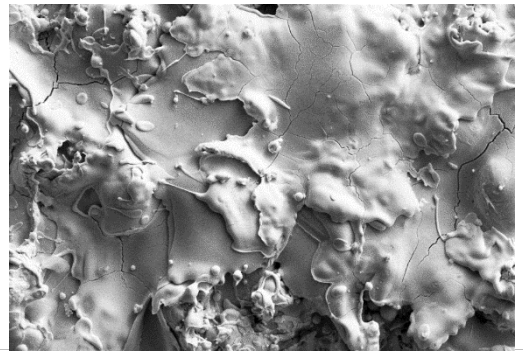
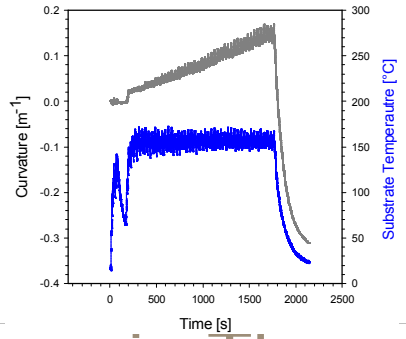
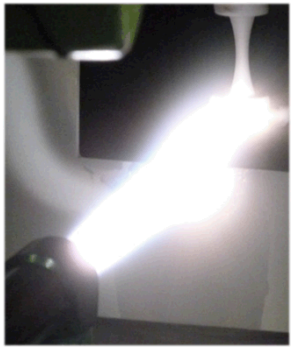
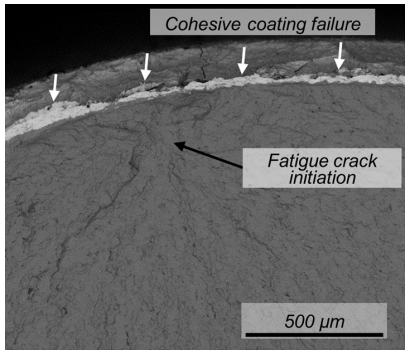
SAND2017-1096PE










# Residual Stress in Thermal Spray Coatings and its Implications on Coating-Substrate Fatigue Life

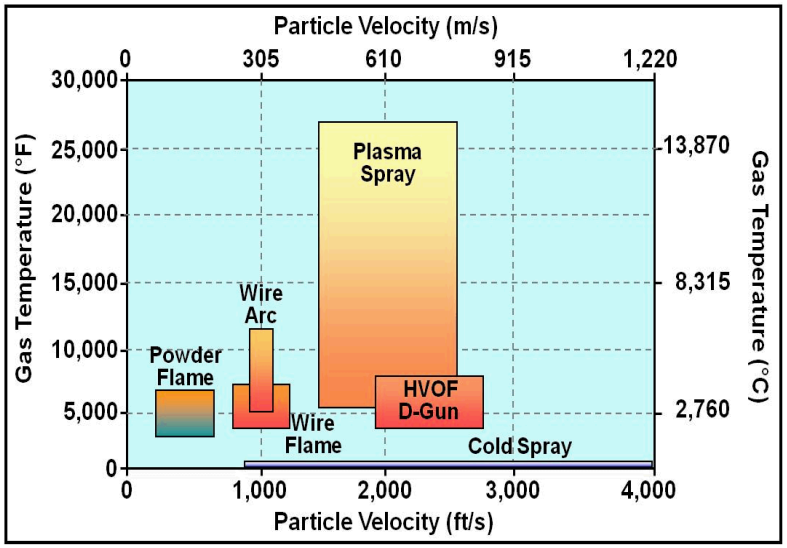
Andrew Vackel

- Thermal Spray Background
- Residual Stresses Sources and Measurement
- Fatigue of Thermal Spray Coated Substrates

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

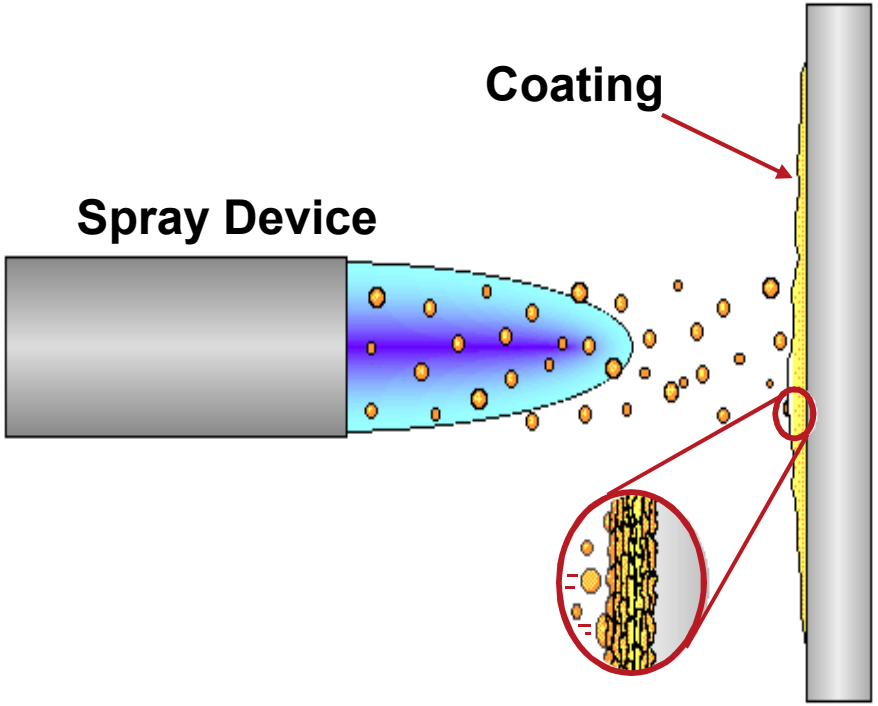
# Thermal Spray (TS) Technology

- Thermal spraying = coating processes in which heated/melted materials are deposited onto a surface.
- High deposition rate over large area. *mostly constrained by line-of-sight.
- Thickness range ~ 20 um to several mms, depending on process/feedstock.
- Quality assessed by measuring porosity, oxide content (in metallic coatings), hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.



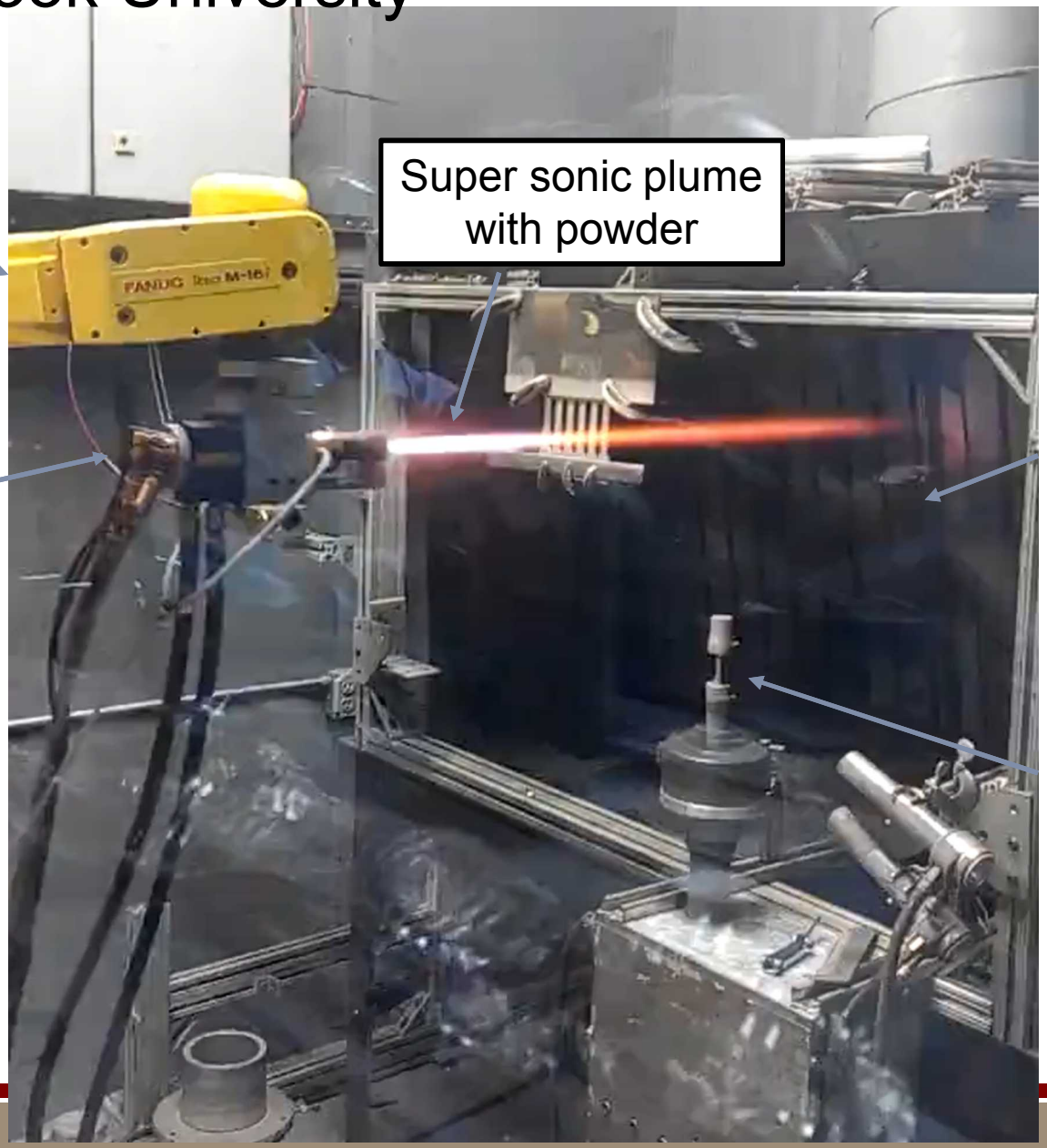

*Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.

***Different Thermal Spray processes allow access to different regimes of particle temperature and velocity space.***




**Particle Temperature & Velocity at impact determine coating microstructure and properties.**

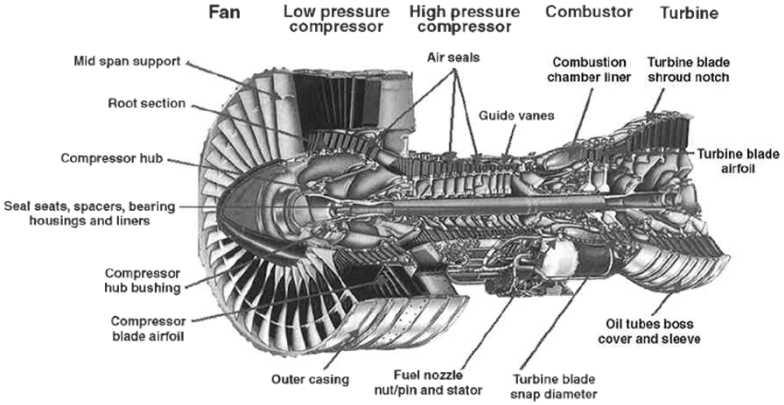
# High Velocity Oxy-Fuel (HVOF) Torch at Stony Brook University



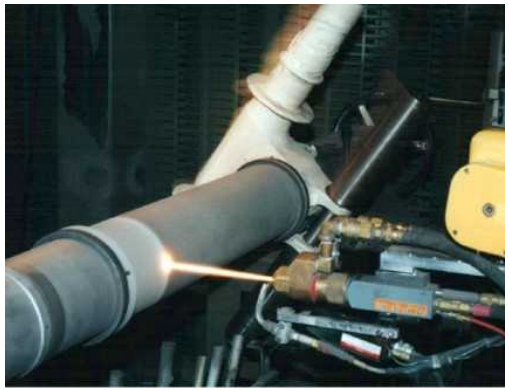
# Industrial Applications – Passive Coatings

- Aerospace
  - Gas Turbines
  - Landing Gear
- Automotive
- Biomedical
- Computers
- Infrastructure
- Marine
- Paper Making
- Petrochemical
- Power Generation
- Printing
- Textiles
- Electronics

Hydroxyapatite coating on a hip implant

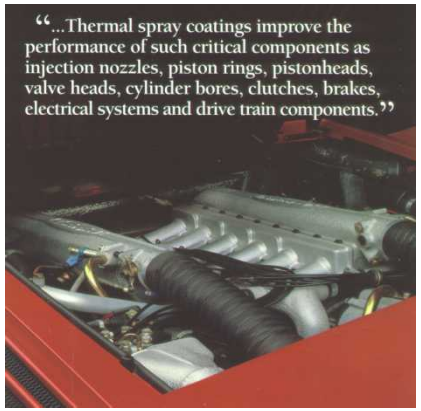



Gas Turbines are full of sprayed coatings!

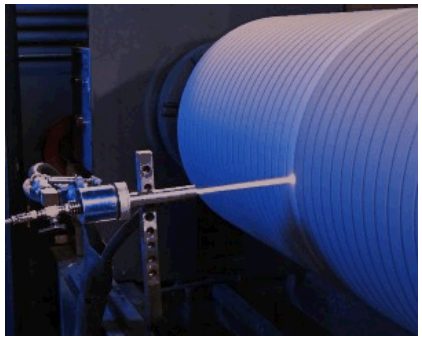


Hard Chrome Replacement on a Landing Gear Strut

The Wuhan Junshan Bridge over the Yangtze River is covered with 35,000 $m^2$ (~8.5 acres) of thermal sprayed zinc coating!




Auto applications include pistons, valves, cylinder bores, clutches, and drive train components.



