Correlating Thermal Barrier Coating Microstructure Between Engine Run Combustion Hardware and Furnace Cycle Testing

Solar Turbines
A Caterpillar Company

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Abstract

Microstructural investigation was performed on thermally cycled buttons as well as on engine run combustion hardware with operating hours from ~30,000-40,000 hours. The thermally grown oxide (TGO) layers of both were compared, and it was found that TGO composition as well as morphology differed significantly. Thermally cycled buttons showed a relatively thick and uniform TGO layer comprised of alumina above the bond coat with a layer of mixed oxide spinel forming directly above the alumina layer. However, engine run hardware had thin, non-uniform TGO layers with large clusters of mixed oxides scattered throughout the bond coat. Based on TGO thickness only, the engine run combustion liners would still have over 50% remaining life before coating failure. However, the ability to predict remaining life based solely on TGO thickness is uncertain due to the difference in oxide formation. Further analysis is recommended to better understand the impact of TGO growth and the presence oxide clusters on coating life for engine run hardware.

Background

Combustion liners are inspected at engine overhaul, where a combustor can be repaired and successfully operated for another overhaul cycle. As part of the repair, the thermal barrier coating (TBC) is typically removed and reapplied, even though the condition of the coating presently has been in excellent condition. To determine if the coating can be used for another overhaul cycle, condition assessment of the coating from overhaul engines is needed. The objectives of this project are:

1. to determine the condition of combustor liner TBCs at overhaul intervals to establish a more accurate lifetime prediction.
2. to compare the coatings on engine run hardware with microstructural characteristics found in laboratory furnace cycle testing.

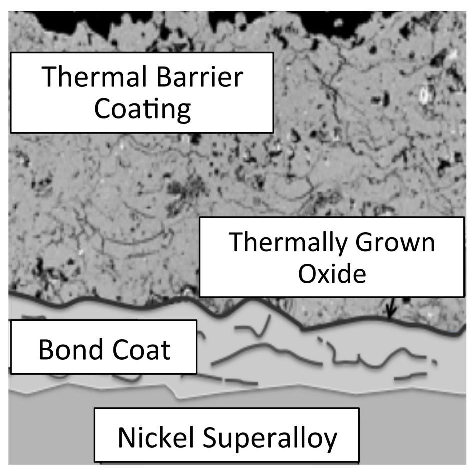

Figure 1. Schematic showing the coating system used on combustor liners. The first coating layer is the bond coat, the top layer is the thermal barrier coating, and the third layer that develops in service is the thermally grown oxide.

Introduction

Currently at Solar, TBC lifetime estimates are based on thermally grown oxide (TGO) thickness when the ceramic topcoat has separated from the bond coat on thermally cycled buttons. However, the environments that TBCs experience in a turbine versus in a laboratory thermal cycling furnace are very different.

It is known that when the TGO reaches a certain thickness, the strain in the multilayer system becomes too great causing spallation of the ceramic topcoat from the base layers[1,2]. This critical TGO thickness is defined as the life-limiting thickness and is used when comparing TBC coated parts from the field[3]. However, the life limiting thickness is strongly influenced by the composition of the TGO. Therefore, TGO thickness and composition of thermally cycled buttons up to failure were compared with TBC coated combustion hardware received from the field after 30,000-40,000 hours of operation in this study to evaluate the validity of basing part lifetime prediction on thermal cycling test results.

Experimental

The coating system used consists of a Ni superalloy base with a NiCrAlY bond coat and an air plasma sprayed (APS) YSZ TBC. The nominal coating composition of the starting materials is shown below in Table I.

Table I. TBC and bond coat starting compositions according to Solar specifications.

Coating	Elemental Composition	Weight Percent (%)
Bond Coat	Nickel	Balance
	Chromium	22
	Aluminum	10
	Yttrium	1
TBC	Zirconia	Balance
	Yttria	7
	Others	4 max.

