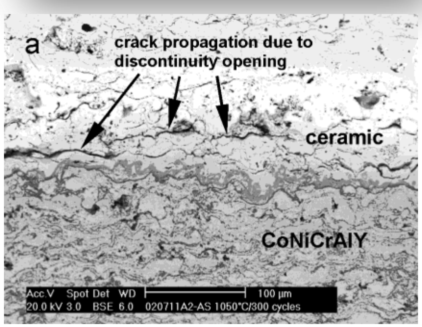
Physics of Failure in Aerospace IVHM



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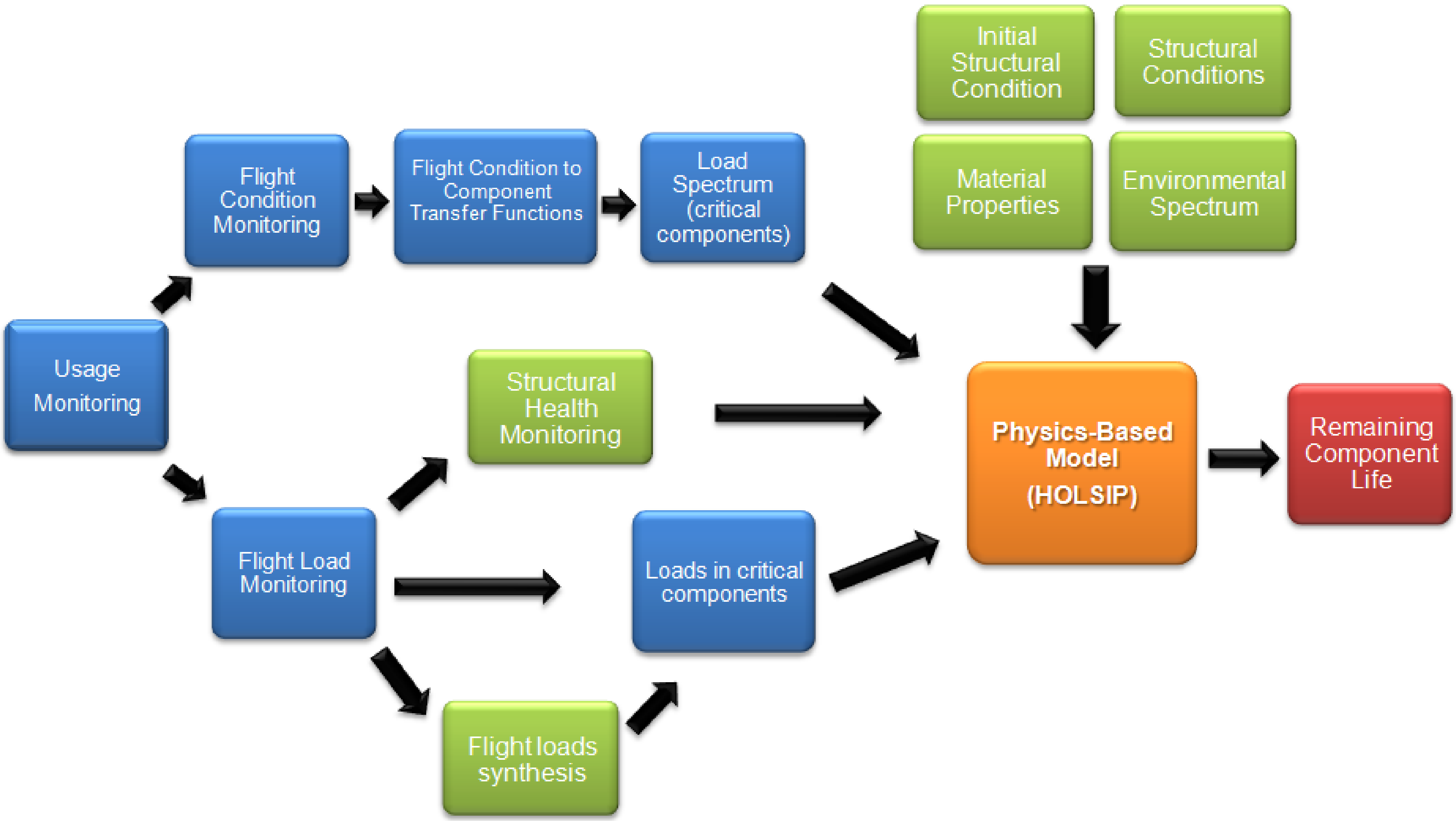
PoF in Aerospace IVHM

- As a component of the IVHM for the Royal Canadian Forces (RCAF) NRC Aerospace has been looking at Physics of Failure in a number of military aircraft.
- They are grouped into various categories related to their operating environment
  - **Rotorcraft**
  - **Transport Aircraft**
  - **Offensive Aircraft**
- Examples of Failure modes are: Fatigue, Wear & Corrosion and others driven by mechanical , electrical, thermal and/or environmental factors. .

