposure (aging) time increases. It means delamination of the TBC does not occur at that converged temperature regardless of aging time. According to the conservative delamination line, the maximum operating temperature can be obtained as 990°C, where TBC delamination does not occurs can be obtained.

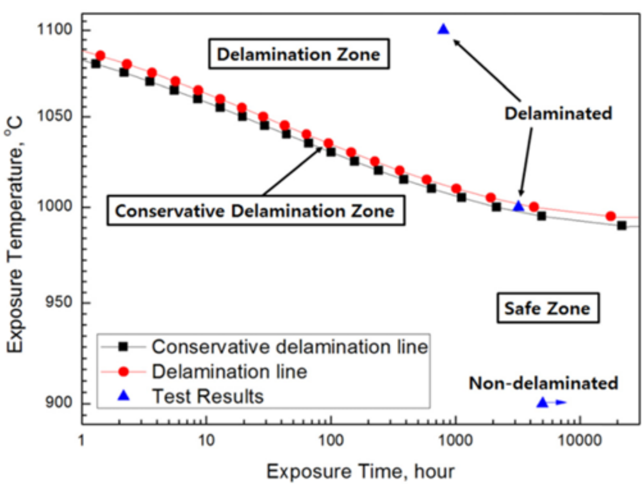

Fig. 9 Stress-Based delamination map and isothermal test results

5. Conclusions

(1) Isothermal aging on coin-type TBC specimens was conducted, and TGO thickness behavior was investigated. The TGO thickness growth prediction method was suggested based on isothermal aging test results. Suggested TGO thickness growth prediction method also can be applied to the thermal fatigue condition.

(2) Finite element analysis was performed to investigate the thermal stress on TGO layer (TGO thickness: 0.1 - 6 μm, Temperature: 900 - 1200°C). FEA results were arranged into Eqs. (4)-(8), and the thermal stress on TGO can be calculated by the equations according to its thickness and temperature.

(3) Finally, stress-based delamination map was suggested. Delamination map has 3 parts. The first part is safe zone (under the conservative delamination line), and the TBC delamination does not occur at safe zone. The second is zone conservative delamination zone (the area between conservative delamination line and delamination line). There is a possibility that the TBC delamination occurs at conservative delamination zone. The last area is delamination zone (the area above delamination line). The TBC delamination must occur at delamination zone. Since this delamination map is based on both test results and FEA analysis results, the delamination map in this paper can be used to predict the delamination life time not only at tested area but also at untested area. In other words, TBC delamination life at any aging temperature and time can be predicted, by Eqs. (1)-(8).

(4) Commercialized coatings for gas turbines has equivalent operating hours of 20,000 - 100,000. It means TBC delamination does not occur at such temperature condition. From the suggested delamination map, the maximum operating temperature (990°C) where TBC delamination does not occur can be obtained.

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