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EXPERIMENTAL AND CFD EROSION STUDY OF HIGH-TEMPERATURE AIRCRAFT GAS TURBINE MICRO-COATING BEHAVIOUR

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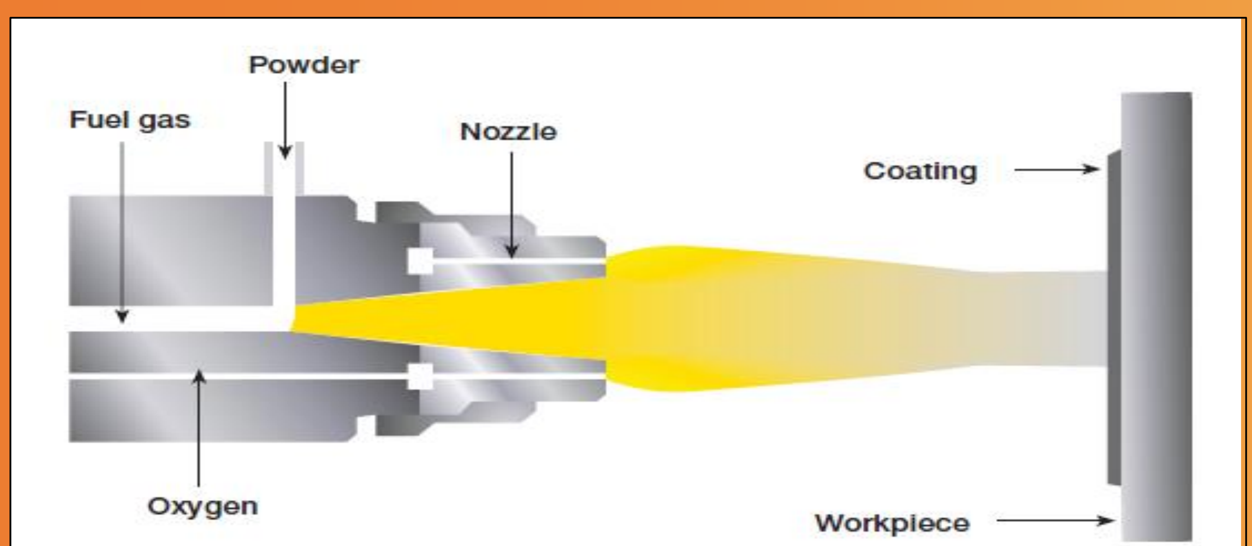
1.INTRODUCTION

- High temperature corrosion protection is a critical area in modern gas turbine engine (GTE) design. It continues to motivate extensive studies aimed at developing robust thermal barrier coatings for enhancing the protection of components from extremely corrosive working environments. Corrosive gases also induce erosion of the surface coating which may lead to spalling, crack proliferation etc. In this presentation we describe recent HVOF (high velocity oxy fuel) experiments conducted on micro-coated stainless steel samples to simulate high-temperature behaviour of gas turbine blades. The rectangular steel test sample used is 20mm x 10 mm x 1.5mm. The AISI 304 steel is selected since it has excellent tolerance to high temperature with reference to oxidation and has good mechanical properties since it is known to increase the strength, efficiency and life span of the blades [1]. Results are presented for NiCrAlY as a coating material via the HVOF technique on the AISI 304 sample at 750, 800 and 900 Celsius respectively for synthetic air environments over a 100 hour duration. Additionally a comprehensive discrete phase model (DPM) CFD analysis [2] is conducted in **ANSYS FLUENT** software via the SIMPLE algorithm for the micro-coated sample. This allows a prediction of particle erosion and accretion rates can be monitored at wall boundaries. The k-epsilon turbulence model [3] is deployed. Extensive visualization of vorticity contours, erosion rate, pressure distribution and turbulent kinetic energy are shown. CFD simulations capture the surface spalling on the coating and also crack generation zones identified in the experimental results. The study provides insight into actual thermal barrier coating performance.