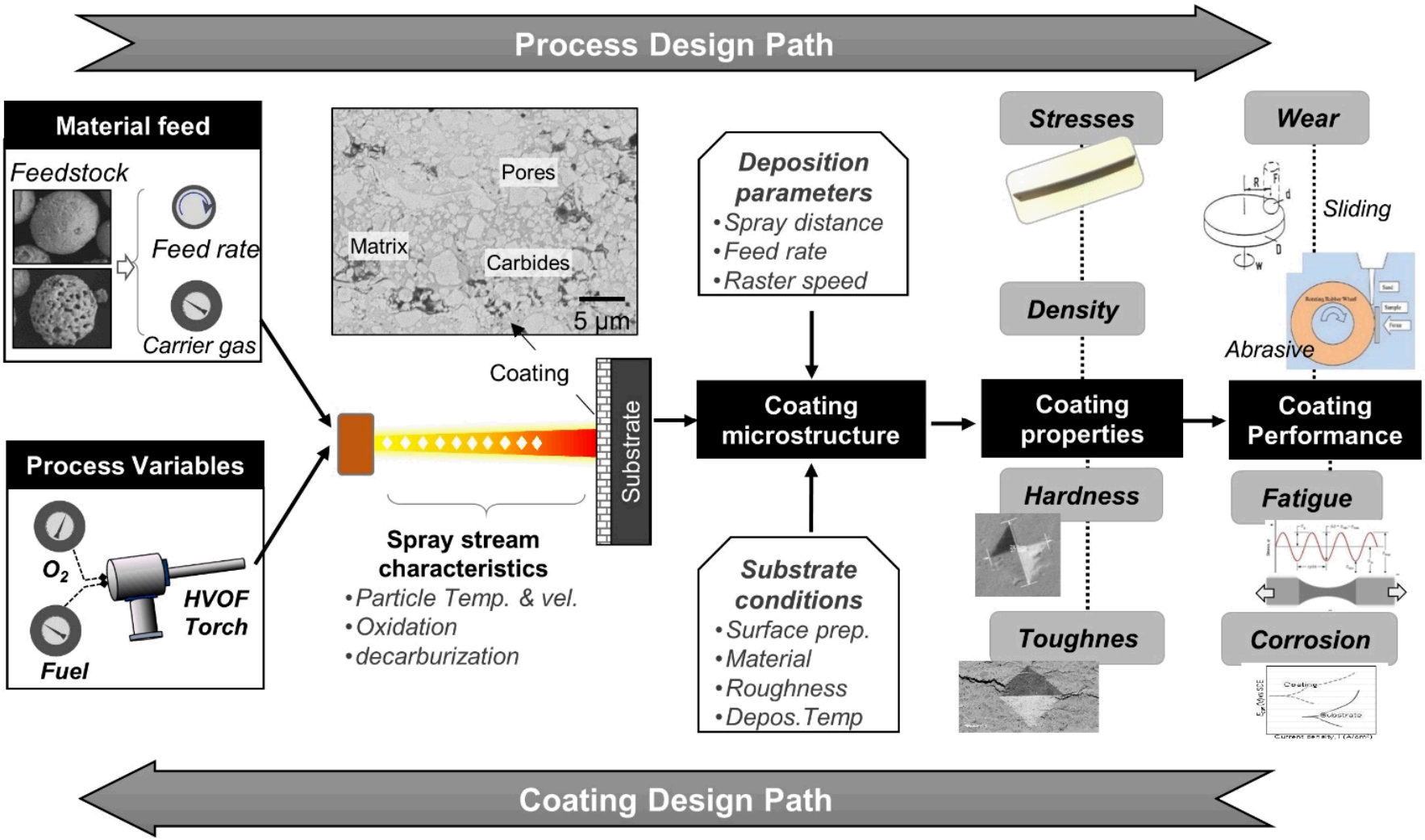
Ceramic Coating a Printing Roll

Thermal Spray Coatings find niche surface modification applications in many industries.

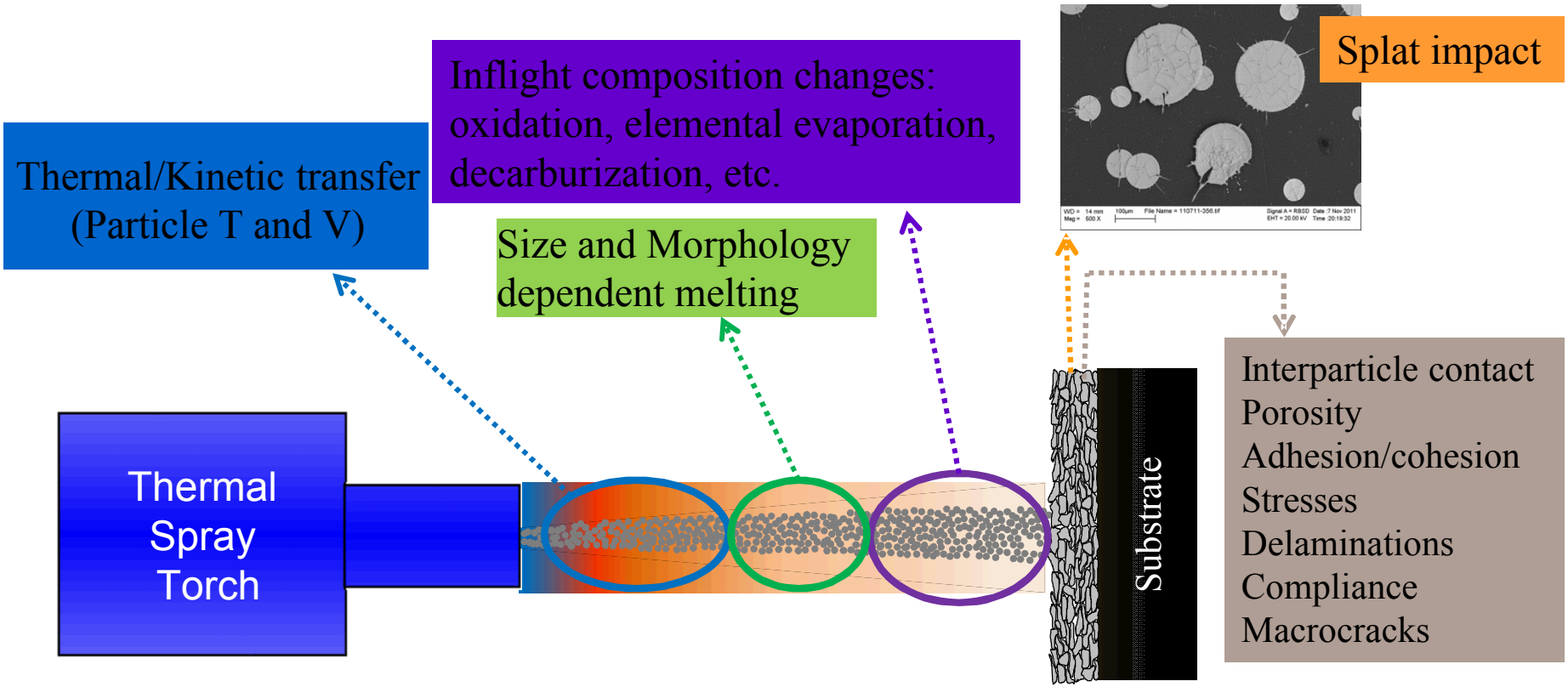


Handbook of Thermal Spray Technology, 2005, ASM International

# Thermal Spray: Processing, Structure, Properties, and Performance



# Particle-Plume interactions




What goes in ≠ what comes out

# Splats: Building Blocks of TS coatings

## Substrate and Splat interaction

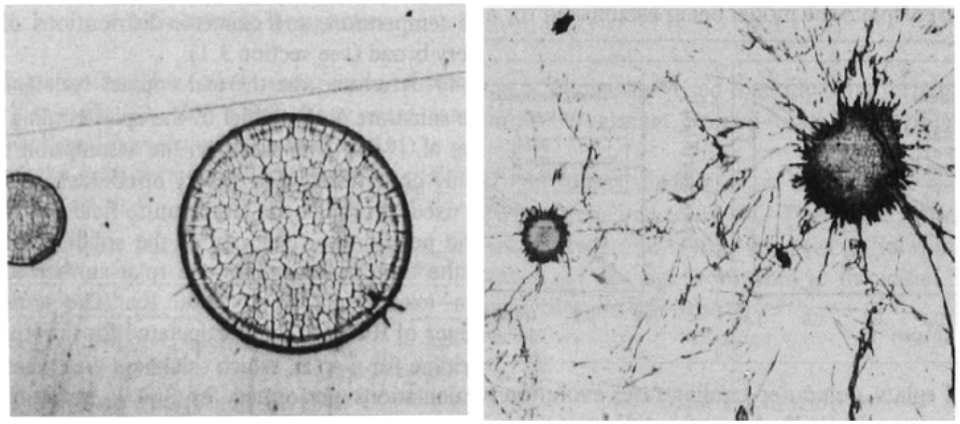
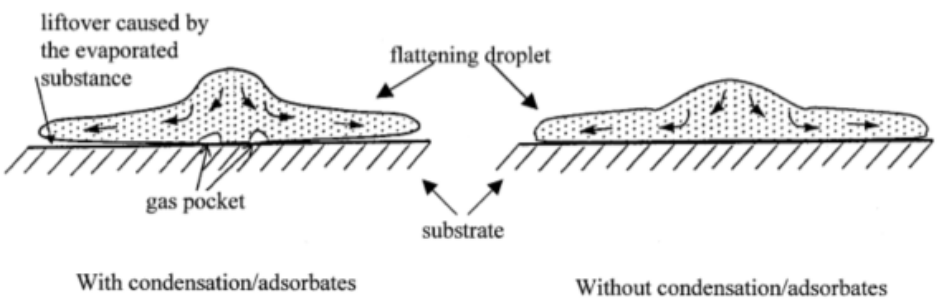


**Fig. 5**. PSZ splats collected on 304 L substrates (Ra ~ 0.05 μm) : a) hot substrates (300°C), b) cold substrates (75°C).

*Fauchais et al. Parameters controlling the generation and properties of plasma sprayed zirconia coatings, Plasma Chemistry and Plasma Processing, Vol.16, No. 1 (1996)*




*Jiang et al. Role of condensates and adsorbates on substrate surface on fragmentation of impinging molten droplet during thermal spray, Thin Solid Films 385 (2001) 132-141*

## Process Selection

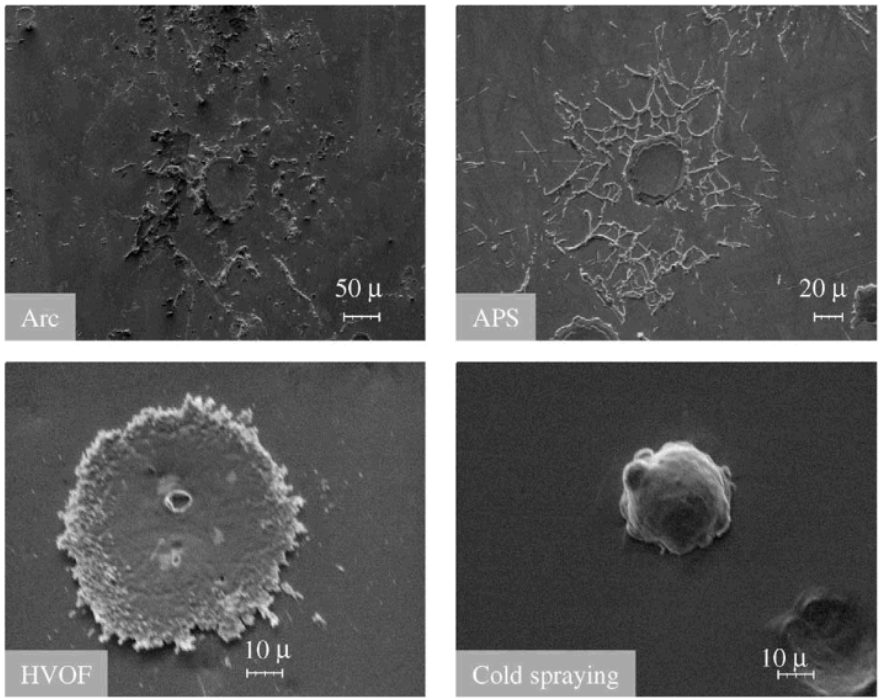
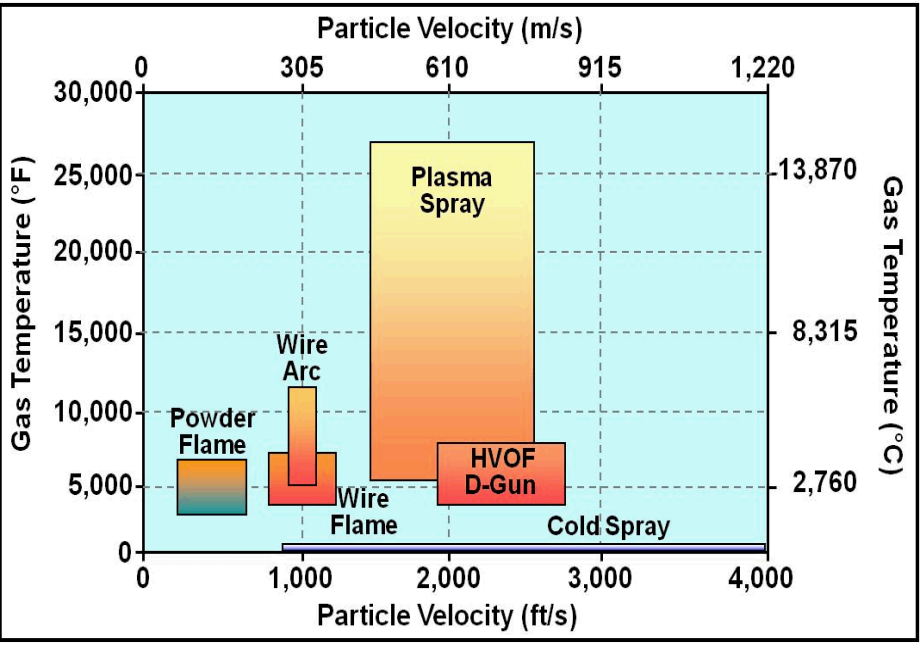


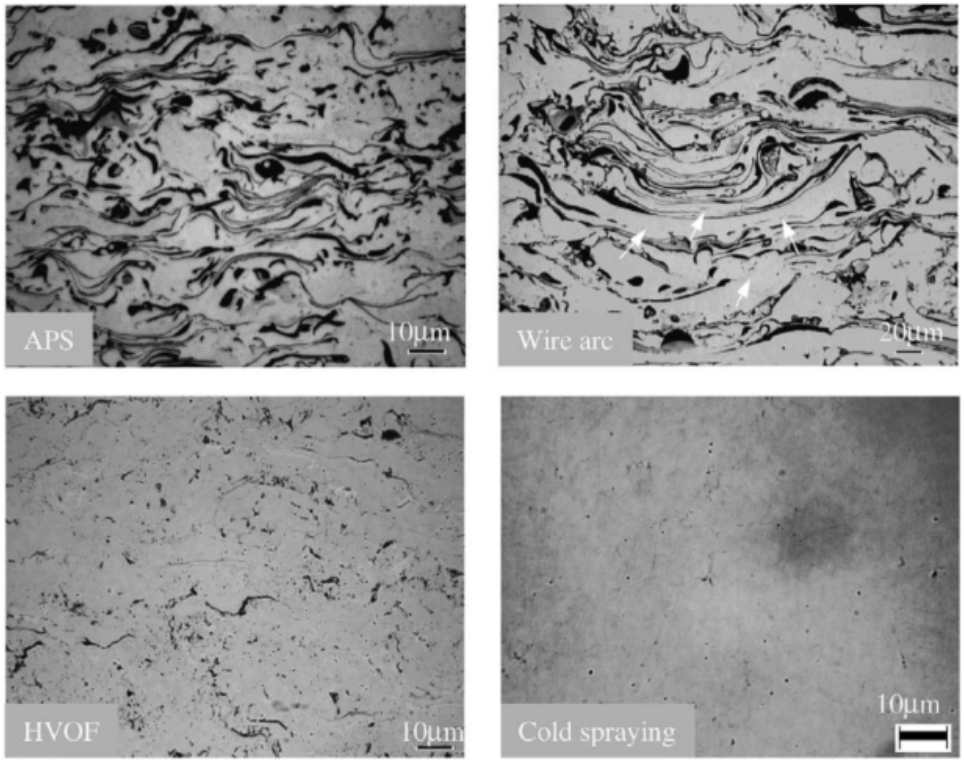

Fig. 3. Morphologies of Ni–5 wt.%Al splats produced with different techniques.

