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# Thermal shock resistance of air plasma sprayed thermal barrier coatings

N.A. Fleck [a,*], A.C.F. Cocks [b], S. Lampenscherf [c]

[a] *Cambridge University Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK*
[b] *Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK*
[c] *Siemens AG, Corporate Technology, CT RTC MAT CPM-DE, Otto-Hahn-Ring 6, 81739 Munich, Germany*

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**Abstract**

The spallation resistance of an air plasma sprayed (APS) thermal barrier coating (TBC) to cool-down/reheat is evaluated for a pre-existing delamination crack. The delamination emanates from a vertical crack through the coating and resides at the interface between coating and underlying thermally grown oxide layer (TGO). The coating progressively sinters during engine operation, and this leads to a depth-dependent increase in modulus. Following high temperature exposure, the coating is subjected to a cooling/reheating cycle representative of engine shut-down and start-up. The interfacial stress intensity factors are calculated for the delamination crack over this thermal cycle and are compared with the mode-dependent fracture toughness of the interface between sintered APS and TGO. The study reveals the role played by microstructural evolution during sintering in dictating the spallation life of the thermal barrier coating, and also describes a test method for the measurement of delamination toughness of a thin coating.


*Keywords:* Thermal barrier coatings; Sintering; Delamination; Fracture; Air plasma sprayed coating

## 1. Background

Air plasma sprayed coatings are ubiquitous in gas turbines and are used extensively to provide thermal and environmental protection to creep resistant components. They form an important part of a multi-layered system comprising a bond coat (BC), thermally grown oxide (TGO) and the APS TBC top coat. The as-deposited APS coating comprises yttria stabilised zirconia (YSZ) splats, with intervening cracks and equiaxed pores, as shown in Fig. 1. A typical TBC layer is 300–500 μm thick, while the splats have a radius of 10–50 μm and a height of about 1–5 μm. Each splat comprises columnar grains of diameter 0.1–0.2 μm, and these extend over the height of the splat. The splats are separated by cracks, which are bridged by asperities, comparable in size to the columnar grains, Eriksson et al.[1] The asperities undergo sintering when the TBC is held at elevated temperature, and this leads to a progressive increase in stiffness (both in-plane and out-of-plane) with time. Such an evolution in microstructure is evident from the two micrographs as shown in Fig. 1. Pores of diameter 1–20 μm also exist, which occupy about 15% of the coating volume.

In the recent studies of Fleck and Cocks[2] and Cocks et al.[3] it is shown that the compliance of the coating is largely dictated by the compliance of the bridged inter-splat cracks, with the porosity making a more minor contribution. Cocks et al.[3] derived a full constitutive description of the sintering of the APS coating and highlighted the role of asperity sintering in dictating the in-plane and out-of-plane moduli. The level of in-plane stress in an APS coating at steady state engine temperature is determined by asperity sintering and Coble creep of the fine-scaled columnar-grained splats. They show that the sintering-driven rate of increase of in-plane modulus in a constrained coating is typically half that experienced by a freestanding coating. In the present study we report experimental data for the evolution of in-plane modulus with time at temperature for a freely sintered coating and invoke the time shift as predicted by Cocks et al.[3] to determine the evolution of modulus in a constrained coating. The increase in modulus leads to an increase in thermal stress during cool-down and reheat, and thereby to an increase in energy release rate associated with a delamination crack.

Zhao et al.[4] and Thery et al.[5] have also assumed that the Young's modulus of the coating increases with time at temperature due to sintering in their assessments of delamination failure. They obtained the lifetime of the coating by equating the energy release rate after cool-down to room temperature to the interfacial toughness. Zhao et al.[4] assumed that the

* Corresponding author. Tel.: +44 1223 332600.
*E-mail address:* nafl@cam.ac.uk (N.A. Fleck).

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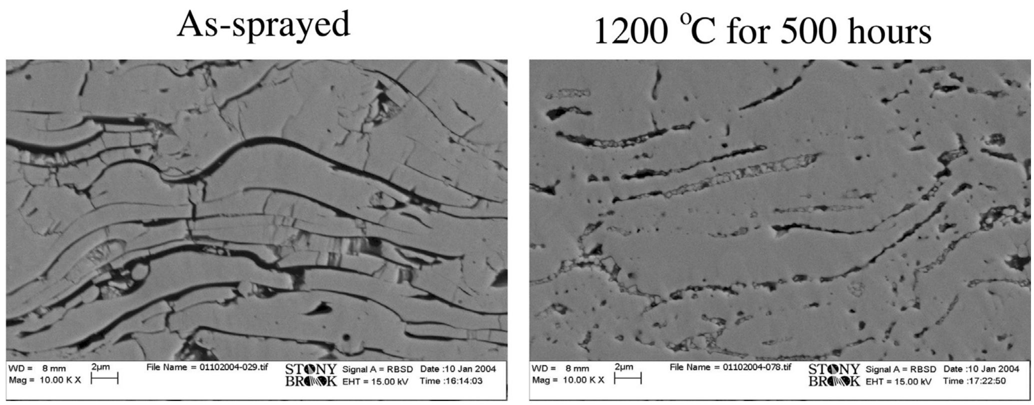