Thermal cycling tests:

1” dia. buttons were cycled in air in a CM Furnace where 1 cycle follows:

23˚C ↗ 1150˚C ⟶ 10 hrs. ⟶ 1150˚C ↘ 23˚C

Failure of the TBC was specified as the number of cycles that caused complete spallation of the coating from the substrate/bond coat.

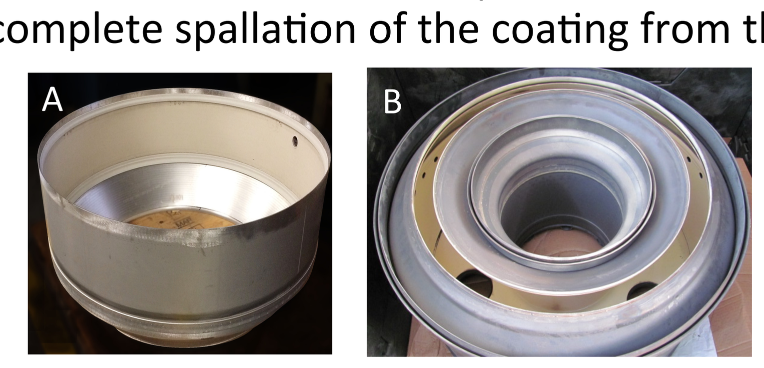

Figure 2. Combustion hardware used to compare with thermally cycled buttons. Image A shows a TBC coated outer combustor liner, and image B shows full combustor assembly.

Specimens were examined using optical microscopy on an Olympus GX51 then coated with a thin layer of Carbon using an Electron Microscopy Sciences 150R ES sputter coater to prepare the surface for scanning electron microcopy (SEM). A Jeol JSM-6460LV SEM was used, and the composition of the coatings were found using EDAX Genesis Energy Dispersive Spectroscopy (EDS). Compositional spectra were obtained using a dead time between 20-30% at 15 keV accelerating voltage, and elemental weight percentages are reported with carbon omitted.

Results and Discussion

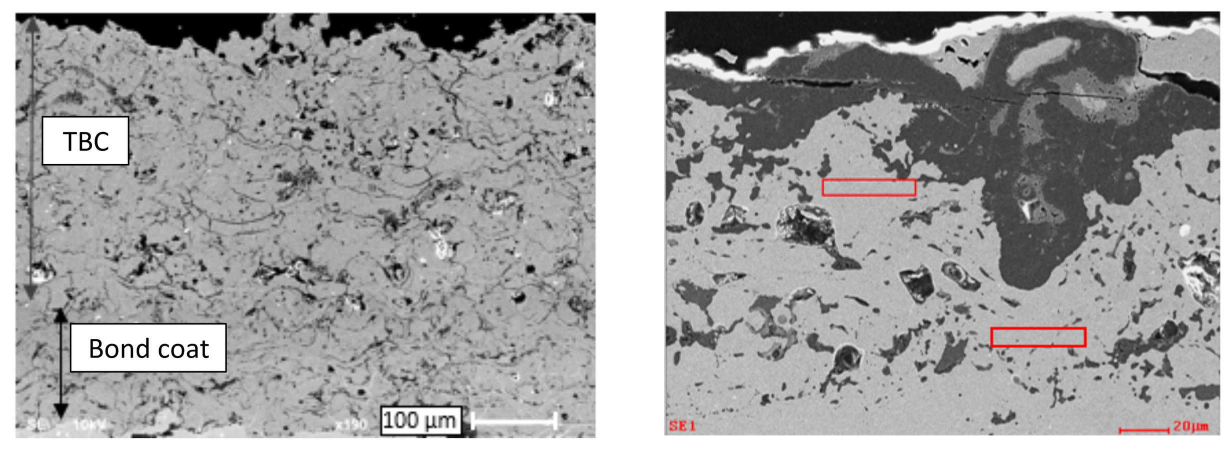

Figure 3. Image at right is an SEM image of the as received APS TBC on a NiCrAlY bond coat. Image at left highlights areas of the bond coat where EDS area analysis was performed at the TBC-bond coat interface as well as at the bond coat-metal interface. Bond coat after 94 cycles is pictured.