*Sampath et al. Role of thermal spray processing method on the microstructure, residual stress and properties of coatings: an integrated study for Ni-5 wt% Al bond coats, Materials Science and Engineering A364 (2004) 216-231*

# Microstructural variety based on TS process



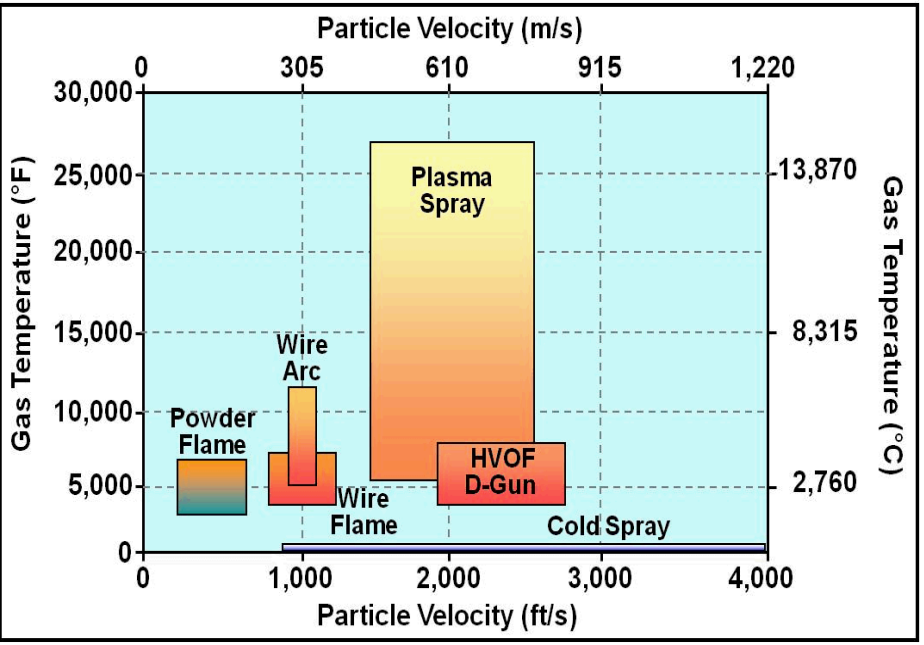

*Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.



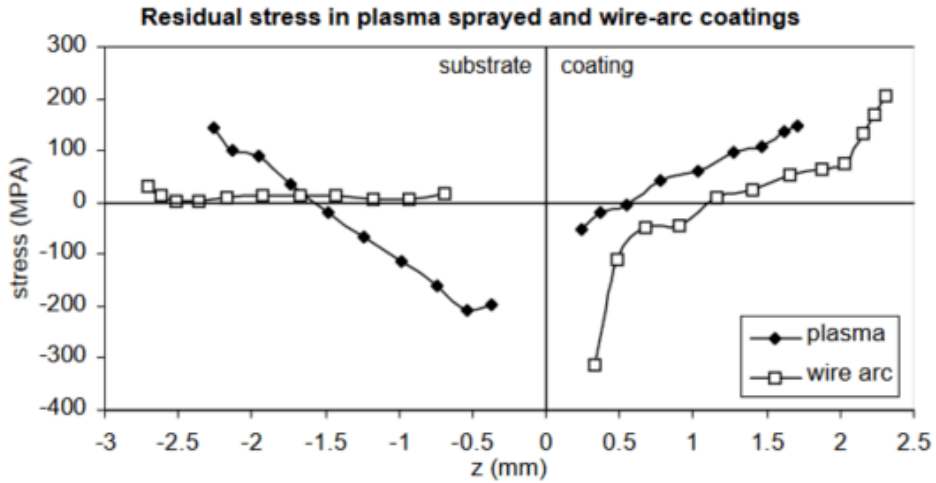

*Sampath et al. Role of thermal spray processing method on the microstructure, residual stress and properties of coatings: an integrated study for Ni-5 wt% Al bond coats, Materials Science and Engineering A364 (2004) 216-231*

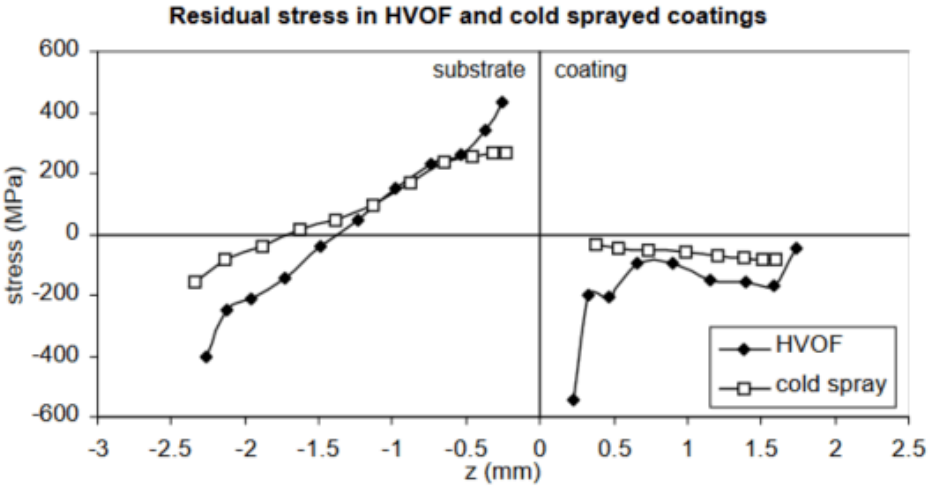
Microstructural variety for single feedstock chemistry: Tailorable process for different applications

# Residual Stress in TS Coatings



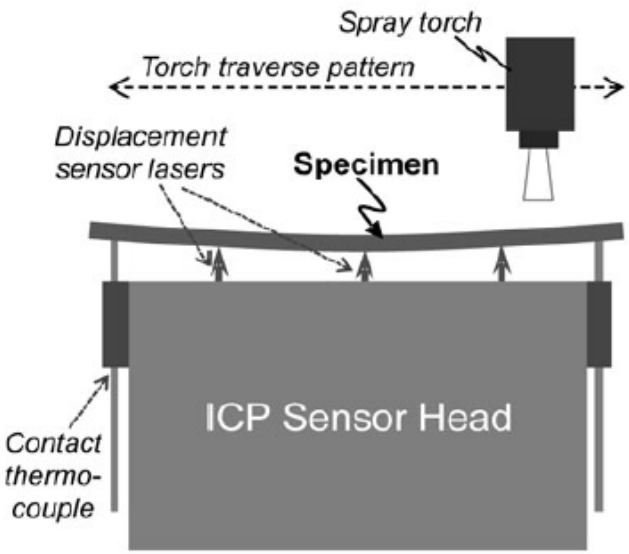

*Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.



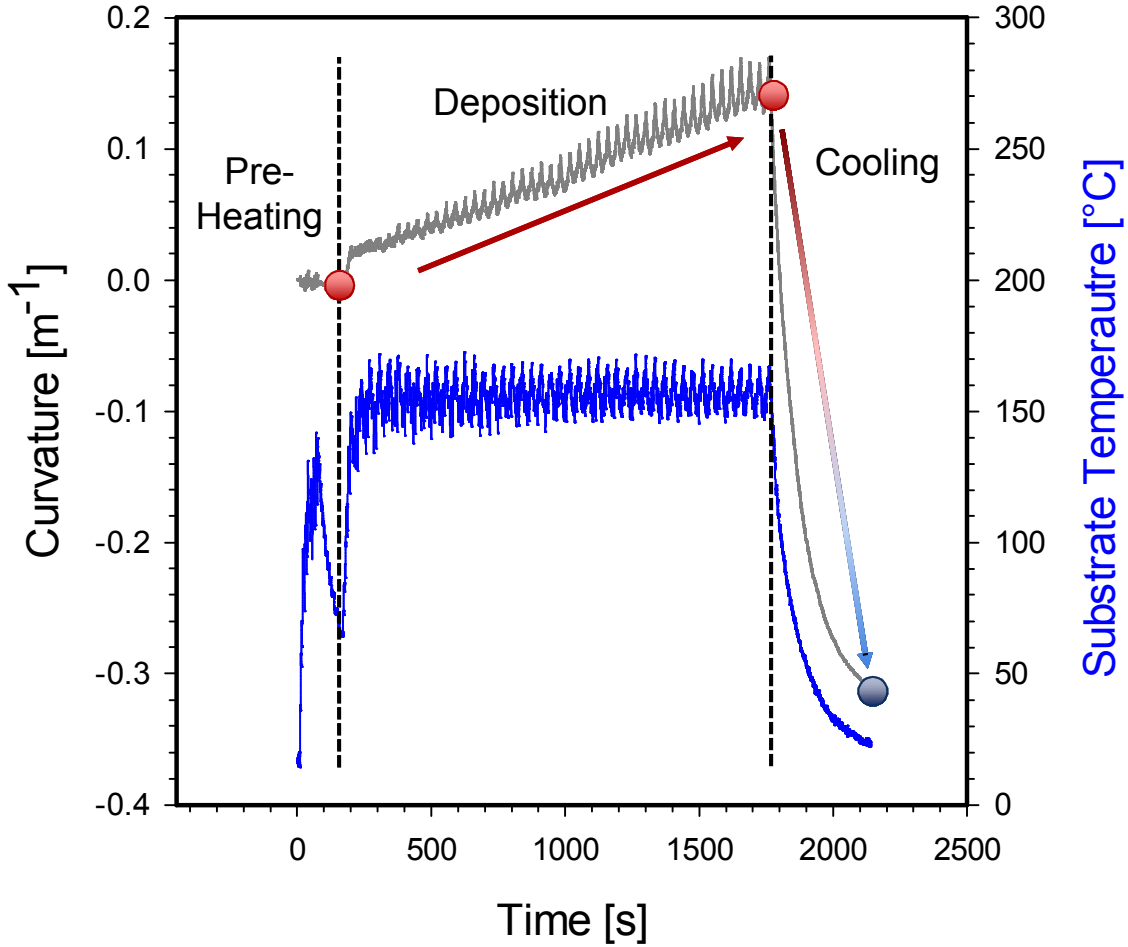




*Sampath et al. Role of thermal spray processing method on the microstructure, residual stress and properties of coatings: an integrated study for Ni-5 wt% Al bond coats, Materials Science and Engineering A364 (2004) 216-231*

# In-situ Coating Property (ICP) Sensor for thermal spray coatings




Dwivedi et al., 2013




$$\sigma_{Film} = \frac{E'_{sub}\, t_{sub}^{2}\, \Delta K}{6\, tfilm}$$

# Stress relief mechanisms and microstructure

Stress relief mechanisms in thermal spray droplets

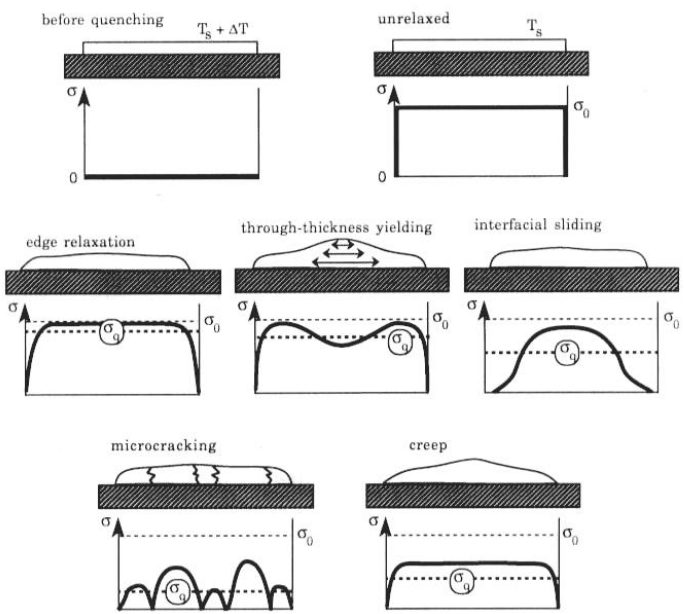
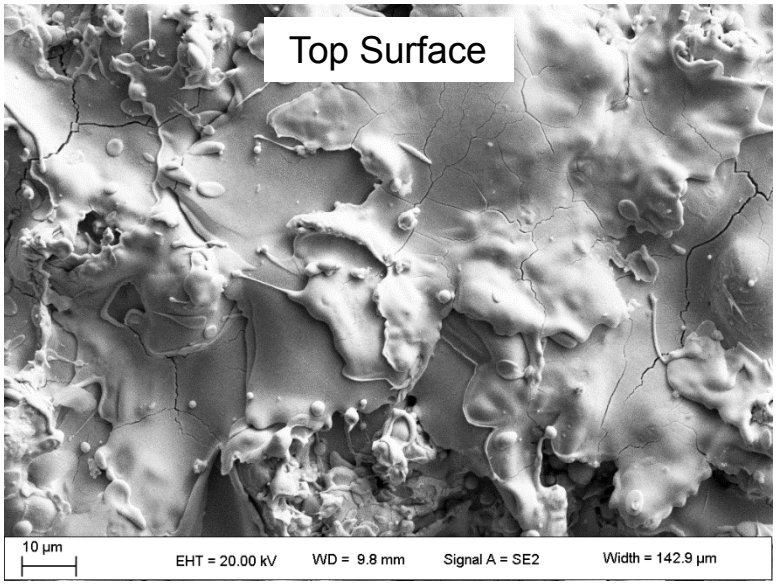
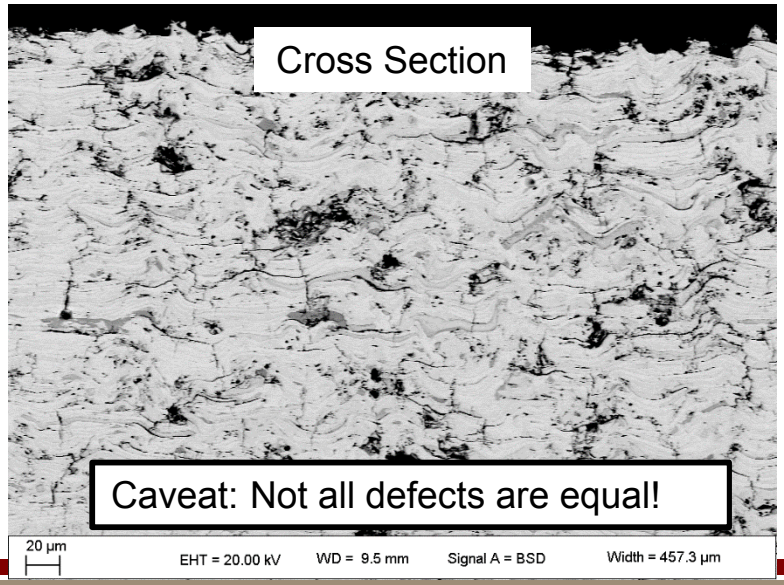