2.EXPERIMENTAL ASPECTS

High-velocity oxy fuel (HVOF) is a thermal spray coating technique which achieves higher density and harder coatings with less porosity, better adhesion strength, and minimum oxidation while much smaller compressive residual stresses are produced because the powder particles acquire a high kinetic energy during the spraying process and the flame temperature is lower. The sample is sand-blasted and ultrasonically degreased in acetone for 15 minutes and finally cleaned with ethanol prior to coating. The bonding material (adhesive) is composed of SA (super alloy NiCrAlY) and is applied on the specimen (all six surfaces) using a HVOF device at 3400 Celsius. This is the bond coat. Following this the sample is micro-coated with aluminium-titanium oxide coating materials (60:40 ratio) again using HVOF also at 3400 Celsius. After completion of the coating process, the resulting sample is cleaned in acetone and then secured inside a Thermoblance (TGA 92-16 Setaram) in synthetic air (1 bar pressure) commencing from room temperature (20 Celsius) and heating up to 1000 Celsius at a rate of 40 Kelvins/minute. During this heating process the coated sample is exposed to significant oxidation in the Thermobalance, for a period of 72 hours. Following this it is cooled again at a rate of 40 Kelvins/minute. All tests were conducted at the **University of Juame I, Castellón, Spain** in September 2018.