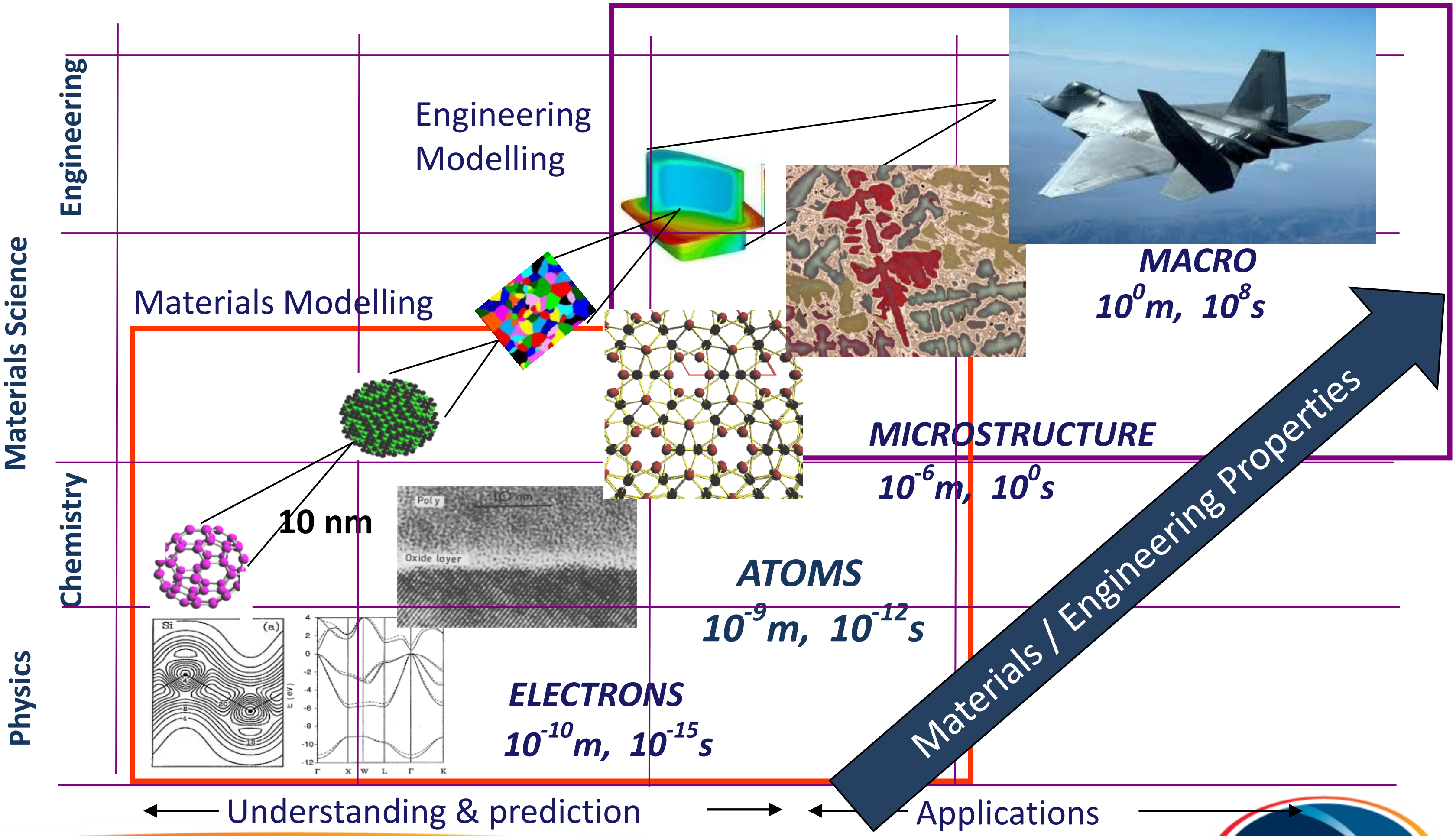
Aerospace System IVHM

- Structures including LG Systems
- Avionics
- Control Systems
- Propulsion Systems