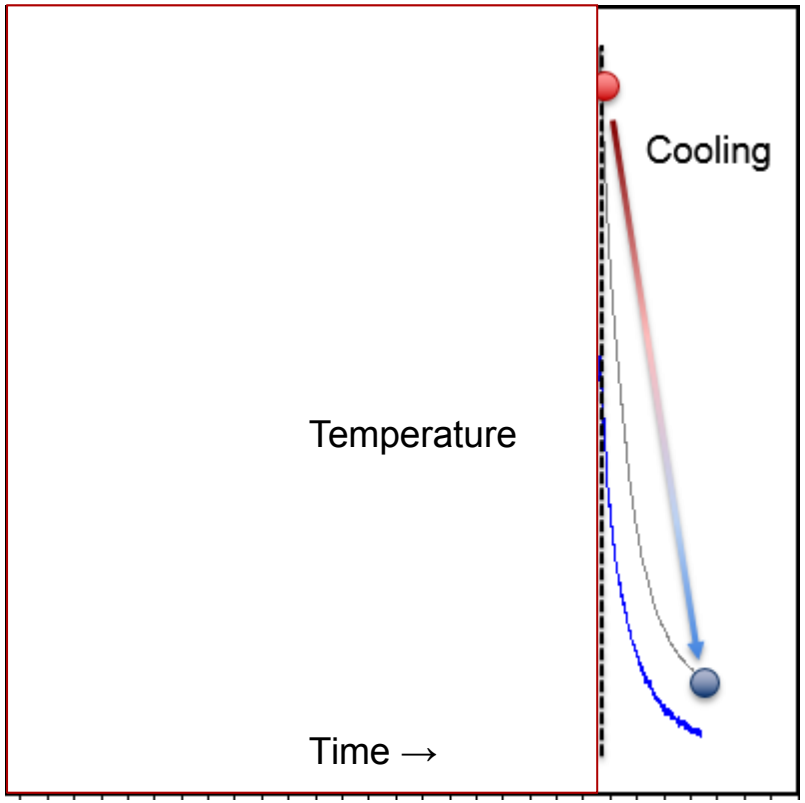

Fig. 2. Schematic illustration of the stress distributions within a single splat before and after various stress relaxation phenomena have taken place.

[1] *Kuroda & Clyne . The Quenching Stress in Thermally Sprayed Coatings, Thin Solid Films, 100 (1991) 49 -66*

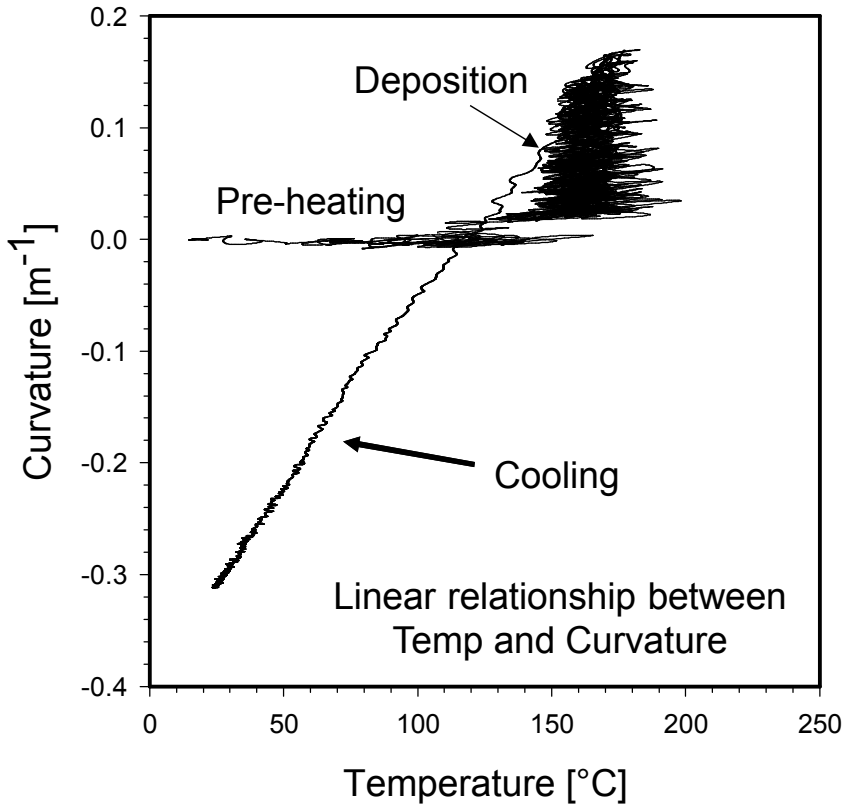


# Coating stiffness measured via thermal strain




$$\Delta\kappa = \frac{6E_d E_s hH(h+H)\Delta\alpha\Delta T}{E_d^2 h^4 + 4E_d E_s h^3 H + 6E_d E_s h^2 H^2 + 4E_d E_s hH^3 + E_s^2 H^4}$$

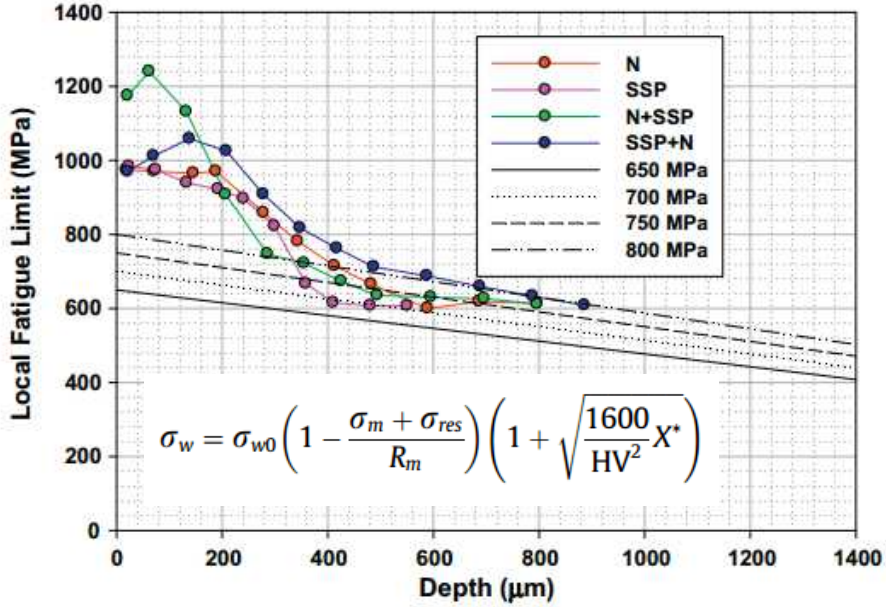



Caveats

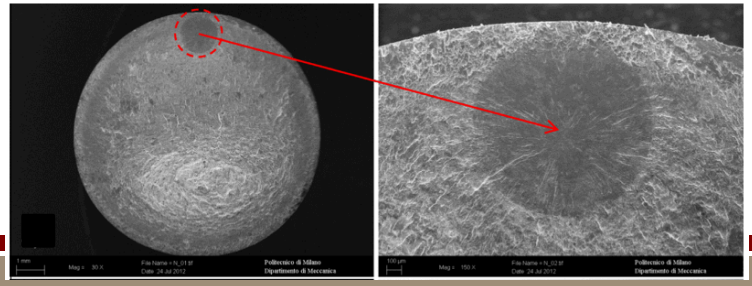
- Must know CTE of coating material (can be altered by processing)
- Does not take temperature dependent properties into account
- Requires substantial CTE difference between coating and substrate for measurement
- Assumes 1-D curvature

# Mechanical fatigue of coatings and surface treatments

Material surface treatments greatly affect mechanical fatigue life




*Hassani-Gangaraj et al. "The effect of nitriding, severe shot peening and their combination on the fatigue behavior and micro-structure of a low-alloy steel" - International Journal of Fatigue 2014*



TS coating processing difference has demonstrated a large influence in fatigue life

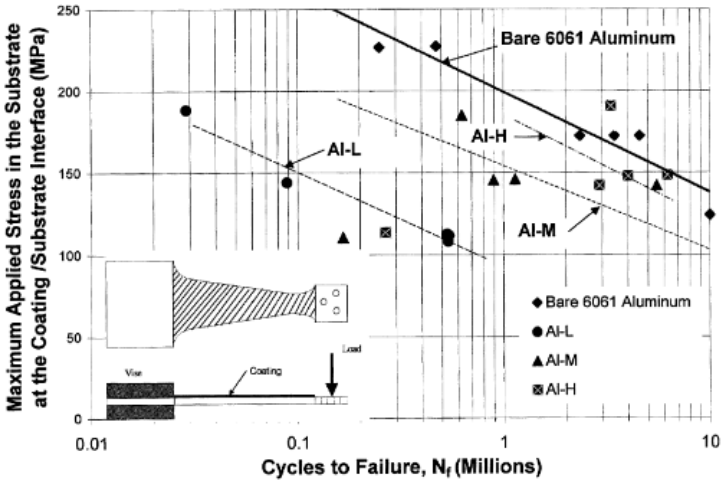
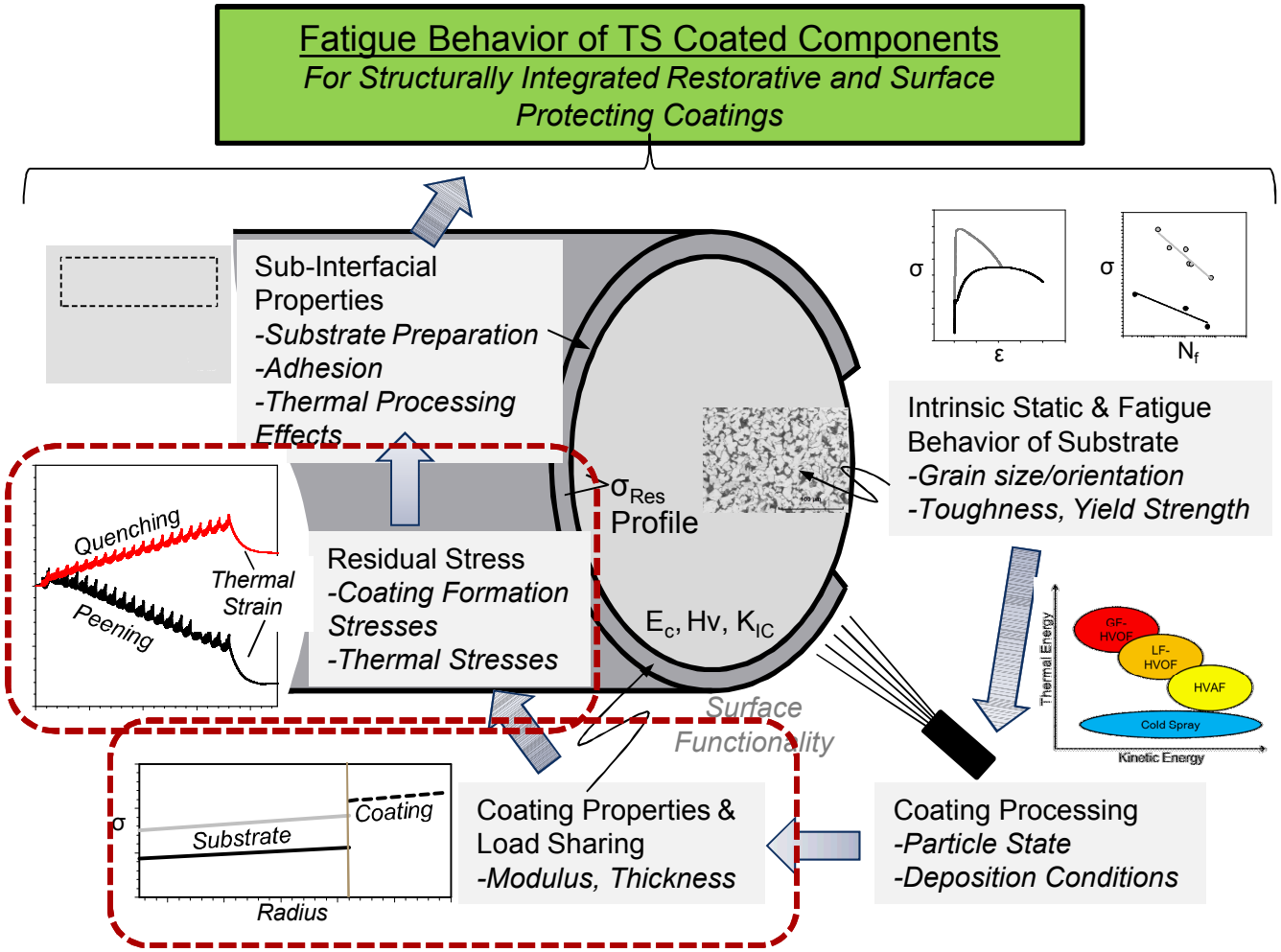



Fig. 5. Fatigue life in bending of WC–Co thermal spray-coated specimens on 6061-T6511 aluminum substrate.