Thermal Cycling Tests

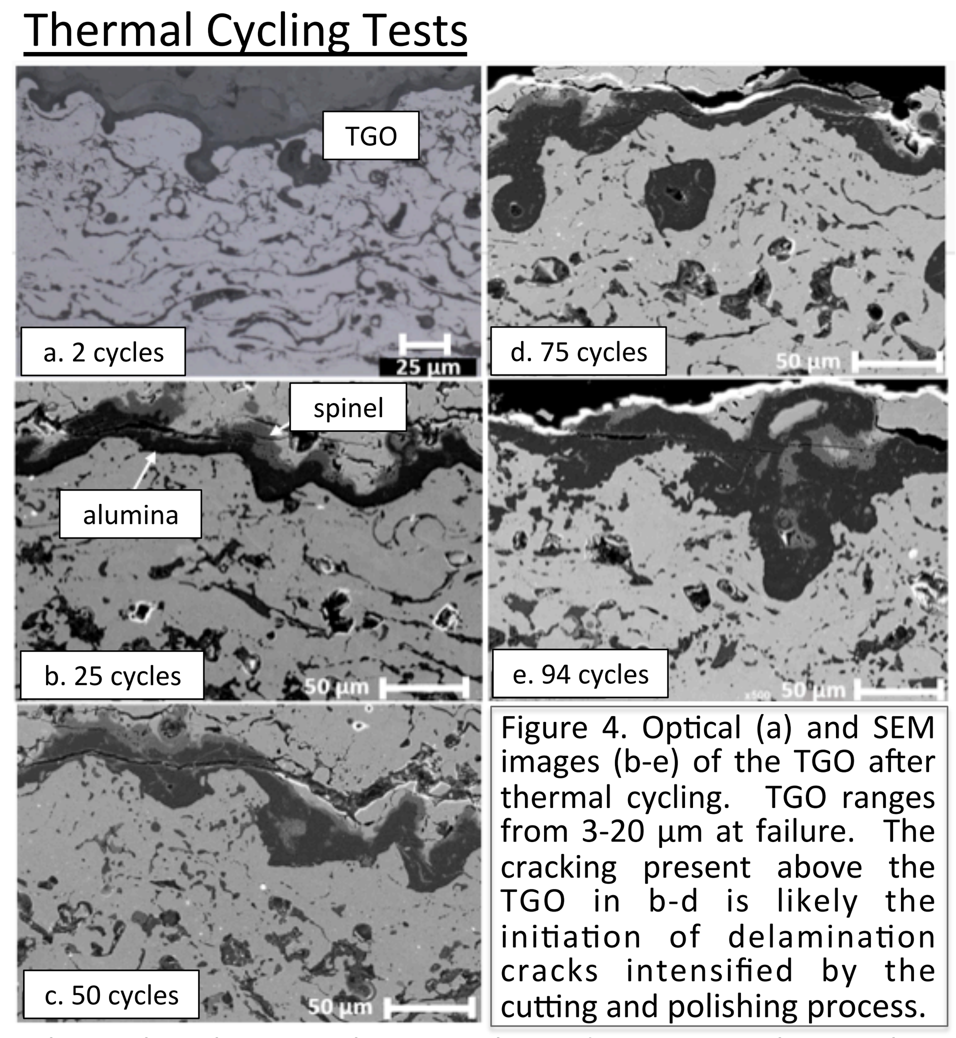

Figure 4. Optical (a) and SEM images (b-e) of the TGO after thermal cycling. TGO ranges from 3-20 µm at failure. The cracking present above the TGO in b-d is likely the initiation of delamination cracks intensified by the cutting and polishing process.

Thermal cycling test buttons showed even TGO layers that consisted of alumina (dark phase) with a thin layer of spinel (light gray) directly above the alumina layer. The presence of this spinel layer will decrease the life of the coating.

