Finite element thermal stress simulation of nano-coated gas turbine blade samples under high temperature

Kadir, A, Beg, OA, Beg, TA and Jouri, WS

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1. INTRODUCTION

Several studies have been communicated in recent years considering nano-coating protective layers for gas turbine environments. They have generally shown that improved protection is achieved compared with conventional thermal barrier coatings (TBCs) which are susceptible to various life limiting issues associated with their operating environment including erosion, corrosion, oxidation, sintering and foreign object damage (FOD) [1,2]. Nano-coatings engineered for high temperature applications have been investigated for surface roughness and topography, residual stress, adherence, damage tolerance and resistance, tribological properties, lubrication, coefficient of friction and hot hardness. Motivated by these developments, in this presentation we describe recent finite element thermal stress simulations of nano-coated (Aluminium Oxide/Titanium Oxide metallic nano-particle mix). The simulations demonstrate that largely due to the higher thermal conductivity and smaller size of nano-particles, they achieve improved bonding in coatings and dissipate heat better than conventional micro-coatings. Greater integrity of the coating is achieved and lower susceptibility to corrosion gas penetration is obtained with nano-coatings compared with micro-coatings.

2. NANO-COATING PROPERTIES

Since a continuum-based finite element approach is adopted, molecular variations in nano-particle dynamics in the coating cannot be simulated. Instead an average value of materials properties is adopted for a 60/40% Titanium oxide (TiO$_2$)-: aluminium oxide (Al$_2$O$_3$) mix nano-coating (powder). The table below summarizes the key material properties (Young modulus, Poisson ratio, density and thermal conductivity) for the original nano-powders and the composite nano-coating:

3. ANSYS THERMAL STRESS FORMULATION

In ANSYS to simulate coupled thermal stress analysis, the stresses are related to the strains as follows [3]:

\[
\varepsilon = [D] \sigma = \varepsilon_0 + \varepsilon_1 + \varepsilon_2 + \varepsilon_3
\]

\[
[D] = \begin{bmatrix}
1 & v & 0 \\
v & 1 & 0 \\
0 & 0 & \frac{1 - v}{2}
\end{bmatrix}
\]

\[
\sigma = \begin{bmatrix}
\sigma_x & \sigma_y & \sigma_z \\
\sigma_y & \sigma_x & \sigma_z \\
\sigma_z & \sigma_y & \sigma_x
\end{bmatrix}
\]

\[
\varepsilon = \begin{bmatrix}
\varepsilon_x & \varepsilon_y & \varepsilon_z \\
\varepsilon_y & \varepsilon_x & \varepsilon_z \\
\varepsilon_z & \varepsilon_y & \varepsilon_x
\end{bmatrix}
\]

\[
\varepsilon_0 = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\[
\varepsilon_1 = \begin{bmatrix}
\sigma_x \nu & \sigma_y \nu & 0 \\
\sigma_y \nu & \sigma_x \nu & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\[
\varepsilon_2 = \begin{bmatrix}
\frac{1}{2} \sigma_x^2 & 0 & 0 \\
0 & \frac{1}{2} \sigma_y^2 & 0 \\
0 & 0 & \frac{1}{2} \sigma_z^2
\end{bmatrix}
\]

For the 3-dimensional analysis, thermal strain vector takes the form:

\[
\varepsilon = \begin{bmatrix}
\varepsilon_x & \varepsilon_y & \varepsilon_z
\end{bmatrix}^T
\]

\[
\sigma = \begin{bmatrix}
\sigma_x & \sigma_y & \sigma_z \\
\sigma_y & \sigma_x & \sigma_z \\
\sigma_z & \sigma_y & \sigma_x
\end{bmatrix}
\]

\[
[D] = \begin{bmatrix}
1 & v & 0 \\
v & 1 & 0 \\
0 & 0 & \frac{1 - v}{2}
\end{bmatrix}
\]

4. ANSYS MESH AND THERMAL STRESS ANALYSIS

A three-dimensional model was created using the ANSYS static structural geometry modeller to represent a steel sample under high temperature corrosion. A two-layered domain in (x,y,z) space is created with the base layer representing the gas turbine blade substrate (AlSi 304 super alloy) and the upper layer simulating the Aluminium-Titanium oxide nano-coating, as shown below. Note the nano-coating completely engulfing the substrate specimen. The fixture (cylindrical hole) is also shown in order to compare simulations with future HvOF experiments. Shows below the front (top) and 3-D view of the model. The clamping is achieved via the hole which penetrates the entire substrate and is filled with nano-material during the casting process. The nano coating thickness is 0.816 mm. The substrate sample dimensions are 10.89mm (length) and 20.76mm (width). The boundary conditions imposed on all six faces of the coated model is a thermal one due to the hot gas at an average temperature of 1000°C. The structural boundary condition is the fixing hole where the model is constrained.

The von Mises or equivalent stress $\sigma_e$ (output as SEQV) is computed as:

\[
\sigma_e = \sqrt{\frac{1}{2} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right]}
\]

The equivalent stress is related to the equivalent strain $\varepsilon_{eq}$ through:

\[
\varepsilon_{eq} = \sqrt{\frac{1}{2} \left[ (\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 \right]}
\]

5. CONCLUSIONS

In all cases the nano-coating is found to provide superior thermal protection to the steel substrate (AlSi 304 super alloy). High stress areas are completely eliminated with nano-coating whereas they are present with titania micro-coatings. Although titania oxide has excellent thermal resistance properties, the alumina nano-powder when mixed with titania, produces an improvement which is in contrast to inter-diffusion and this leads to stability during exposure to elevated temperatures for long periods of time, thus preserving the sharp-interface and minimizing thermal stresses which are necessary for good thermal insulation performance. The alumina material tends to form an amorphous structure which is deposited onto a substrate which is held at a relatively low temperature and in the alternative it tends to form a crystalline structure when applied by a super deposition to a substrate held at a relatively high temperature. Either case will result in a very resilient nano-coating which achieves excellent bonding to the super alloy substrate and prevents the penetration of hot gases at the nanoscale. The micro-scale degradation are mitigated. This is not possible in the micro-coating which fails, permits heat penetration, has reduced integrity and eventually cracks. Alumina being brittle to the coating layer and in contact with the substrate has the desirable characteristics that can be achieved. The nano coating substrate which forms on the substrate due to oxidation of the substrate will be alumina, therefore having a nano-structured alumina layer in the coating adjacent to a naturally occurring alumina layer will probably provide the best coating adherence as noted in [4]. Overall much lower stress, strains and deformations are produced with nano-coatings compared with micro-coatings.

REFERENCES


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