On cooling rate dependent spallation of $\alpha$-alumina films grown by oxidation

[Abstract]

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Tolpygo and Clarke [1,2] presented an excellent experimental study on the room temperature spallation failure of $\alpha$-alumina films grown by oxidation on Fe-Cr-Al alloy. Their observations are remarkable and thought-provoking. In their work, $\alpha$-Al$_2$O$_3$ films of different thicknesses were formed on the surface of Fe-Cr-Al heat-resistant alloy substrates of different thicknesses by oxidizing them at 1200°C for different time periods. Then, the film-substrate material systems were cooled to room temperature at different cooling rates. Cooling causes an increase of compressive in-plane residual stress in the $\alpha$-Al$_2$O$_3$ films due to thermal expansion mismatch between the films and the substrates. Their major observations were as follows: No separation or spallation failure occurs during cooling at any rate. For specimens cooled to room temperature at rates in the range $5^\circ$–$200^\circ$C min$^{-1}$, circular interfacial separations develop, apparently spontaneously, at a constant compressive residual stress far below the critical buckling stress: The separations nucleate, grow in separation distance and propagate radially. After a period of slow and stable growth, some of these separations then grow abruptly and the oxide spalls off. It is also interesting to note that no separation or spallation occurs at any specimen at extremely slow cooling rates ($\leq 2^\circ$C min$^{-1}$) where the magnitude of the compressive residual stress is the smallest and at very fast cooling rates ($\geq 500^\circ$C min$^{-1}$) where magnitude of the compressive residual stress is the largest. Various explanations for the phenomenon were proposed and thoroughly and insightfully examined by Tolpygo and Clarke [1,2] without conclusions.

The earlier work [3,4] from the last two authors hypothesizes that pockets of energy concentration (PECs) in the film-metal material system exist due to dynamic and non-uniform plastic relaxation or creep in the film and Fe-Cr-Al alloy substrate during cooling. PECs are the cause of film separation and spallation at constant in-plane compressive stress after cooling to room temperature. PECs are formed during cooling and are randomly distributed. Their energy depends on cooling rate, film thickness, metal thickness, etc. More
details about PECs regarding their origin and the resulting bubble energy will be explained at appropriate points in the following development. Based on this hypothesis, an analytical mechanical model is developed [3,4] to predict the spallation behavior, including the separation nucleation, stable and unstable growth, and final spallation and kinking off. The predictions from the developed model are compared against experimental results and excellent agreement is observed. The mechanical model is also extended to predict the spallation behaviour of thermal barrier coatings in aero-engine turbine blades with good agreement with test results [5].

The present work focuses on the cooling rate dependent spallation behaviour and discovers that the PECs are closely related to the cooling rates. At both extremely slow cooling rates (≤2°C min⁻¹) and very fast cooling rates (≥500°C min⁻¹) the residual stresses in the α-alumina films are independent of cooling rates, and hence any non-uniform distribution of cooling rates results in no variation of residual stresses in the α-alumina films. No PECs are available in the films. In contrast, at cooling rates in the range 5°–200°C min⁻¹, the residual stresses in the α-alumina films are strongly dependent on cooling rates, and hence any non-uniform distribution of cooling rates results in variation of residual stresses in the α-alumina films. The present work shows that a small variation of residual stresses can provide enough PECs for spallation at different cooling rates. A mechanical model is developed which gives predictions in excellent agreement with test results [1,2].

References