Engine Run Combustion Hardware

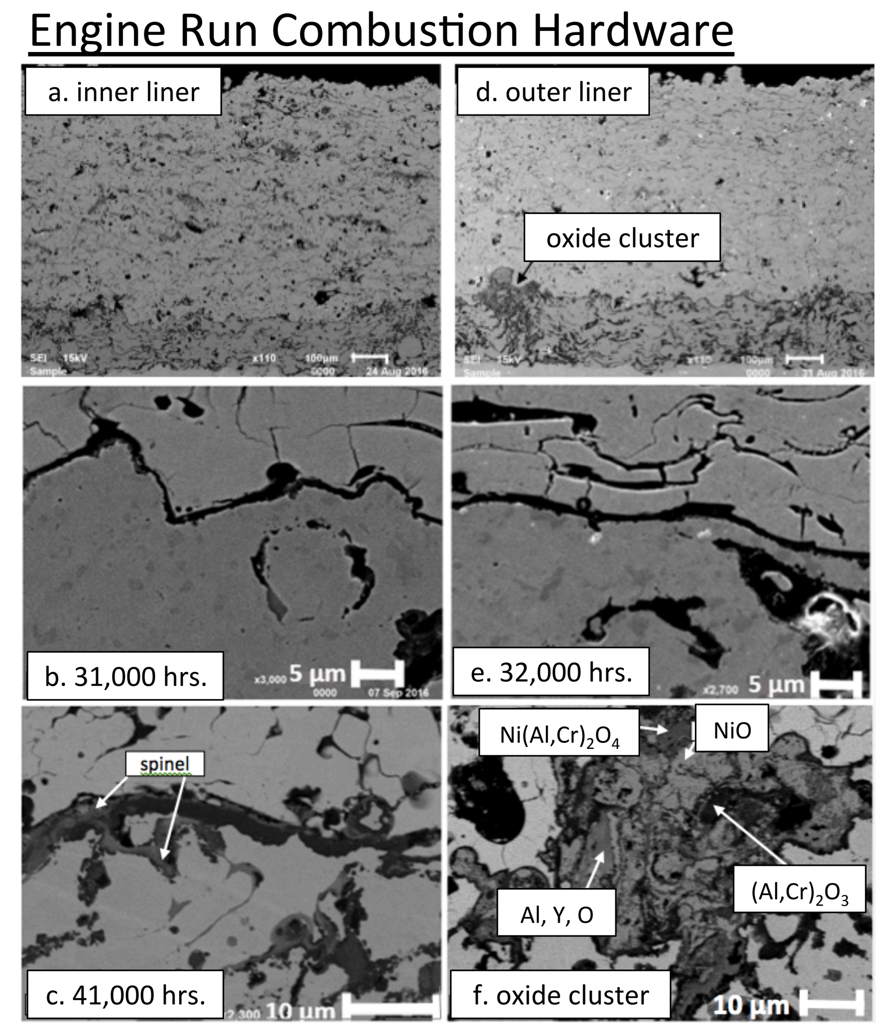

Figure 5. Images a and d show representative microstructures of an inner liner and outer liner, respectively. Images b, c, and e show TGOs present in the engine run hardware. Image f shows an oxide cluster.

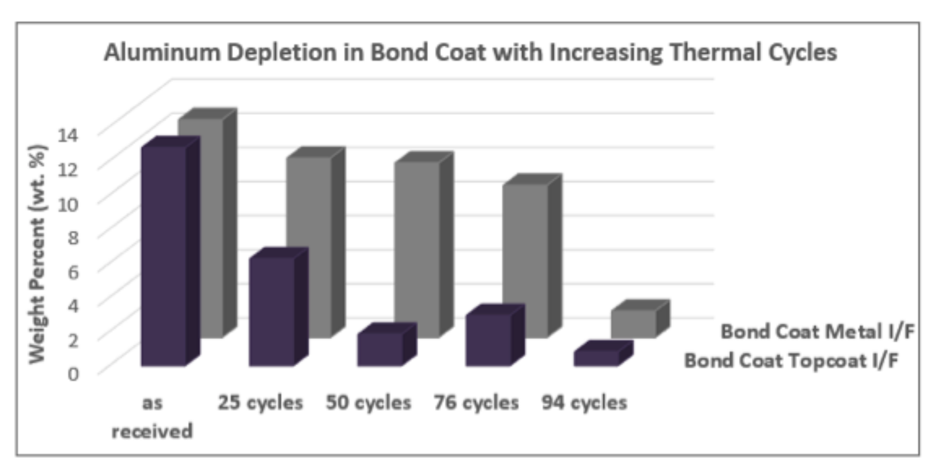

Figure 6. Aluminum composition change in bond coats of thermal cycling test buttons. At 94 cycles, Al is depleted throughout the entire bond coat.