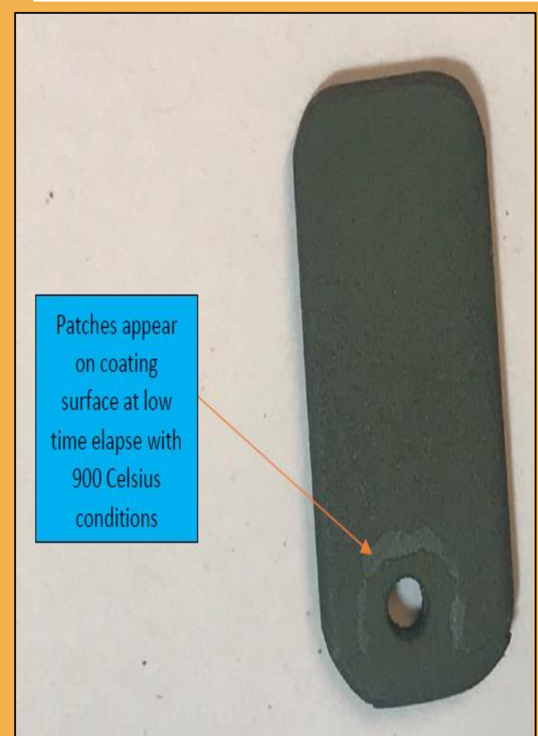
HVOF thermal spray procedure schematic

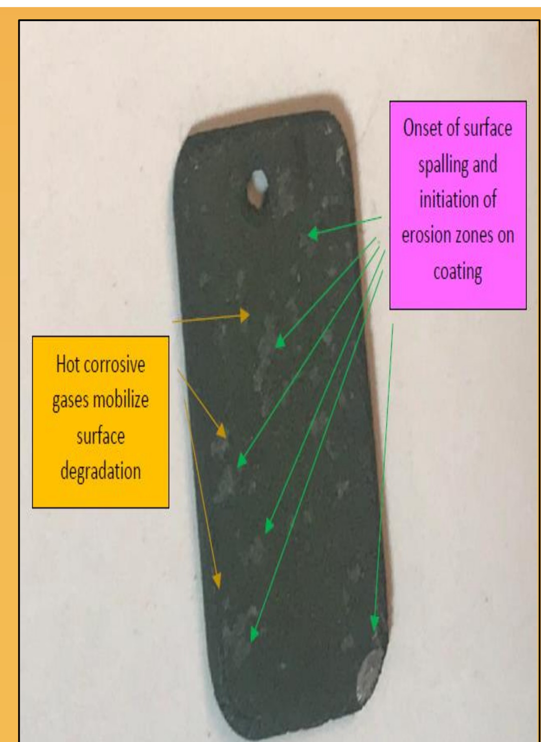
Coated steel sample with fixity

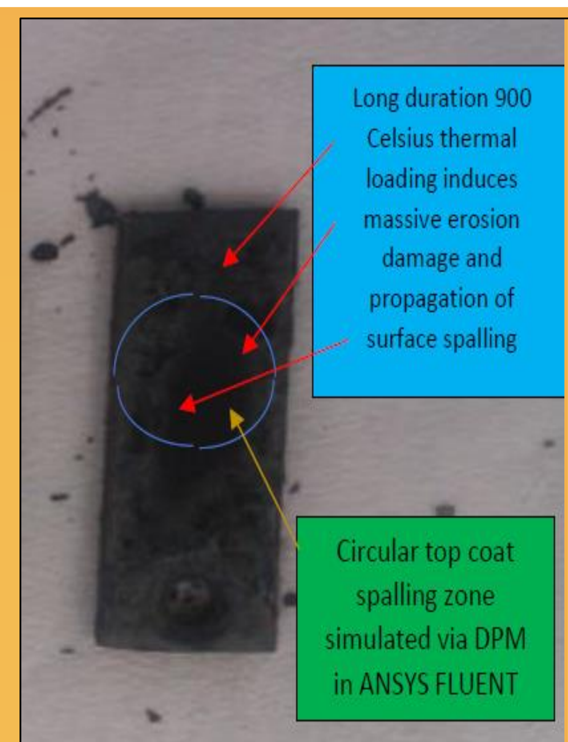
3. THERMOGRAVIMETRIC ANALYSIS (TGA)

The rate of oxidation is a key factor influencing corrosion in high temperature gas turbine engine environments. Oxidation rate provides an approximation of the design life of the material which will be sued as a component in a specific temperature and environment. In addition it produces data and information regarding how fast the oxidation happens and the life expectancy of the material employed under certain atmospheric and thermal conditions. High resistance of the stainless steel is in general associated with the formation of chromic oxide, Cr_2O_3. This protective sale remains under lightly oxidising conditions with development kinetics which follows a parabolic relationship. As the temperature is elevated TGA shows that a parabolic profile of weight gain against time at 900 Celsius. This implies that AISI 304 cannot withstand the increase in temperature and at any time it will fracture. This further indicates that enhancement in temperature is problematic for the substrate or any other component synthesized from AISI 304 super alloy. The oxidation process involves changes. There is generation and growth of a protective oxide scale on the surface of the material. In many cases the scale produced is usually smooth and bonded. It does not spall, break or sustain damage. However in other cases there may be significant spallation or even fracture (crack) formation which continues to proliferate.

At lower temperatures, the protective oxide scale (layer) on the substrate surface is very smooth and adheres quickly to the surface and does not spall, disintegrate or break at all. However at higher temperatures (900 Celsius is relevant to actual gas turbine blade environments) the spallation or the breakdown begins and continues. This is usually attributable to stress generation on the oxide scale during the development or growth process when the weight increases due to the oxidation process. However, at certain locations on the substrate, the scale layer cannot withstand high stress concentrations, and this results in **cracking in the scale and significantly elevated surface erosion of the coating** on the substrate. Fig. left below shows that no cracks are generated in the sample although clear surface erosion is captured. Fig right below however shows patches and the disappearance of the coating material i.e. **massive erosion and ablation**. After exposure to corrosive hot gases the oxidation process clearly generates strong spallation on the sample. This also concurs with other studies [1]. The subsequent CFD analysis is therefore conducted with the objective of aiming to capture the surface erosion characteristics on the sample. In this regard a circular zone is modelled with a 3-D CFD DPM simulation.