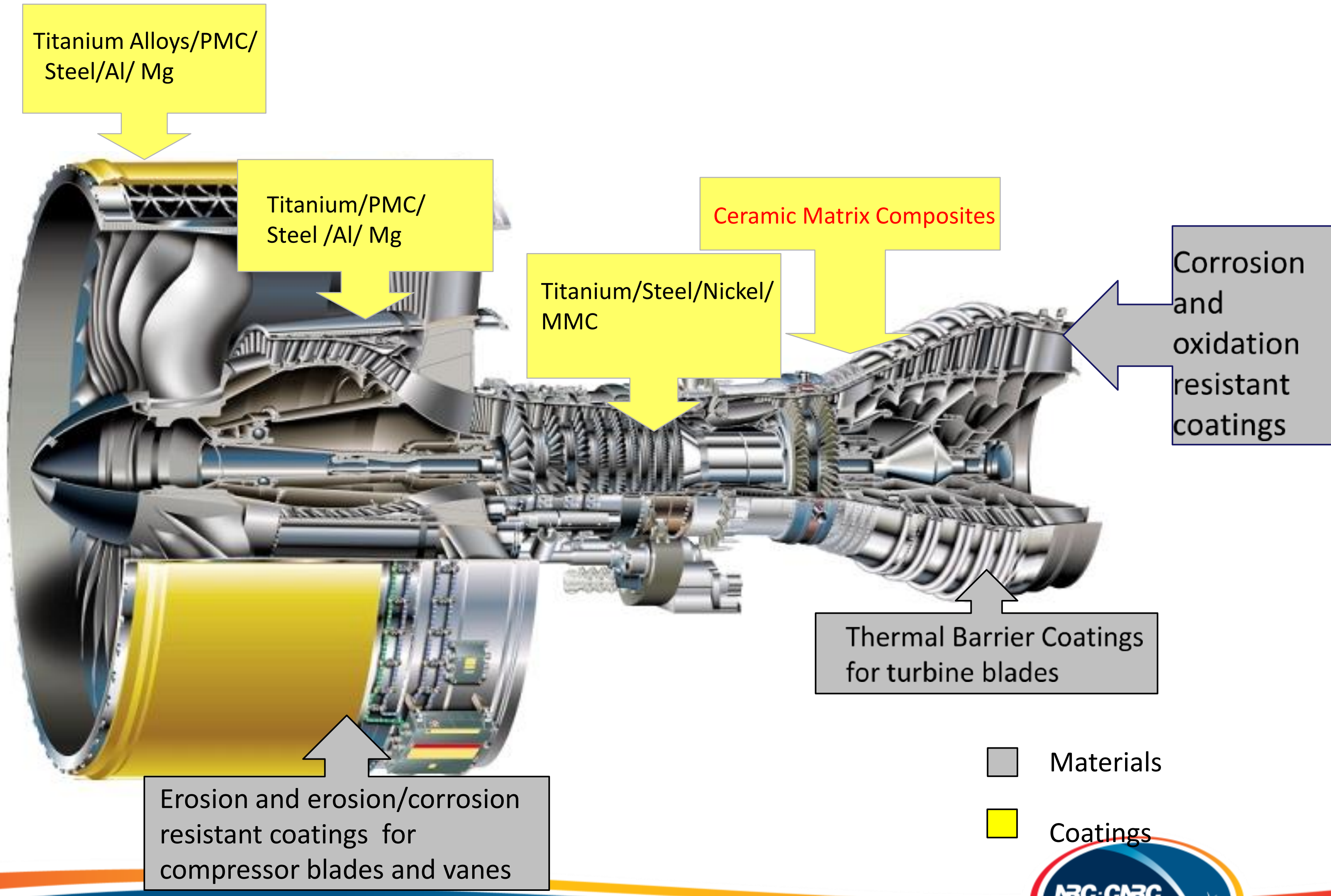
Roadmap for Structural Health Management



Technology Advancement

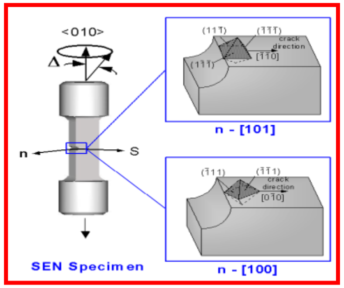


Materials and Coatings for Advanced Gas turbines

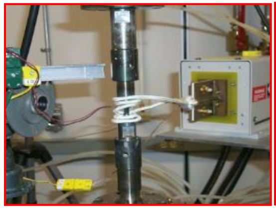
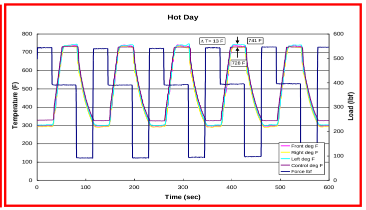