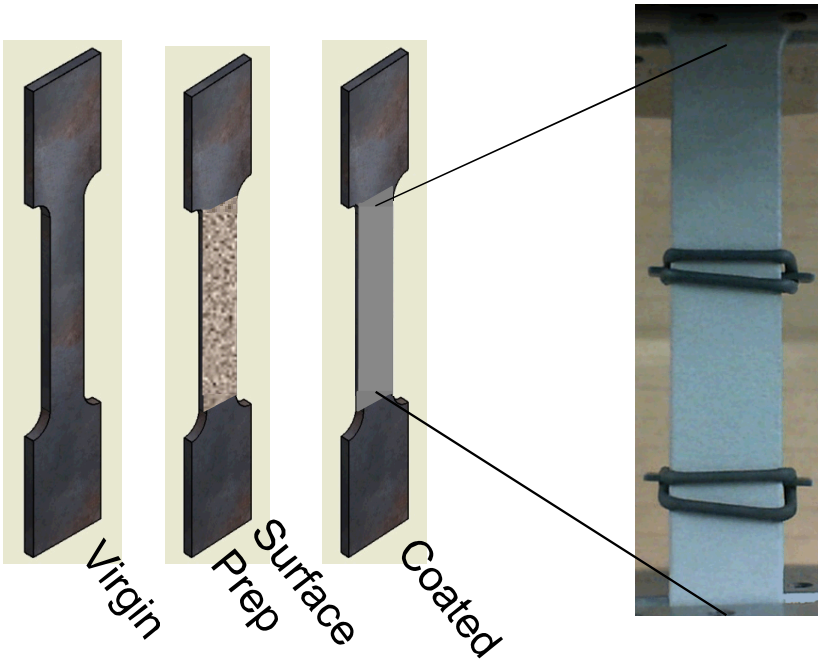
*McGrann et al. The effect of coating residual stress on fatigue life of thermal spray-coated steel and aluminum. Surface & Coatings Technology 108-109 (1998) 59-64*

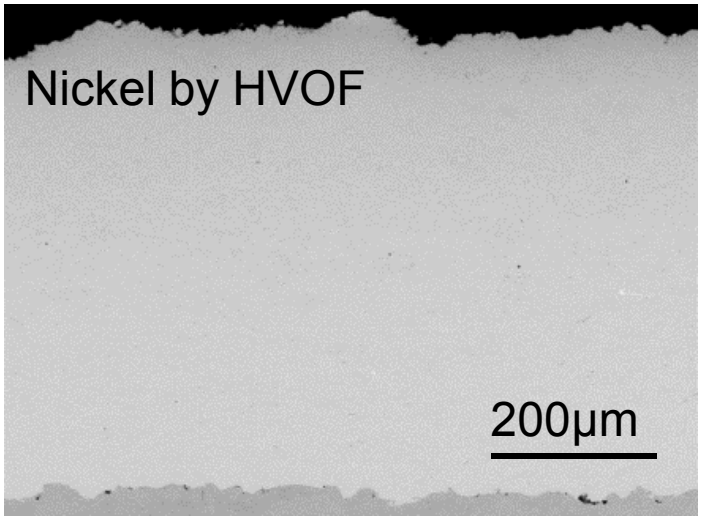
Can we leverage this information for a better understanding and thus prediction of thermal spray coating fatigue life?

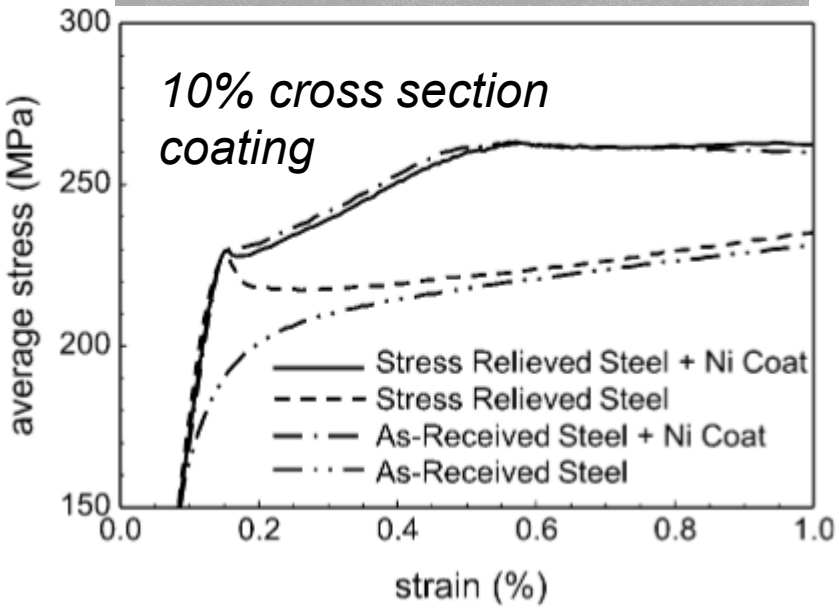
# Design Considerations for Fatigue of Thermal Sprayed Components



# Quasi-static tensile testing of coating-substrate systems



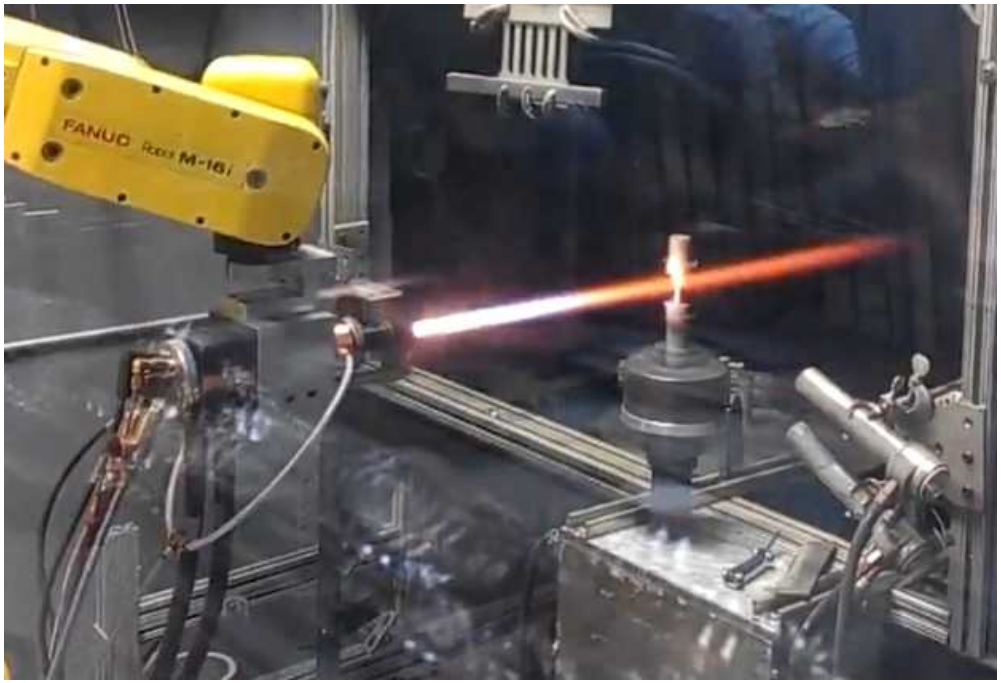

Significant load bearing capability of dense, well adhered metallic coatings

Modulus of HVOF Sprayed Ni to be ~120 GPa (~60% of Bulk)



*Vackel et al. Mechanical Behavior of Spray-Coated Metallic Laminates JTST 2106*

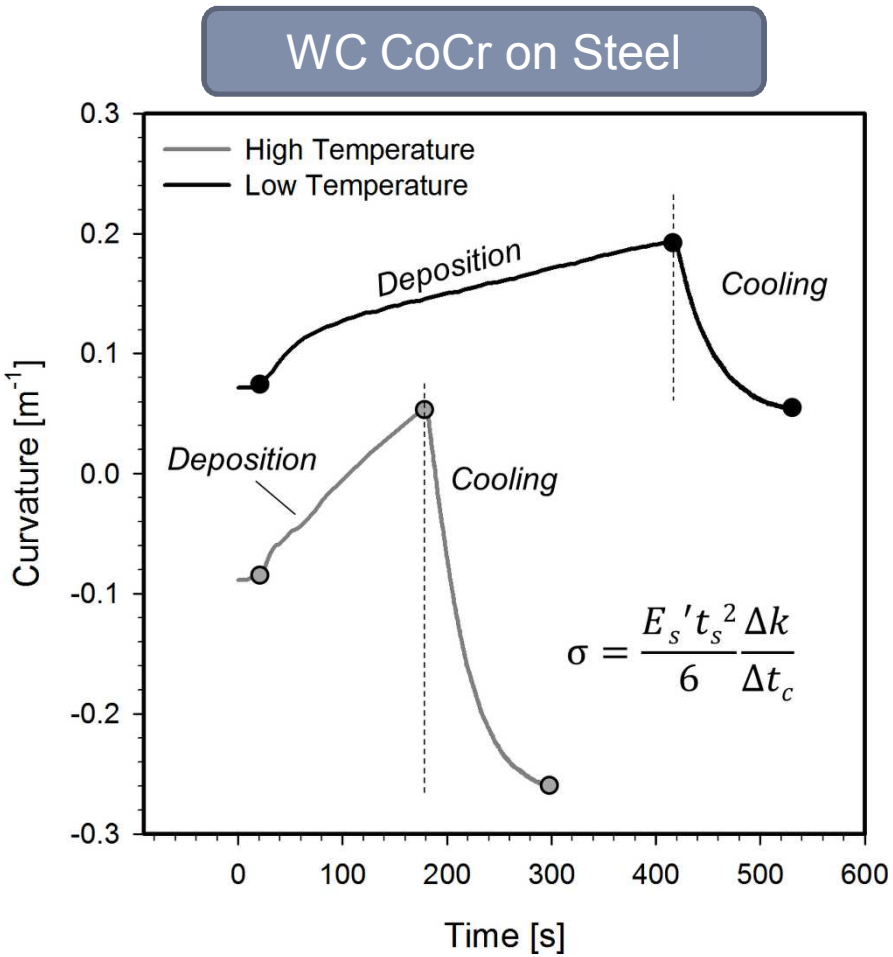
# Rotating Bend Fatigue (RBF) Testing

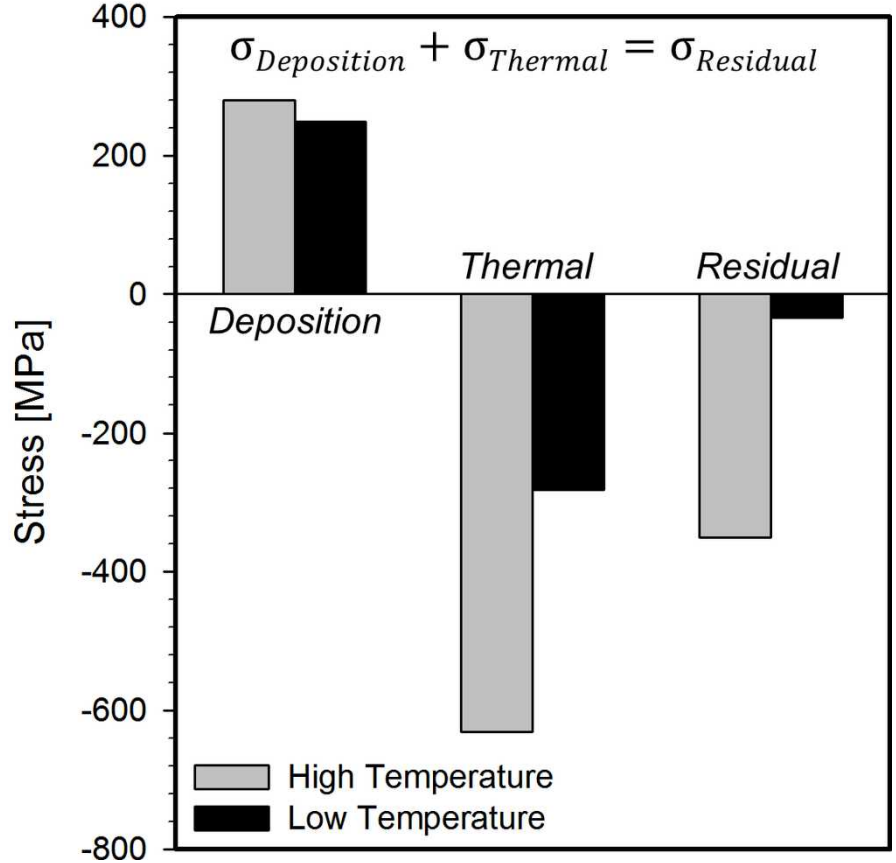



- Provides reversible loading (R= -1)
- Highest stress towards coating and substrate surface
- Repeatable, easy to perform test