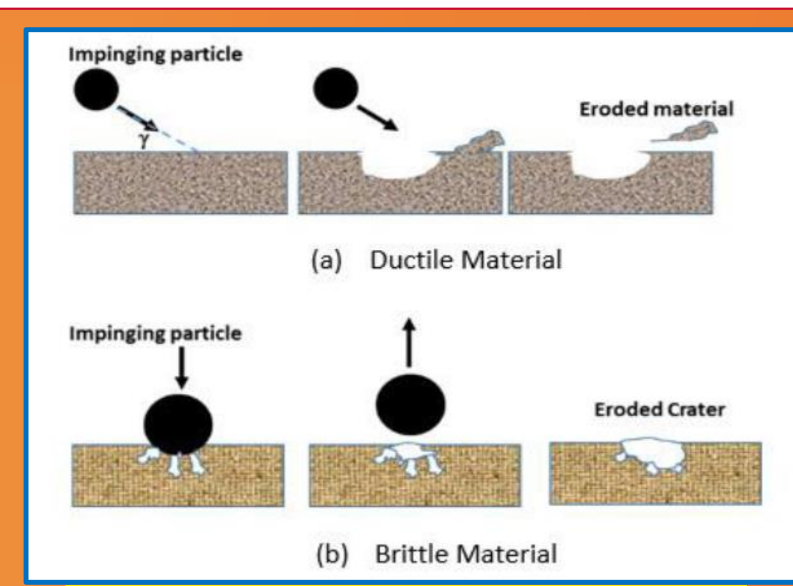
4.DPM CFD EROSION SIMULATIONS

- The CFD analysis is used to generate a representative pressure and thermal field. This grid refinement is conducted in the solver phase of the simulation to avoid altering the main mesh of the structure and avoiding errors. The standard *K-epsilon* turbulence model [3] was used in this simulation to provide enough refinement in the velocity field and simultaneously avoid excessive compilation times required with alternate turbulence models (e.g. RNG). Viscous heating is however switched on to achieve more elegant simulation of the interfacial heat transfer between the coating surface and the corrosive hot gas. Corrosion could not be simulated. However erosion is modelled with the DPM solver. The energy equation is activated to allow a 3-dimensional heat transfer analysis to be included, based on the classical Fourier law (i.e. thermal relaxation effects are neglected). The DPM option is also mobilized to simulate hot gas injection as a continuous stream of high temperature uniform air particles representing corrosive gas impingement on the blade sample onto the model. This provides a facility for computing the corrosion damage induced by hot gas turbine environments. The particles were set at a speed of 5 m/s with a temperature of 1273.15 K (900 Celsius corresponding exactly to the lab. testing conditions). Boundary conditions where left unaltered with the exception of the inlet with a similar velocity condition to that of the injected particles.
- A **SIMPLE** scheme with *second order upwind pressure and momentum* was selected and the solution was left to converge for 1000 iterations. The solution converged after 427 iterations within a time frame of 180 minutes. All simulations were performed using a Lenovo Y510p laptop machine with 8 GB of RAM and an Intel® Core i7-4700MQ CPU @ 2.4 GHz processor with a NVidia® 755m gt SLI GPU running on a Windows 10 platform. The **SIMPLE** (Semi-implicit pressure linked equation) is a very efficient numerical algorithm which computes the discretized momentum equations to generate an interim velocity. The face mass flux is then computed using the momentum interpolation method. The discretized continuity equation is solved to generate the pressure correction. Next the cell-central pressure and velocity are corrected and once convergence is attained the simulations are terminated. Similarly, the temperature values are computed by solving the energy balance equation and updated with corrected results.
- Erosion is a mechanical process that happens due to the repeated impact of solid particles on pipe surface. If the surface material is ductile, repeated particle impacts will result in the formation of craters and platelets; craters will grow with subsequent particle impact and eventually platelets are easily removed into the flow. Many different BCs are available in **ANSYS FLUENT**. When a particle strikes a boundary face, the particle may be reflected via an elastic or inelastic collision, the particle may escape through the boundary (the particle is lost from the calculation at the point where it impacts the boundary), the particle may be trapped at the wall, the particle may penetrate the boundary or slide along the boundary. In the current analysis, the particles once removed from the coating surface are lost forever leading to surface degradation. In ANSYS FLUENT, the erosion model [4] in DPM is based on considerations of impingement angle, impact velocity, particle diameter, particle mass, and collision frequency, and takes the general form:

$$ER = \sum_{p=1}^{N_{trajct}} \frac{\dot{m}_p C(d_p) f(\alpha) v_p^n}{A_{face}}$$

Where,

- $\dot{m}_p$ is the mass flow rate of particles,
- $f(\alpha)$ is the impact angle function
- $C(d_p)$ is the particle diameter function
- v_p is the particle impact velocity
- n is the velocity exponent