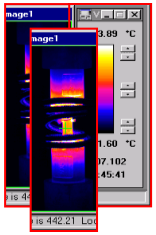
Fatigue in Aerospace Systems

- Fatigue as a damage mode
  - **Low Cycle Fatigue**
  - **High Cycle Fatigue**
  - **Thermal Fatigue**
  - **Thermo-Mechanical Fatigue**
  - **Fretting Fatigue**
  - **Corrosion Fatigue**
  - **Rolling Contact Fatigue**
  - **Erosion Fatigue**





- Interaction of Fatigue modes with other failure modes such as Creep and FOD
- Current emphasis on **INITIATION** rather than **NUCLEATION** of Damage
- Difficult to define the underlying complexity in the Physics of Failures

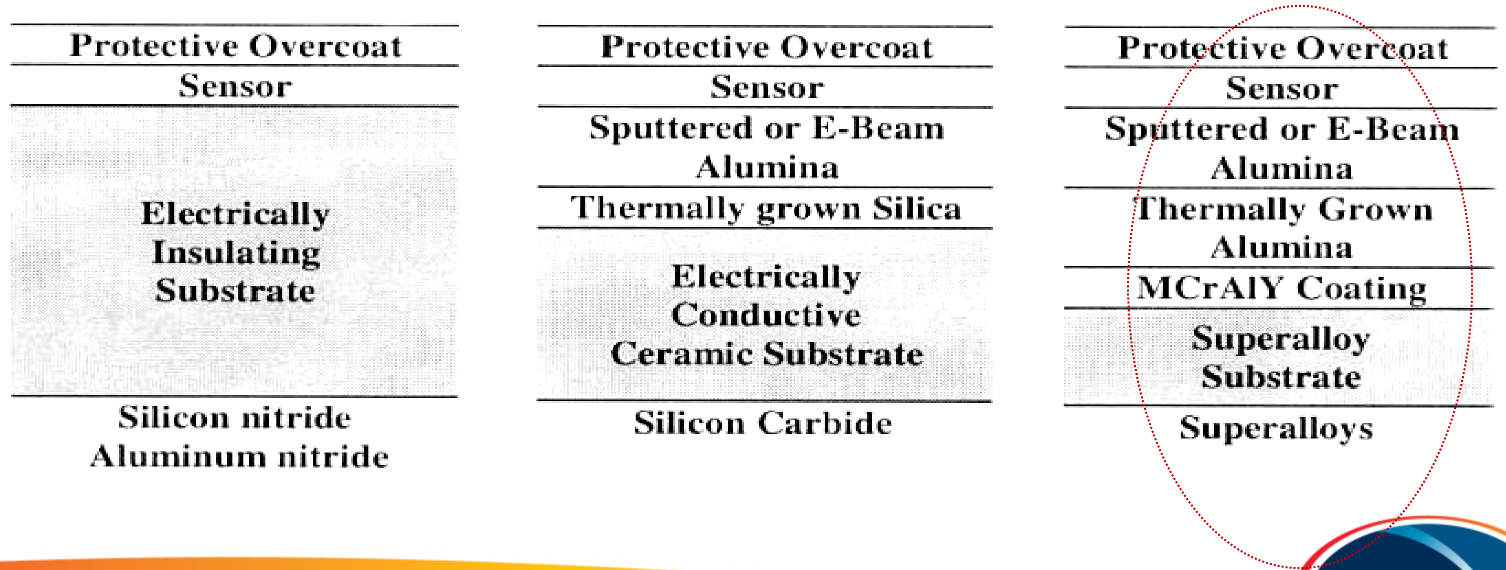
Sensors for Gas Turbine PHM

Sensors are needed for real-time monitoring of temperature, stress, fuel blow out, combustion instabilities, noise and NO_x emission etc.