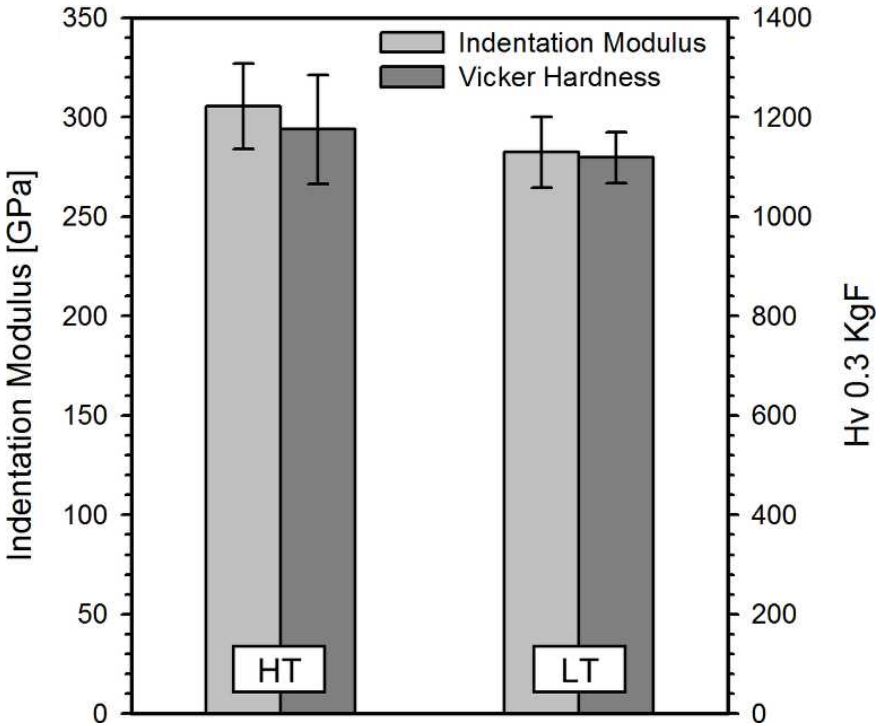
*Systems Integrators LLC*

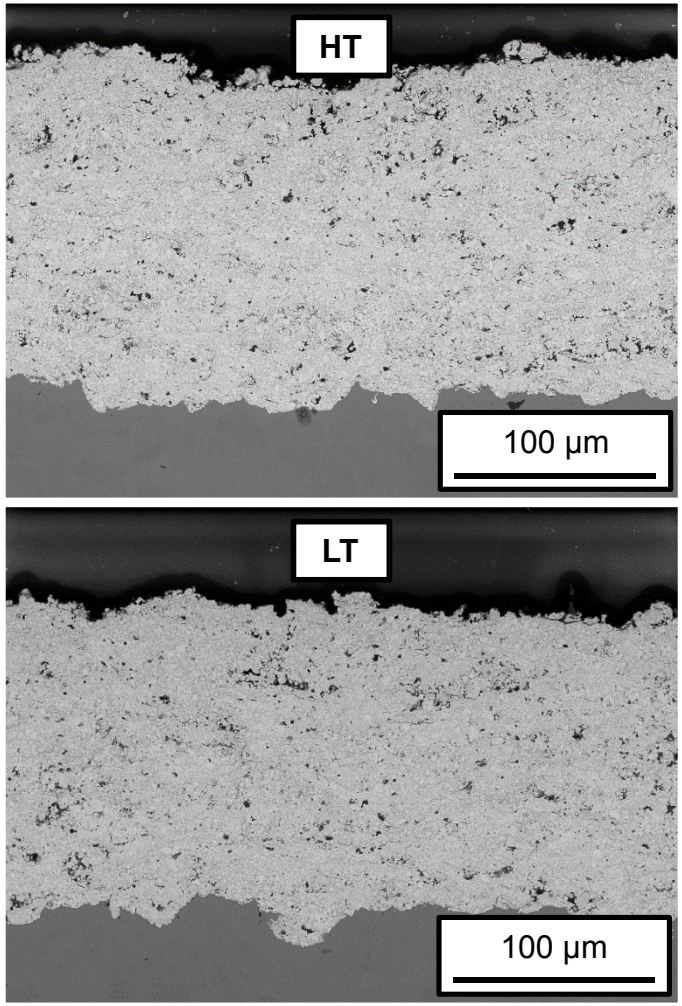
# Experiment design: Residual stress manipulation via substrate temperature



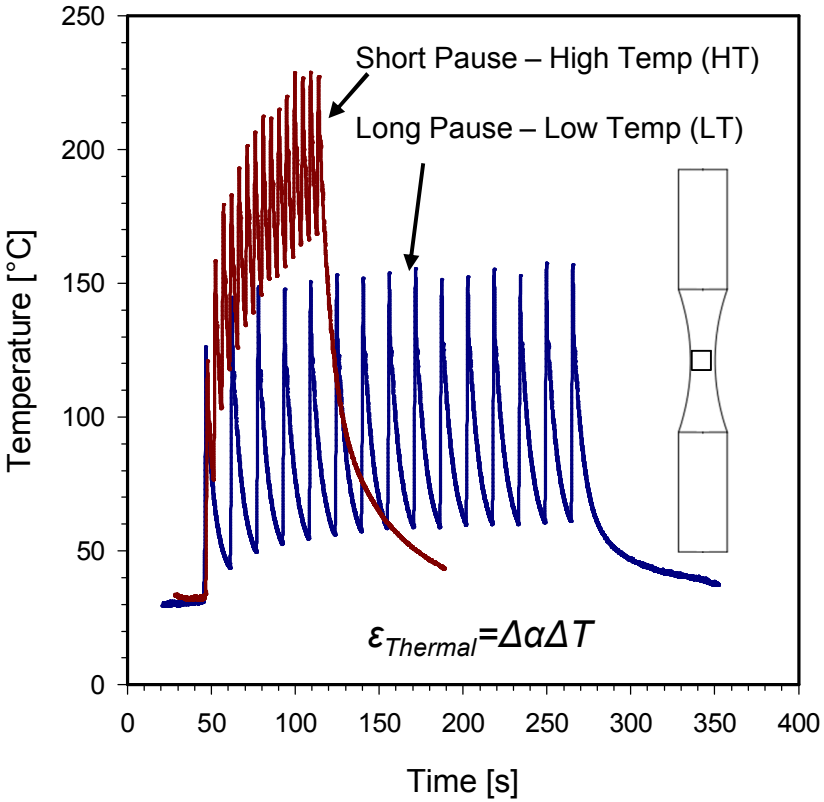
# Coating Properties unaffected by Coating Thermal Stress

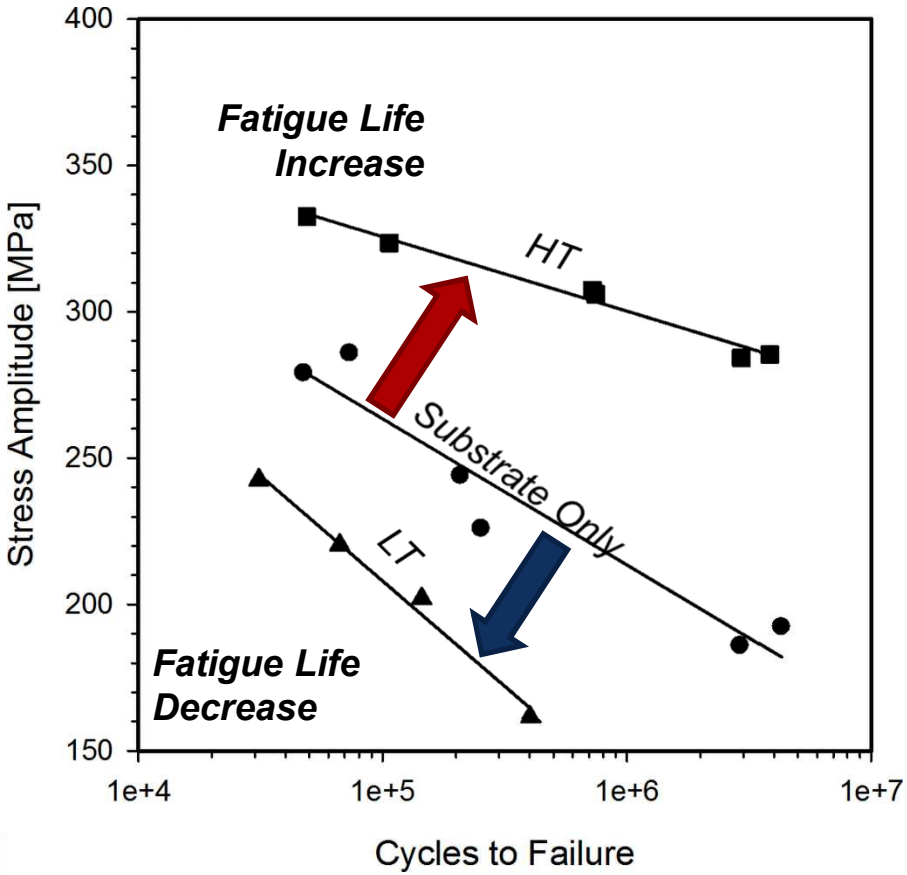



Similar properties, microstructure of coating produced with different levels of thermal stress