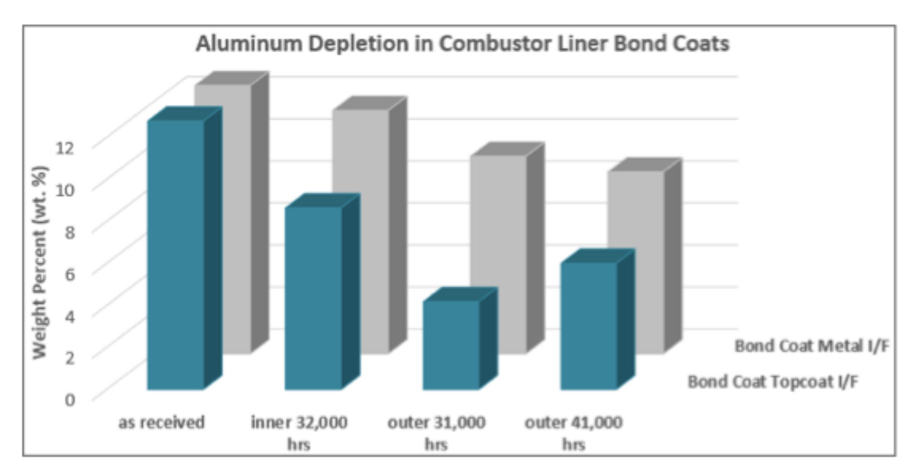

Figure 7. Aluminum composition change in engine run hardware. Al concentration is still sufficient at both the TBC-bond coat and bond coat-metal interfaces.

Conclusions

- A comparative study was completed to investigate the difference in microstructure and composition of thermally cycled buttons and engine run combustion hardware with ~30,000-40,000 operating hours.
- Largest TGO layer thickness found in the engine hardware was minimal at ~3 µm.
- As compared to TGO thickness at failure of thermally cycled buttons, which was 15-20 µm, engine run hardware TBCs have seen well under half their estimated lifetime.
- TGO microstructure and composition differed significantly, however, making that direct comparison uncertain.
- Thermally cycled buttons contained thick, even TGO layers that consisted of alumina with a layer of mixed oxide spinel above the alumina layer. The uniform spinel layer would cause increased strain in the system that would contribute to coating failure.
- The engine hardware had very thin, uneven TGO growth that was mainly alumina with sparse areas of mixed oxide spinel formation. There were also large clusters of oxides found along the TGO.
- It is presently unclear how these oxide clusters will affect TGO growth and the critical TGO thickness to failure in engine hardware.
- Further work to determine the source of the oxide clusters and their impact on coating life is recommended.

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References

1. Evans, A. G.; Mumm, D. R.; Hutchinson, J. W.; Meier, G. H.; Petit, F. S. *Mechanisms Controlling the Durability of Thermal Barrier Coatings*. Progress in Mat. Sci., 2001, 46 (5) 505-553.
2. Rabiel, A.; Evans, A. G.; *Failure Mechanisms Associated with the Thermally Grown Oxide in Plasma-sprayed Thermal Barrier Coatings*. Acta Materialia, 2000, 48 (15) pp. 3963-3976.
3. Li, Y.; Li, C. J..; Zhang, Q.; Yang, G. J.; Li, C. X.; *Influence of TGO Composition on the Thermal Shock Lifetime of Thermal Barrier Coatings with Cold-sprayed MCrAlY Bond Coat*. J. of Thermal Spray Tech., 2010, 19 (1) pp 168-177.