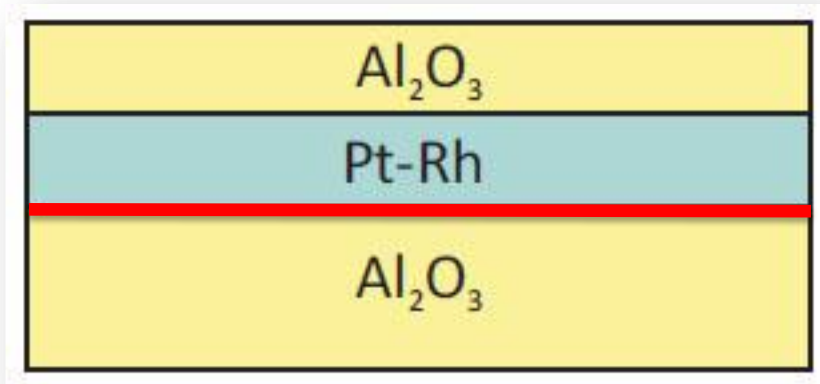
- *Development of new laser fabrication technologies to produce reliable thin film thermocouple (TFTC) and thin film strain gauge (TFSG) sensors for gas turbine application*
- *Evaluation of durability and performance of the thin film sensors in realistic environment*

Sensors for Gas Turbines
Why Thin Films ?

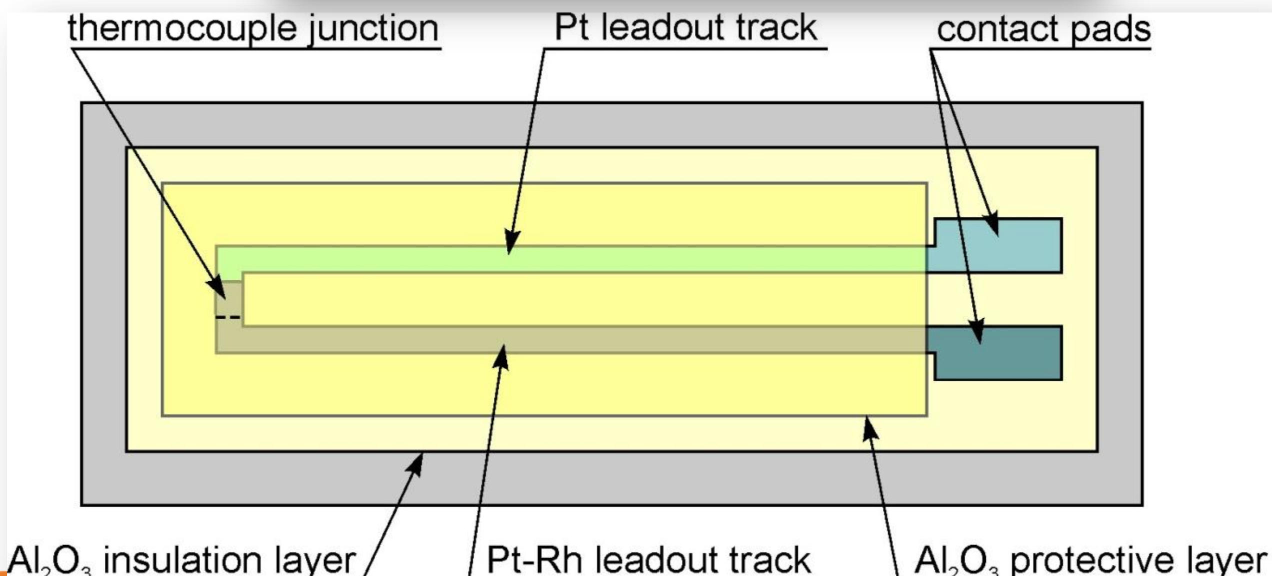
- Owing to small sizes, thin film sensors respond faster to thermal and strain changes than conventional wire sensors and offer superior spatial resolution
- Remains within the aerodynamic layer without any intrusive effects and contributing minimal effects on the modes of vibration of rotating parts
- The response time of thin film sensor becomes shorter as the thickness of sensing layer decreases
- Implication of temperature on lifing calculation +/- 50 degree to +/-2 degree



Adhesive Behavior of Pt/Al_2O_3 and PtRh/Al_2O_3 Interfaces in Thin-film Thermocouple Sensors