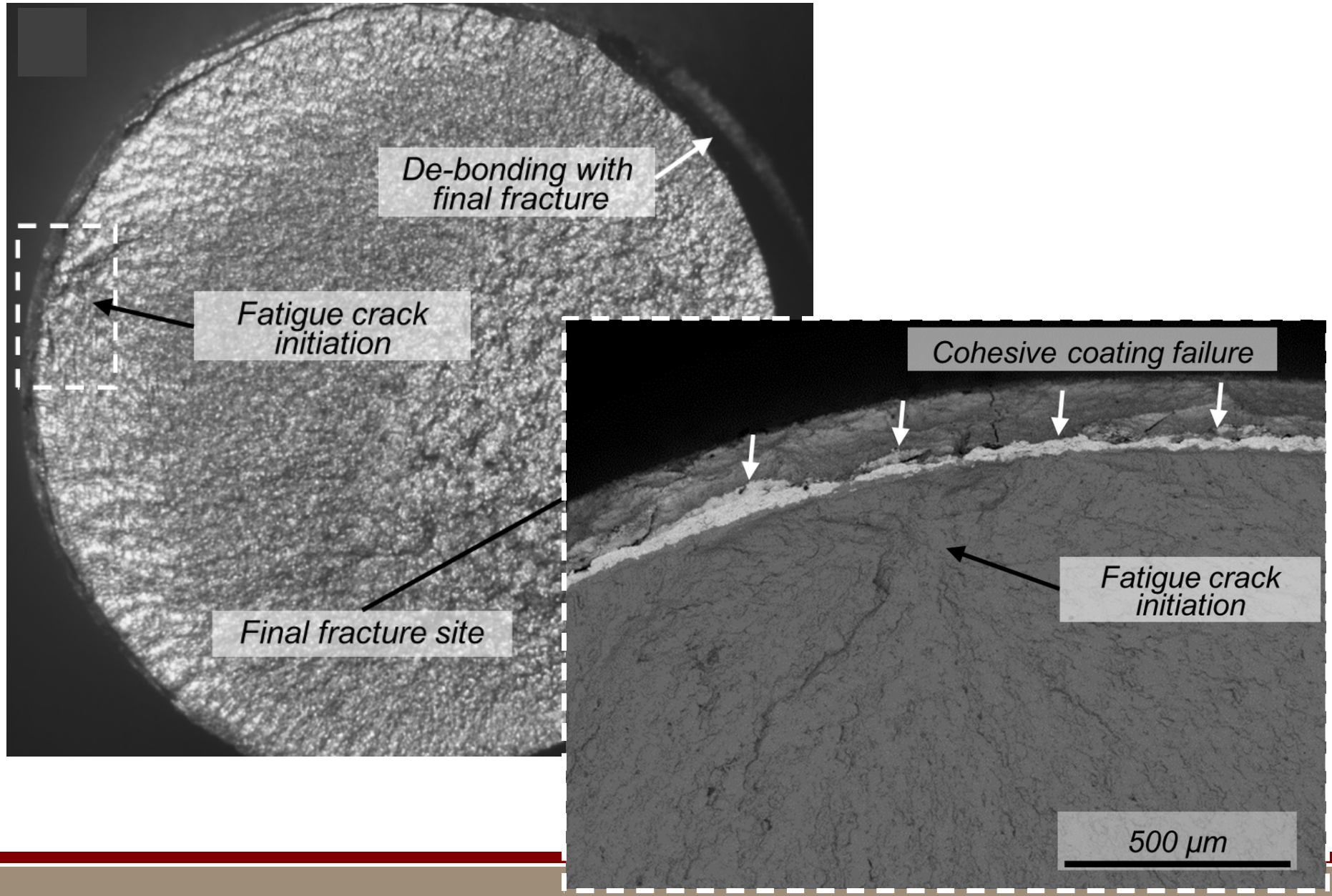
# Rotating Bend Fatigue (RBF) testing



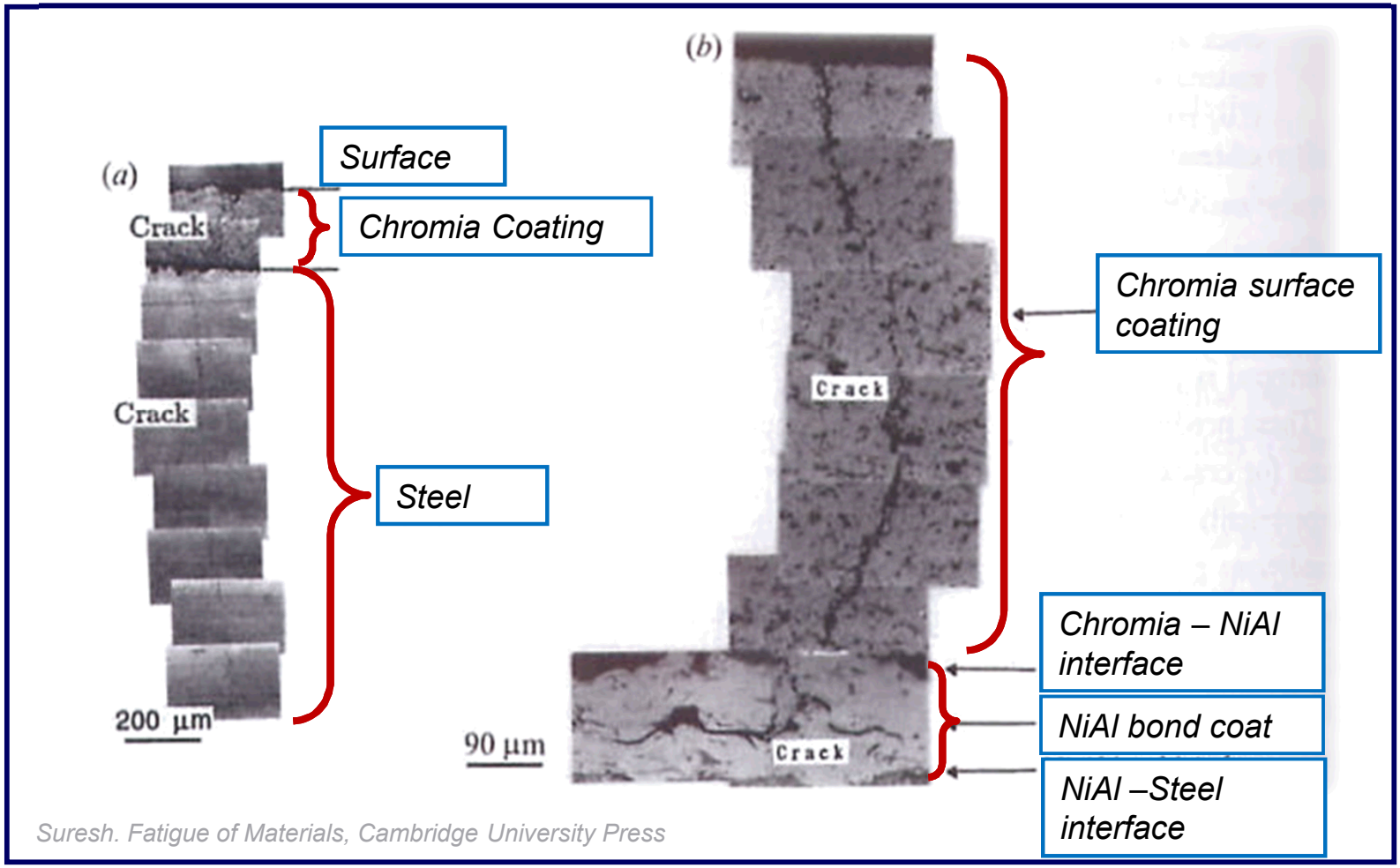



*Systems Integrators LLC*

# Fracture surfaces



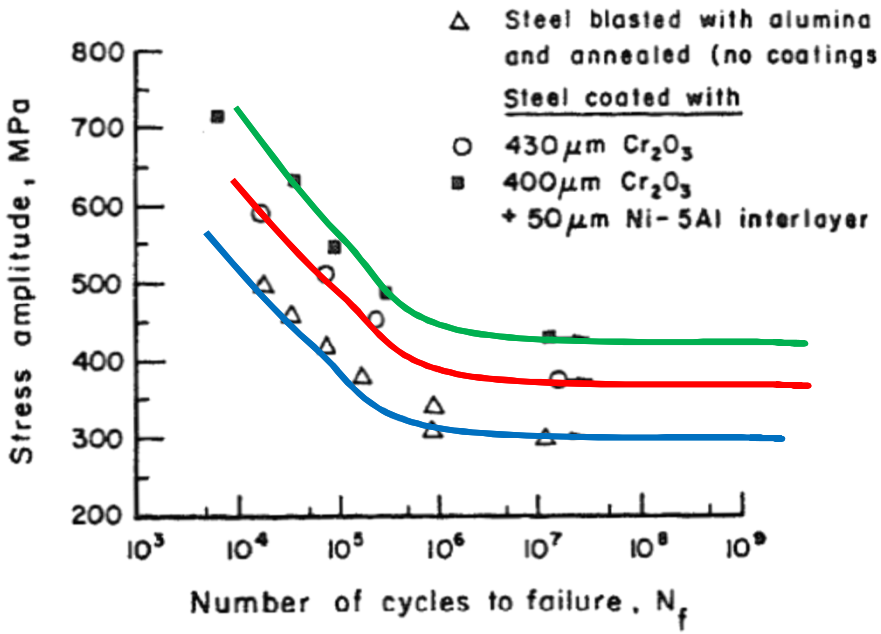
# Fatigue Cracks in Thermal Spray Coatings

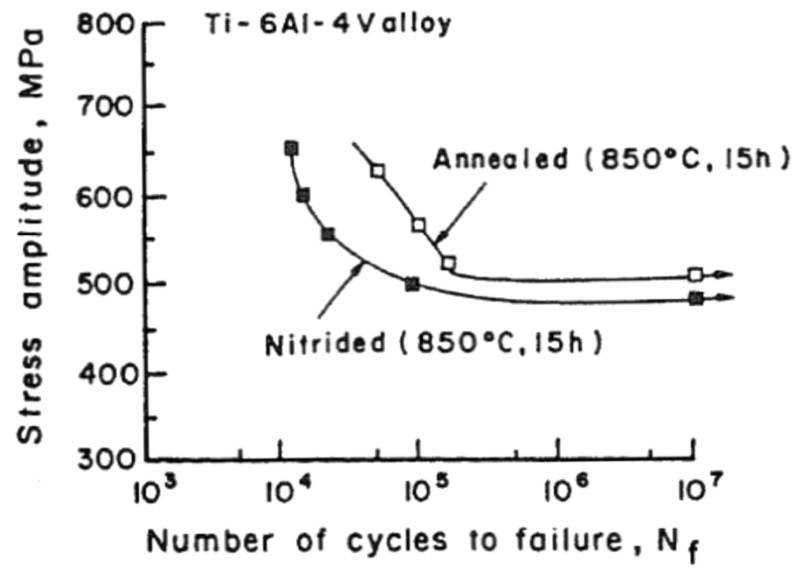



Suresh. Fatigue of Materials, Cambridge University Press

Plasma sprayed (a) chromia coating, (b) chromia top coat with Ni-Al bond coat.

# Thermal Spray vs. other Coating Technologies




*Sugimura, Suresh et al 1993.*

The brittle coating of $Cr_2O_3$ (without the interlayer) considered in Table I can debond from the steel substrate, especially when a fatigue crack propagates through the surface coating, as in Fig. 3(a). Such interfacial debonding and reinitiation of the crack in the substrate at a different site appears to result in an apparent improvement in the fatigue endurance limit over that of the uncoated substrate steel.

# Crack Shielding/Propagation through an Interface

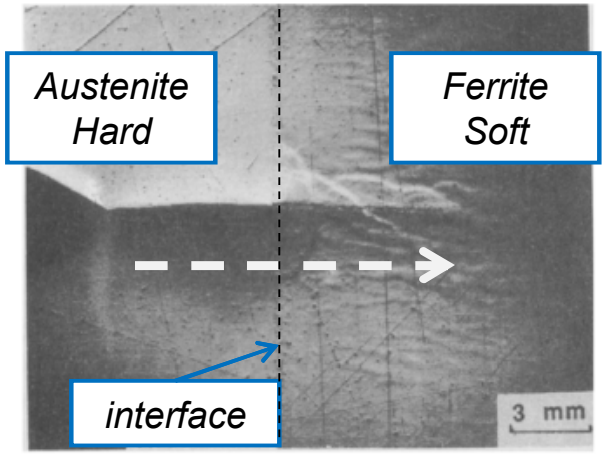



Fig. 17. An optical micrograph of fatigue crack profile as the crack is advanced from the austenite into the ferrite. $\Delta K = 16\ \mathrm{MPa}\sqrt{\mathrm{m}}$ (after Suresh *et al.* [8]).

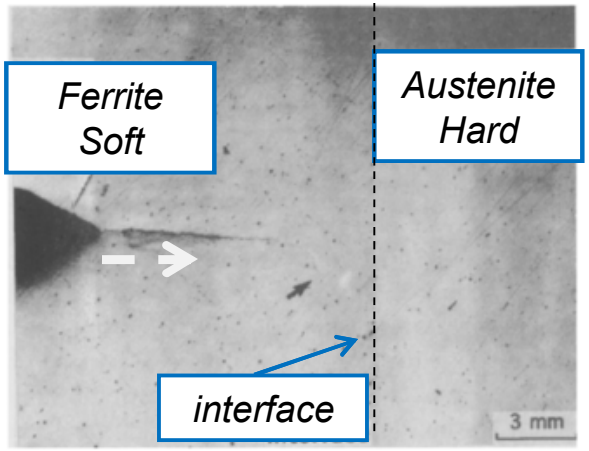
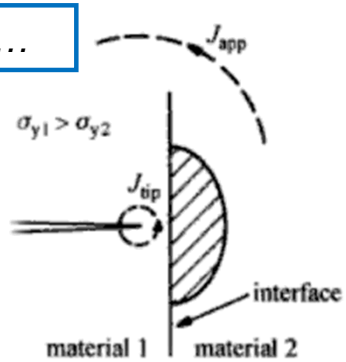
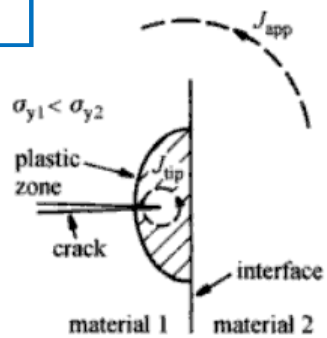



Fig. 19. An optical micrograph of fatigue crack profile as the crack approaches the interface from the ferrite. $\Delta K = 16\ \mathrm{MPa}\sqrt{\mathrm{m}}$. The arrow indicates the crack-tip location (after Suresh *et al.* [8]). See text for details.

Crack advances…




Crack stops…




Does not occur in thermal spray coatings!