Erosion mechanisms for coatings

K-epsilon turbulence model

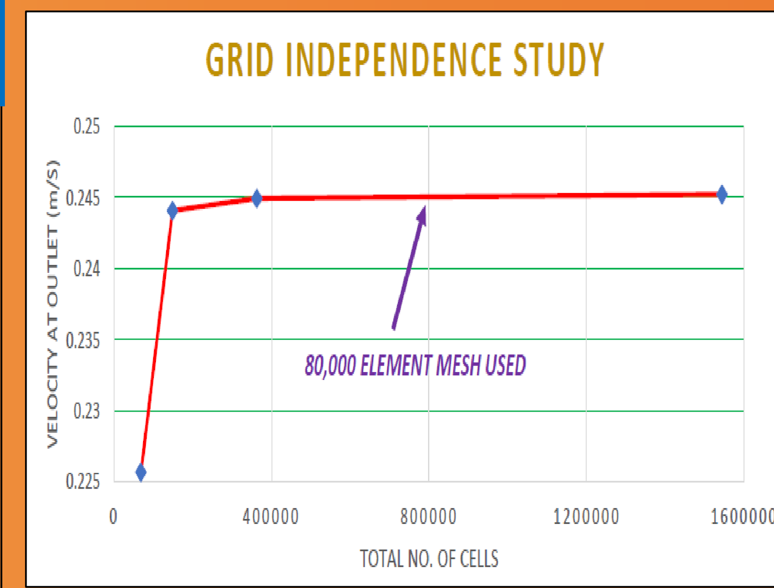
Conservation Equations

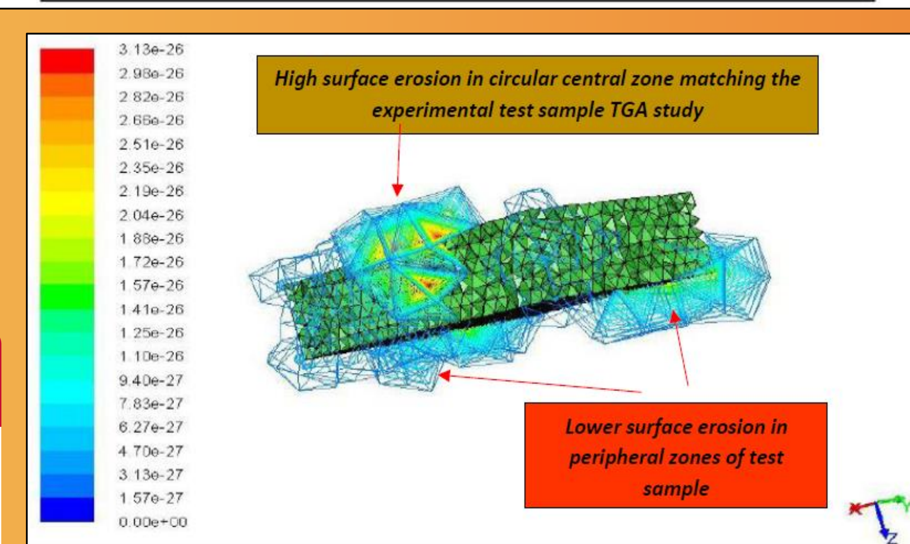
Continuity $$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0$$

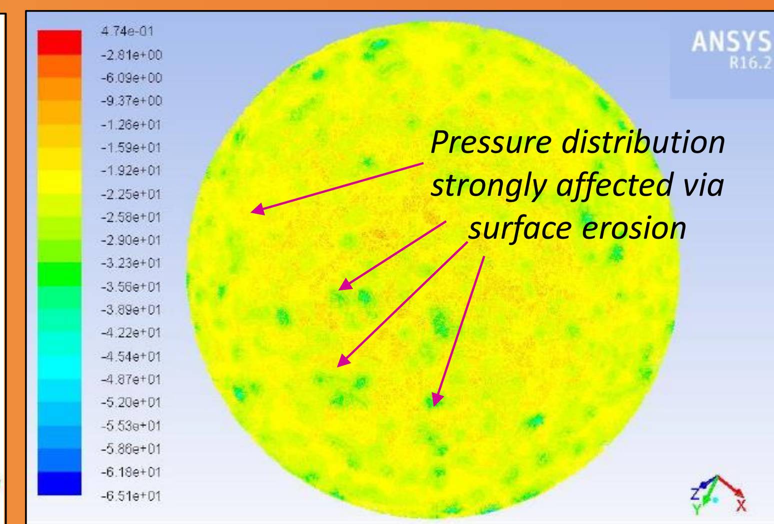
Momentum $$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial P}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}$$