PtRh/Al_2O_3 interface

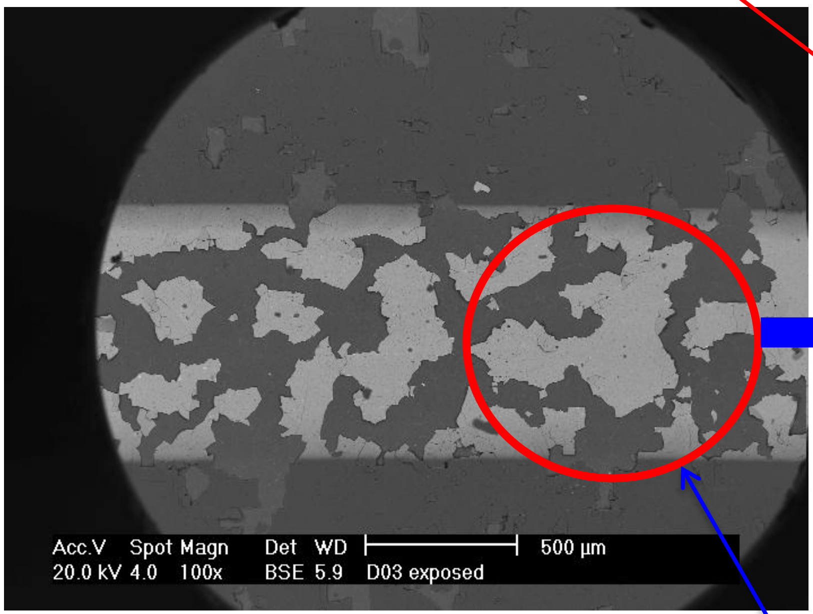


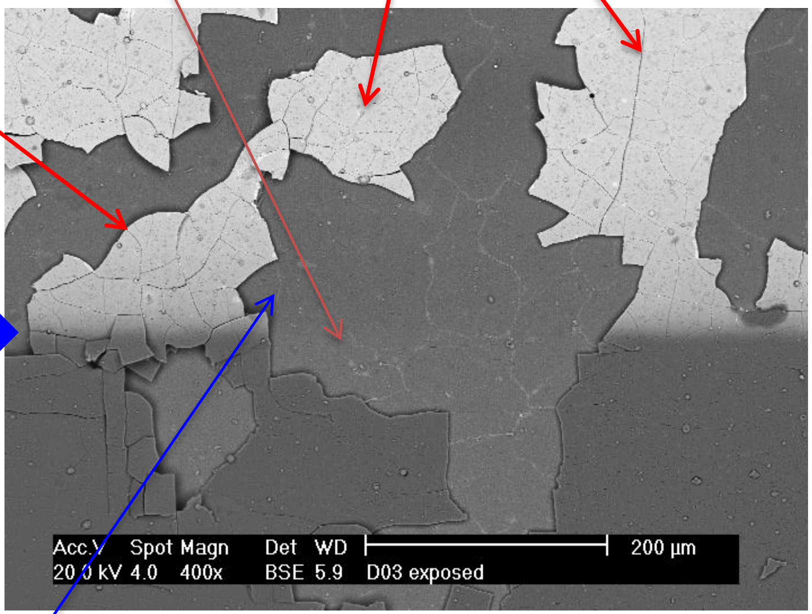
Sensor Microstructure

PtRh

Al_2O_3

PtRh/Al_2O_3 interface





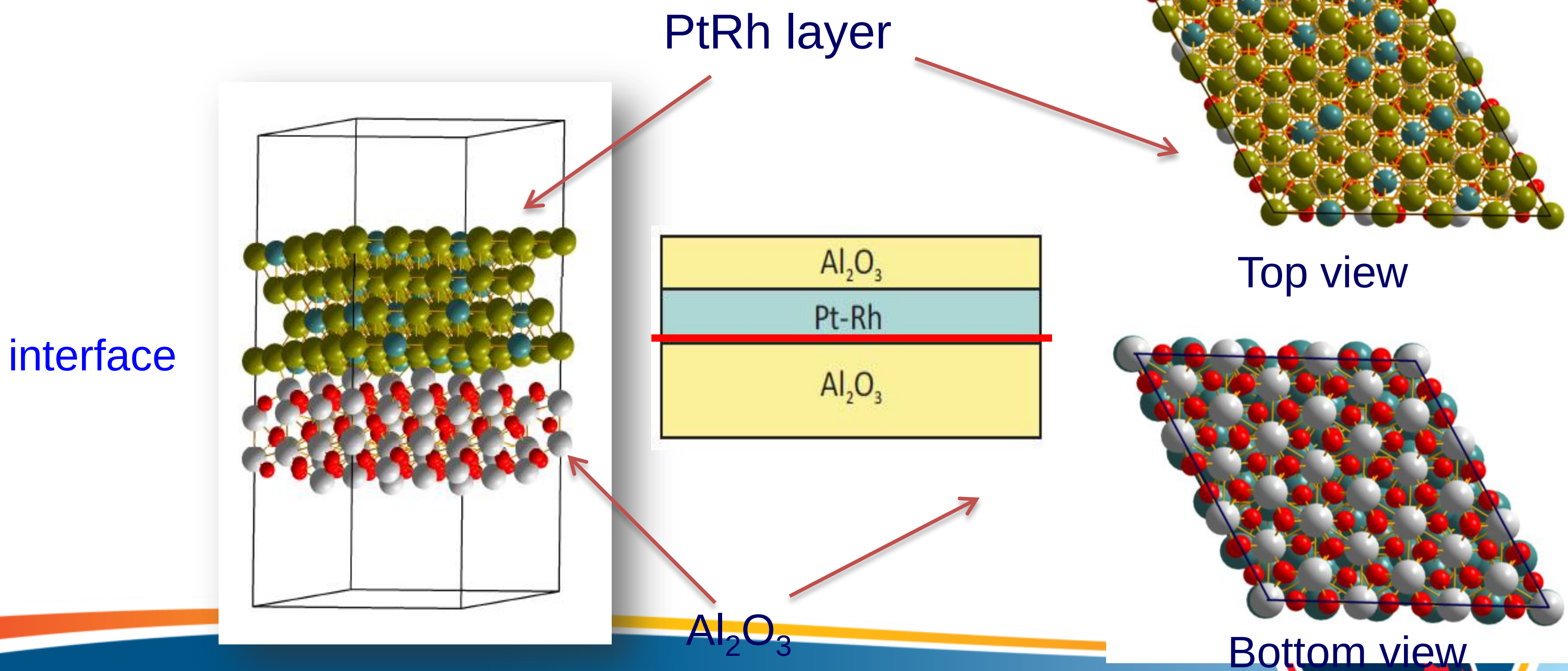
Sensor microstructure after thermocyclic testing followed by exposure to atmosphere for 12 days (SEM-BSE mode): Pt-13Ru leadout track delaminated.