*Sugimura, Suresh et al 1995.*

# Substrate stress relief through coating load bearing

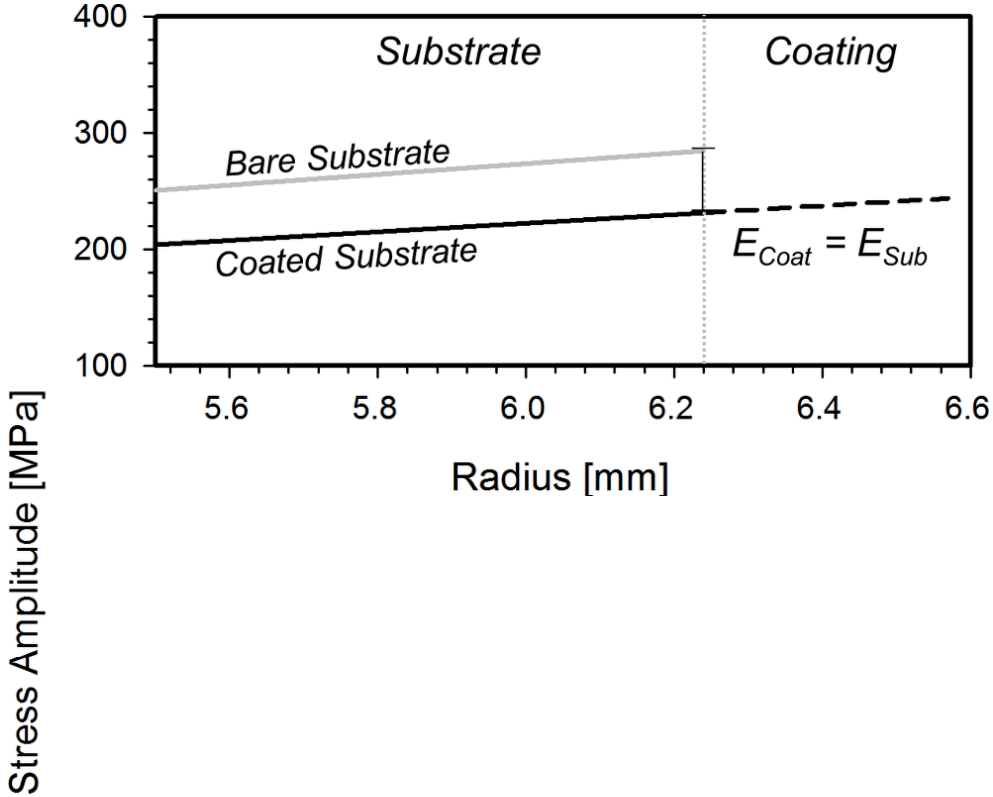
*Rotating Bend Fatigue*

$$K = \frac{64\ M}{E_s \pi D_s^4 + Ec\pi(Ds_{+c}^4 - D_s^4)}$$

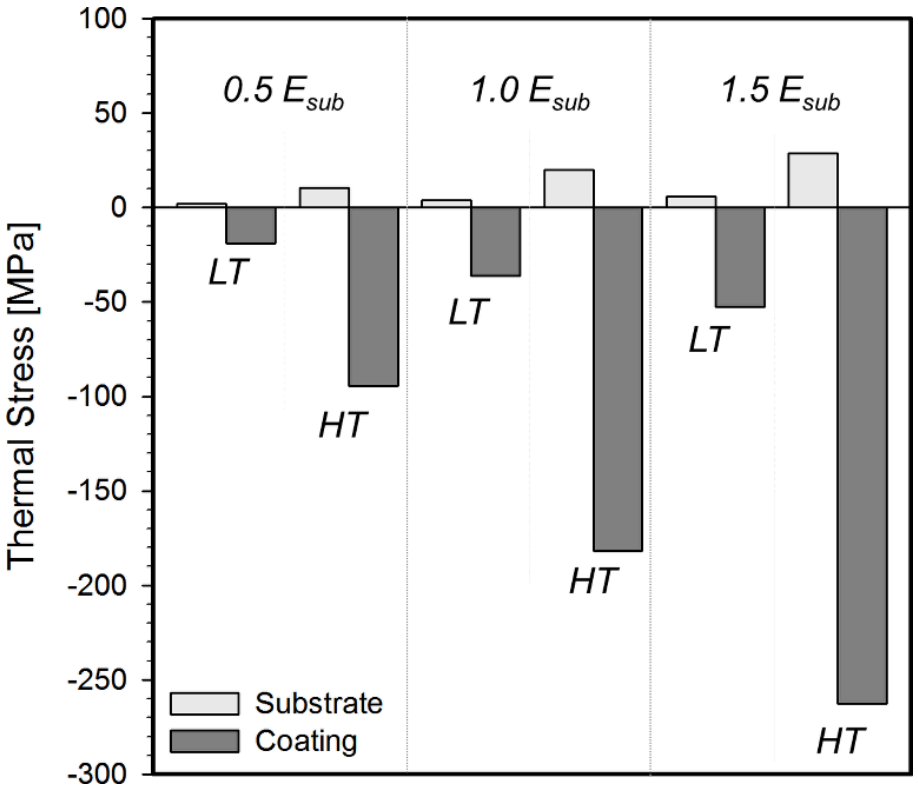
$$\sigma_s = EsKR$$

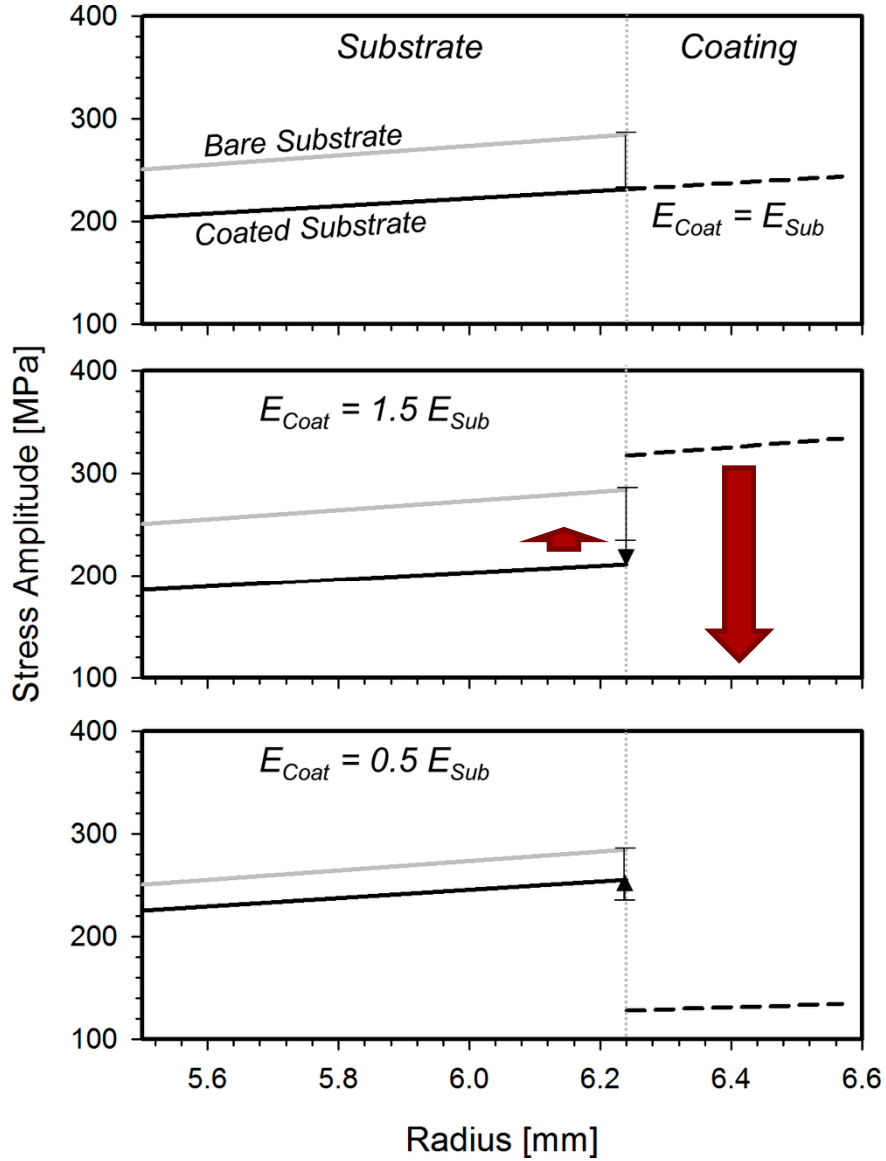
$$\sigma_c = EcKR$$

*For linear-elastic behavior*



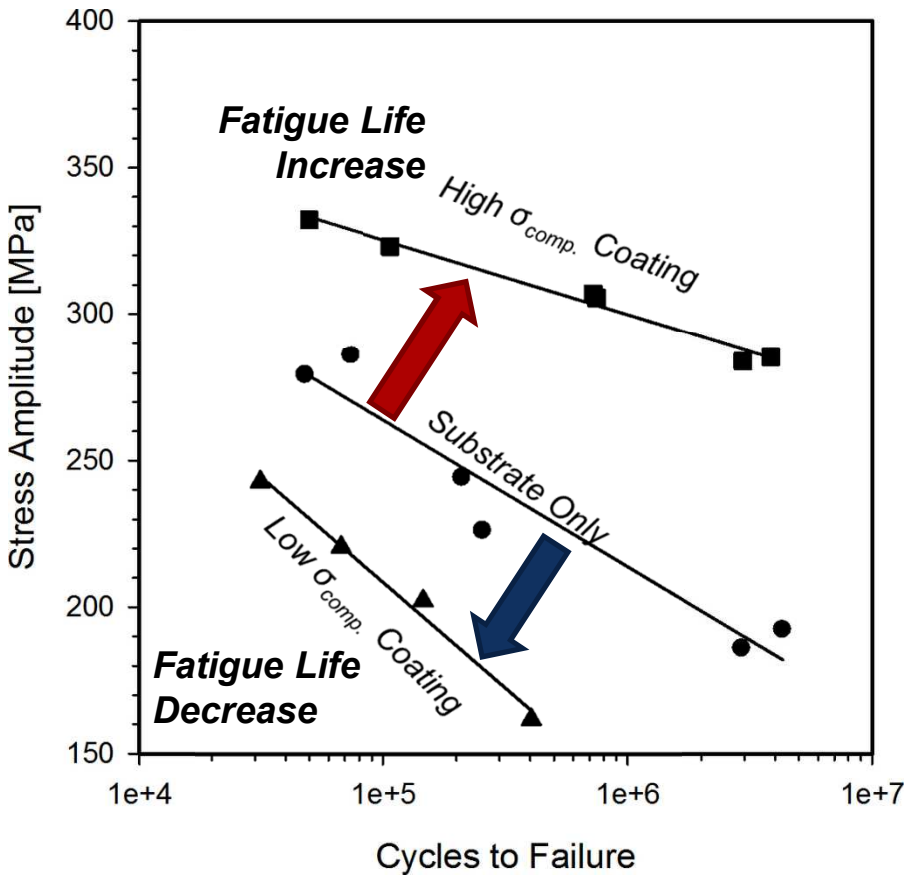
# Superposition of Applied and Thermal Stress




Coating has higher sensitivity to stress based on deposition temperature (Using calculations by Tsui-Clyne)

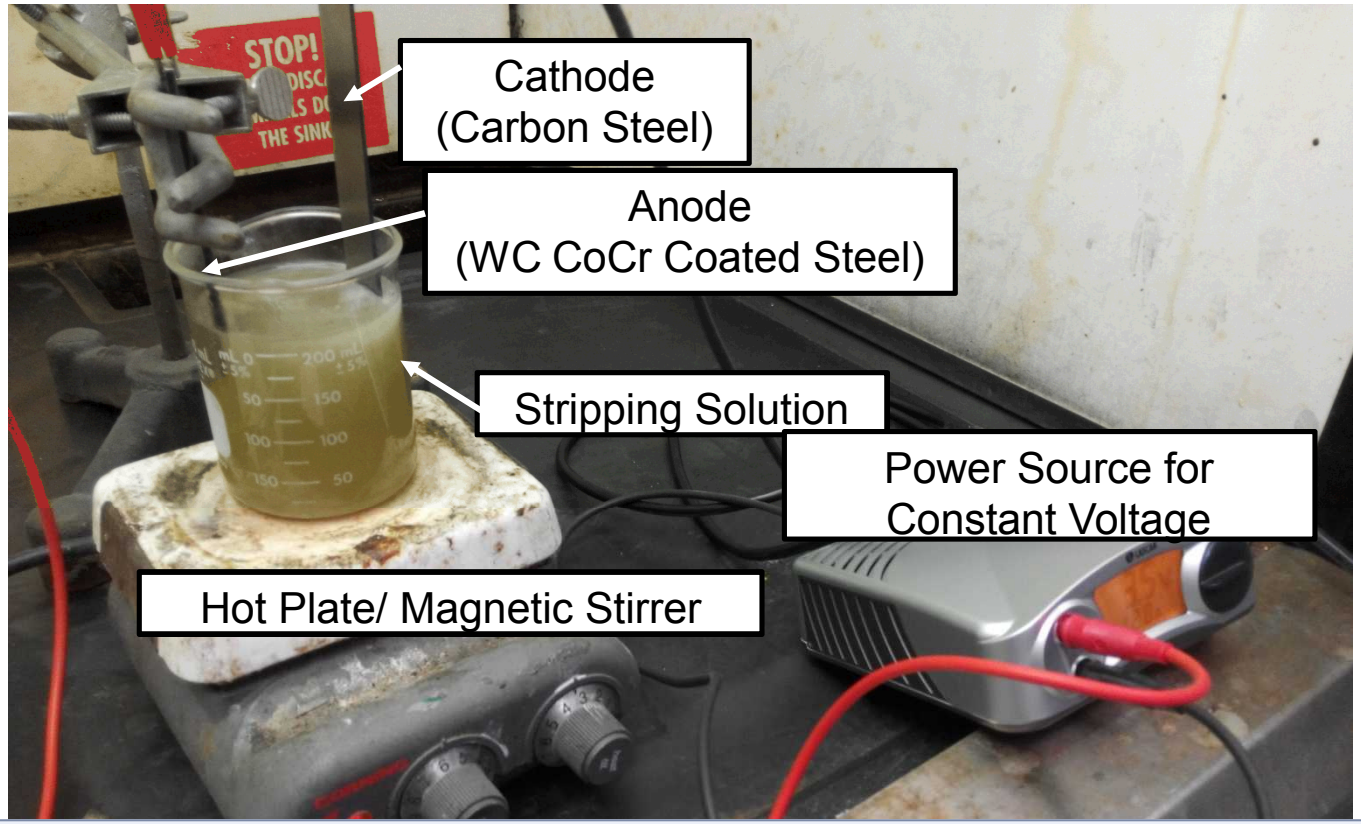
# Compressive stress aids in fatigue life




- High coating stiffness allows load bearing and alleviates stress to the substrate
- Compressive residual stress within the coating (and substrate) deters fatigue damage
- Coating processing influences residual stress in coating to substrate at a magnitude of ~10:1 (geometry dependent)
- Load transfers to substrate (raising stress levels) as the coating deteriorates
- Cracks within the coating do not grow into the substrate due to mechanical bonding mechanism

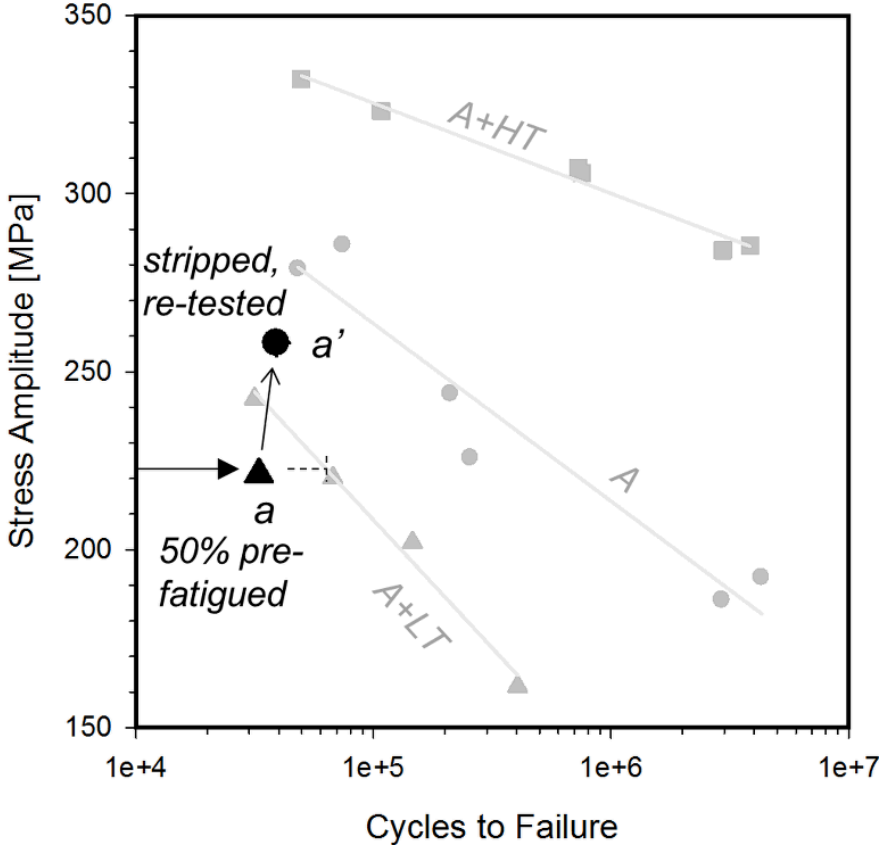
# Coating Stripping

***Coating Process + ~~Coating Presence~~ =***
***Δ Fatigue Life of Coated Component vs. Non-Coated Component***

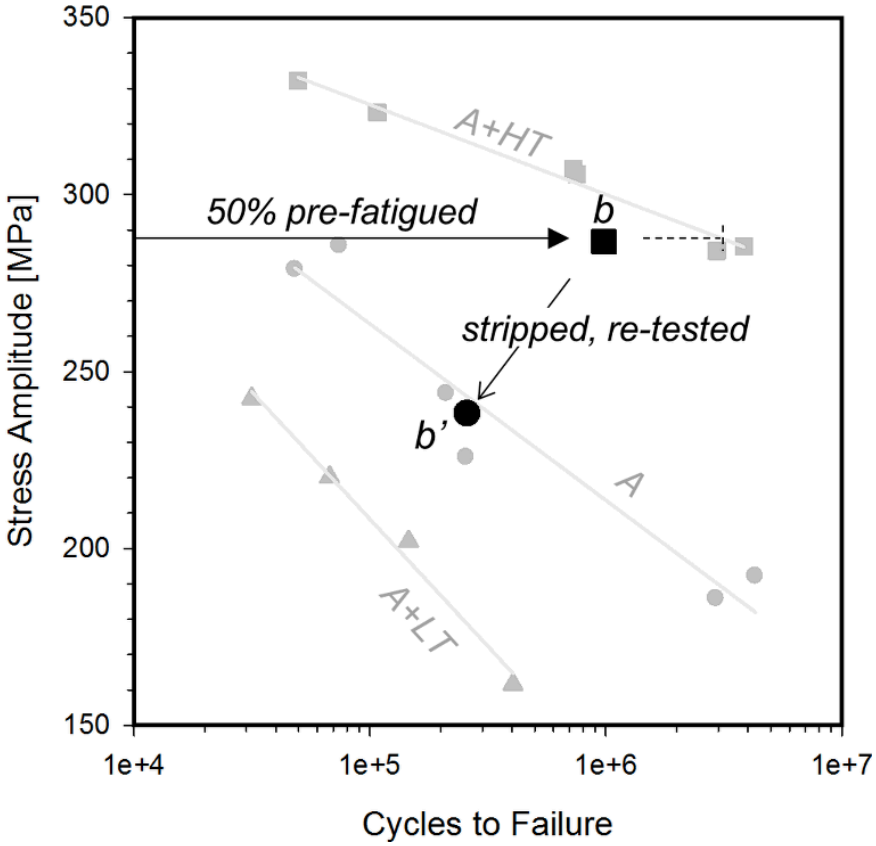



- *De-couples the coating process and coating presence*
- *Removal of the coating allows damage assessment of the substrate material*

# Allowing or Hindering Substrate Damage Accumulation




Damage Accumulated in Substrate



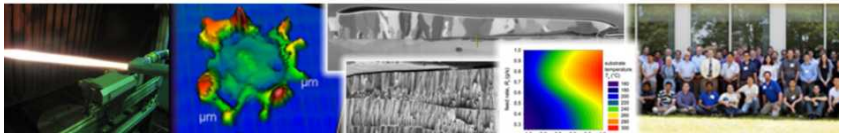

Little to no Damage Accumulated in Substrate

# Conclusions

- Thermal Spray coatings find use in several industrial sectors for protection of engineering components
- Residual Stress is inherent in Thermal Spray coatings and strongly correlated to coating performance, particularly mechanical behavior
- *In-situ* measurement of beam bending during coating application can be used to study residual stresses
- Fatigue behavior of TS coated components is highly influenced by residual stress and can be determine by processing

# Acknowledgements

Center for Thermal Spray Research



Sandia National Laboratories
Thermal Spray Research Lab