Fig. 1. The inter-splat sintering of an APS coating.

Source: Modified from Anand Kulkarni "On the Porosity-property Correlations in Thermo-structural Coatings: Towards an Integrated Approach" State University of New York at Stony Brook, 2002. Used with permission.

interfacial toughness remains constant, while Thery et al.[5] employed the observation that the interfacial toughness of Electron Beam Physical Vapour Deposition (EBPVD) coatings degrades with time at temperature due to the accumulation of voids and rumples at the bond coat interface. A more complete analysis of the mechanics of delamination has been conducted by Evans and Hutchinson.[6] They focused on the role played by infiltration of calcium–magnesium-alumino-silicate (CMAS) in increasing the modulus of the TBC. In particular, they analysed the energy release rate during a full thermal cycle, for the case of a stiff top layer (due to CMAS infiltration) upon an underlying EBPVD coating, including the role of thermal inertia and finite heat exchange at the top surface of the coating. They concluded that thermal inertia plays a negligible role for thin coatings (thicknesses less than 1 mm). Here, we adopt a similar approach for an APS coating, but for the first time, take into account the full profile of Young's modulus with depth due to the sintering gradient through the coating.

### *1.1. Scope of paper*

The possibility of delamination during a cool-down/heat-up thermal cycle (associated with engine shut-down/start-up) is assessed for a pre-existing delamination along the interface between thermal barrier coating (TBC) and underlying thermally grown oxide (TGO). The analysis proceeds as follows:

1. The thermal inertia is taken as negligible. Consequently, the temperature profile within the coating varies linearly with depth for both the long-term hold periods at high temperature and for the shorter intermittent cycles of cool-down/reheat. Measurements of the evolution of in-plane Young's modulus $E$ with time at temperature are reported: it is shown that $E$ scales linearly with the Larsson Miller Parameter (LMP).
2. Coble creep and sintering relax the in-plane stress during the high temperature hold period, as demonstrated by Cocks et al.[3] resulting in negligible stress within the coating. In contrast, a transient cool down/heat up cycle induces thermal stress within the coating, with the attendant possibility of growth of the delamination.
3. The mode I and mode II interfacial stress intensity factors (and thereby energy release rate $G$ and the associated phase angle of loading $\psi$) are calculated over the transient temperature cycle, and the most severely loaded point in the cycle is identified. Progressive sintering within the coating during engine operation leads to an increase in Young's modulus throughout the coating and thereby to a progressive increase in $G$ with time at temperature. Upon equating $G$ with the measured interfacial toughness, the lifetime of the coating is determined.

## 2. The thermal history

Consider the temperature distribution within an APS layer of height $h$, as shown in Fig. 2. We assume that the temperature changes slowly compared with the thermal diffusion time and, at any instant, we take the temperature distribution to be linear through the coating from a surface value of $T_S$ to an interface value of $T_I$ at the TGO: the temperature at a height $y$ above the interface is given by

$$T(y) = T_I + (T_S - T_I)\frac{y}{h} \tag{1}$$

It is envisaged that the TBC is maintained at a steady hot temperature distribution $T^H(y)$ for extended periods and this gives rise to progressive sintering. Consequently, the in-plane

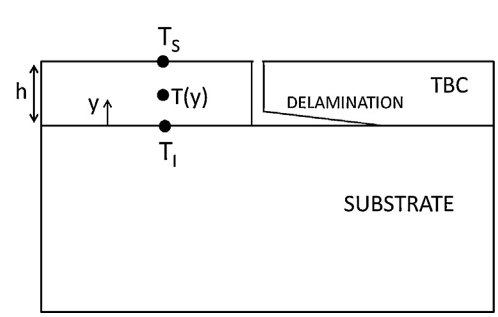


Fig. 2. An APS TBC coating, with a pre-existing delamination crack.