Crack and spllation along the PtRh/Al_2O_3 interface

Physicss of Failure of Thin Film Sensor

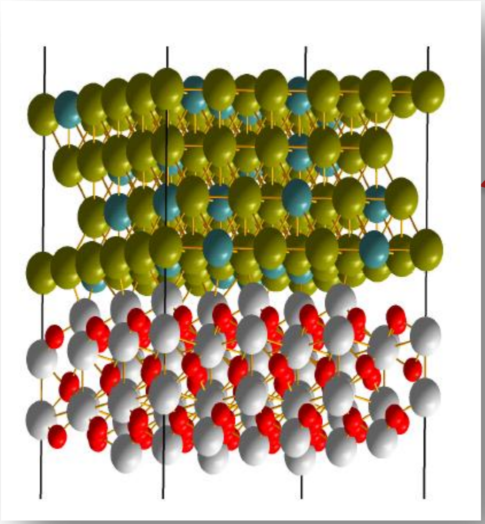
(1) Impurity sulphur (ppm) from bond coat and Hastelloy substrate alloy may cause the thin-film failure ;
(2) Difficulty to perform mechanical testing on thin-film technically;
(3) **Density functional theory can accurately calculate the total energy of the materials systems, and therefore can evaluate, assess materials mechanical properties, reduce the cost and increase the efficiency of materials design and development.**