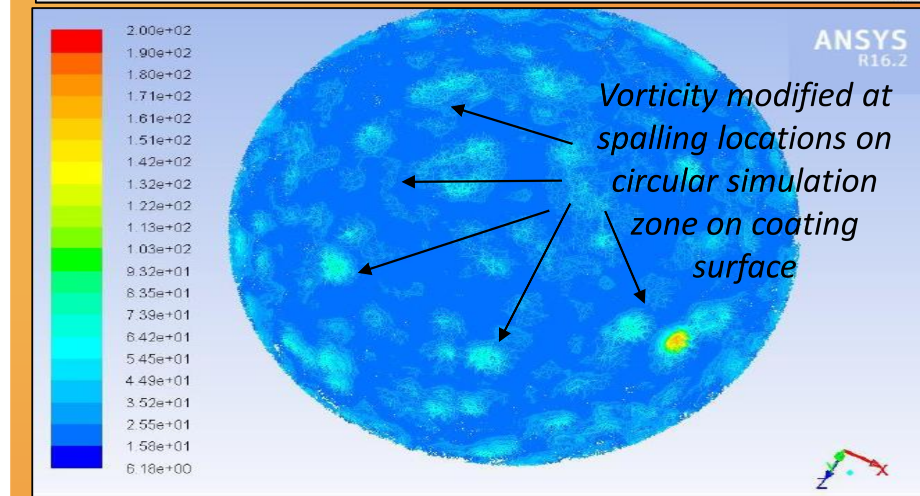
Energy $$\frac{\partial}{\partial t}(\rho h_{tot})+\frac{\partial}{\partial x_j}(\rho h_{tot} u_j)=\frac{\partial P}{\partial t}+\frac{\partial}{\partial x_j}\left(u_i \tau_{ij}+\lambda \frac{\partial T}{\partial x_j}\right)$$

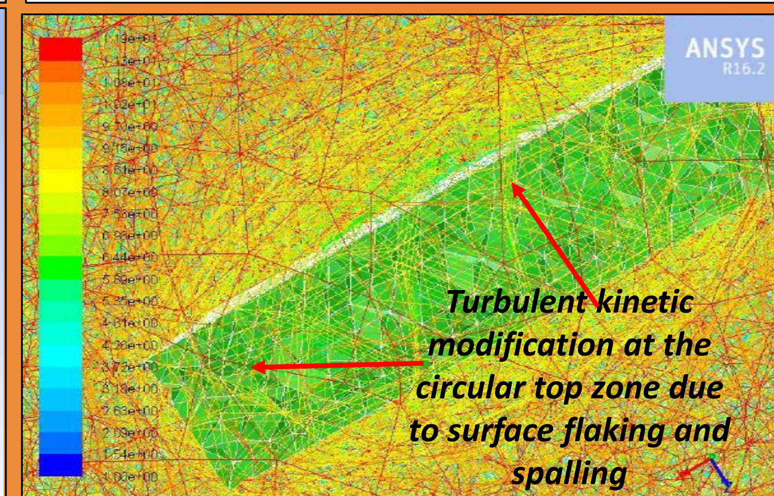
where $$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}+\frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right) \qquad h_{tot}=h+\frac{1}{2}u_i^2$$











5. CONCLUSIONS

Generally good prediction of surface erosion rates has been achieved with the ANSYS DPM simulations. These correlate quite well with the experimental results described earlier, in particular the **same localization of erosion in the circular central zone** is computed. Furthermore the alteration in vorticity, turbulent kinetic energy and pressure distribution on the surface of the eroding coating is correctly simulated. The next stage in the analysis is to plug-in a **chemical corrosive gas model** which can simulate the deposition of oxide layer and thereafter the corrosion-erosion coupled dynamic boundary value problem. .

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