Interface model of PtRh/Al_2O_3



Calculation of work of adhesion W_{ad}

$$W_{ad} = (E^{tot}_{Al2O3} + E^{tot}_{PtRh} - E^{tot}_{Al2O3+PtRh}) / A$$



E^{tot}_{PtRh} : Total energy of slab PtRh

E^{tot}_{Al2O3} : Total energy of slab Al_2O_3

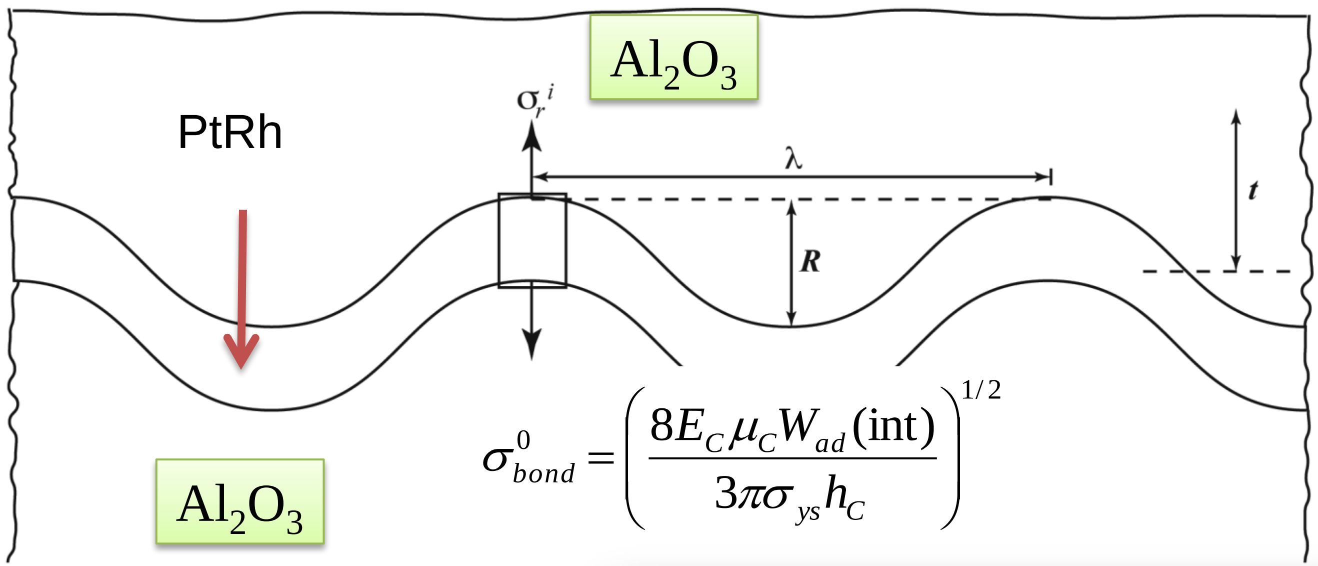
$E^{tot}_{Al2O3+PtRh}$: Total energy of system A: interface area

Bond strength:

$$\sigma^0_{bond} = \left(\frac{8 E_C \mu_C W_{ad}(\text{int})}{3\pi \sigma_{ys} h_C} \right)^{1/2}$$ *

σ_{bond}^o : coating bond strength, E_C : coating modulus μ_C: coating shear modulus, σ_{ys}: yield strength of substrate, h_c : coating thickness.

Coating interface profile



$$\sigma^0_{bond} = \left(\frac{8E_C \mu_C W_{ad}(\text{int})}{3\pi \sigma_{ys} h_C} \right)^{1/2}$$

Residual stress at the coating interface :

$$\sigma_n^i \approx \Delta\varepsilon \frac{[1/\kappa + E_c(1+\nu_s)(R/a)]\sin(2\pi y/\lambda)}{1 + R/t} = \sigma_r^i$$ *

Thermal strain: $\Delta\varepsilon = \Delta\alpha\Delta T$

Net strength on the interface : $\sigma_C(h) = \sigma^o_{bond}(h) \pm \sigma_{resudial}(h)$

Fracture toughness calculation:

Linking atomic scale to micromechanical level

Fracture toughness : materials property against crack nucleation and propagation

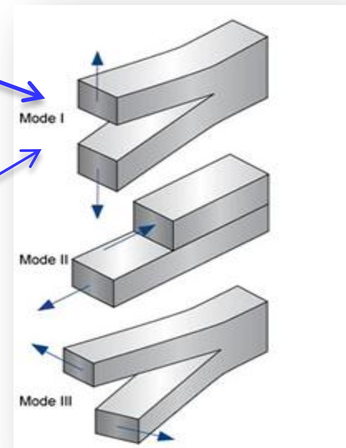
$$G_{SS} = \frac{\sigma^2 h}{E^f}\left(\frac{\sigma}{3\tau} + \pi F(\Sigma)\right)$$

Crack tip energy release rate

$$K_{IC}^{int} = \sigma_C(h)\sqrt{h}\left(\frac{\sigma_C(h)}{\sqrt{3}\sigma_Y} + \pi F(\Sigma)\right)^{1/2}$$

Interfacial fracture toughness

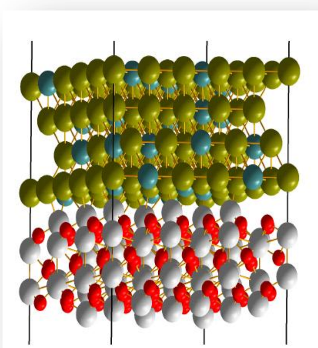
Three types of fracture mode:



Tensile

Shear

Mixed



$$W_{ad} = (E^{tot}_{Al2O3} + E^{tot}_{PtRh} - E^{tot}_{Al2O3+PtRh})/A$$

Atomic scale (DFT)

$$\sigma^0_{bond} = \left(\frac{8E_C \mu_C W_{ad}(\text{int})}{3\pi\sigma_{ys} h_C}\right)^{1/2}$$

$$K_{IC}^{int} = \sigma_C(h)\sqrt{h}\left(\frac{\sigma_C(h)}{\sqrt{3}\sigma_Y} + \pi F(\Sigma)\right)^{1/2}$$

Micromechanical scale experimental measurement