MICROCRACK CLOSURE EFFECT ON INDENTATION TESTING OF THERMALLY SPRAYED MATERIALS

T. Manninen, R. Kouhia, E. Turunen[⋆] and S.-P. Hannula[⋆,†]
TKK Structural Mechanics, [†]TKK Materials Science, [⋆]VTT

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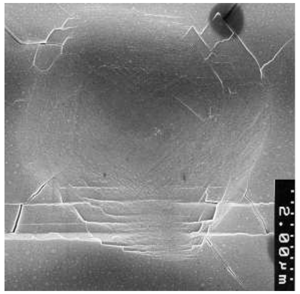
HELSINKI UNIVERSITY OF TECHNOLOGY
Laboratory of Stuctural Mechanics

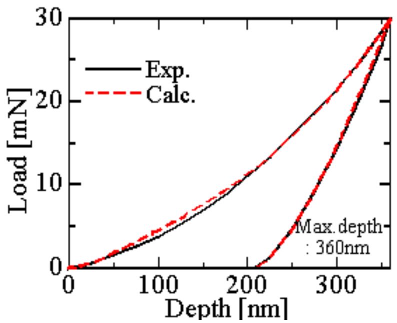
OUTLINE

DEPTH-SENSING INDENTATION TESTING

- Hardeness testing is perhaps the most commonly used means for testing materials. The hardness test result is a single number characterizing the penetration of a spherical or conical tip into the material being tested.



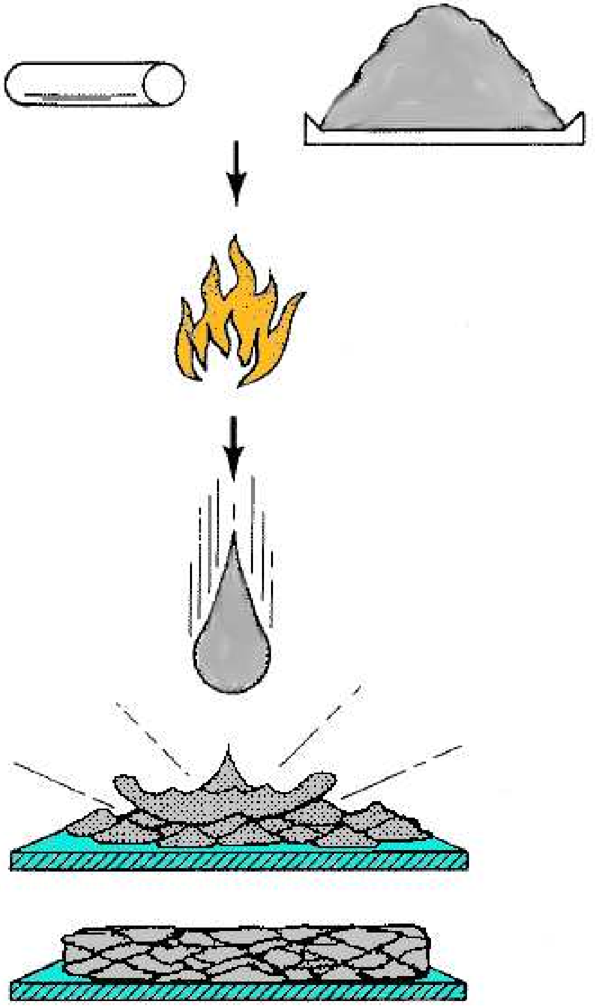
Indentation mark in sapphire.



(P,h) curve for a nanoscale test in Si.

- Depth-sensing indentation (nanoindentation) test is similar, but displacements and forces are measured continuously. The elastic modulus E and hardness H is estimated based on the curve.

THERMALLY SPRAYED MATERIALS



Powder or solid feedstock

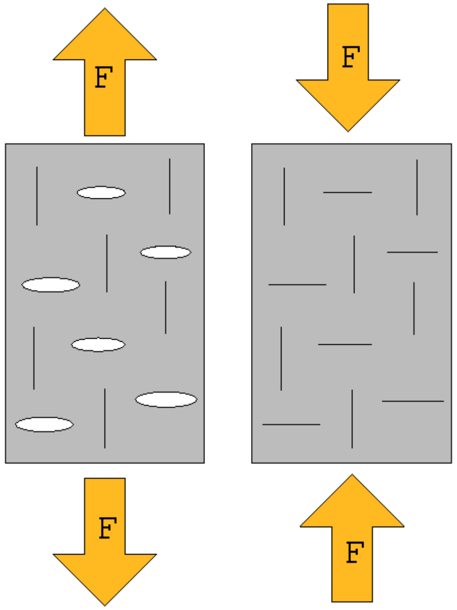
Electric or chemical heat source
melts the feedstock material

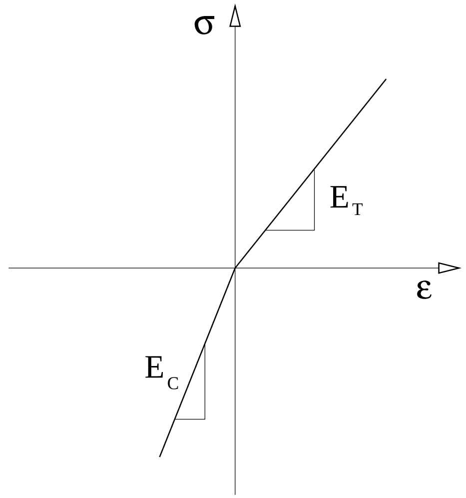
Liquid drops accelerated

Impacting substrate

Coating with lamellar structure
and a large number of microcracks

MICROCRACK CLOSURE EFFECT





- How does a microcracked material behave in indentation testing?
- What is the meaning of measured elastic modulus value?
  $E = E_C$? $E = E_T$? $E = f(E_T, E_C)$?

THE PRESENT WORK

- we study the influence of the microcrack closure effect (MCE) on indentation testing of thermally sprayed (TS) materials
- analytical solution not feasible $\Rightarrow$ FE-simulation of a representative example
- MCE is modelled using a state-of-the-art material model based on continuum damage mechanics
- Indentation testing of TS-materials is currently performed in a routine manner to measure the properties of these materials. What if the results are nonsense?

ELASTIC-DAMAGED MATERIAL WITH MCE

- Thermodynamic approach: material behaviour is completely described by defining the Helmholtz free energy ψ of the material.

- ψ is a function strain ε_{ij} and damage D_{ij}.

- postulated decomposition in 3 parts:

$$\psi = \psi_0(\varepsilon_{ij}) + \psi_1(\varepsilon_{ij}, D_{ij}) + \psi_2(\varepsilon_{ij}, D_{ij}) \tag{1}$$

- ψ_0 corresponds to undamaged elastic material,
  ψ_1 material with open microcracks,
  ψ_2 contains the influence of MCE.

DAMAGE

- Discrete approach by Bargellini et al. (2005):

$$D_{ij} = \sum_k d^{(k)} n_i^{(k)} n_j^{(k)} = \sum_k d^{(k)} N_{ij}^{(k)} \tag{2}$$

- Orientation tensors $N_{ij}^{(k)}$ constructed using a fixed set of directions in $\mathbb{R}^{3\times3}$:

$$\begin{array}{ll}
N^{(1)} = e_1 \otimes e_1 & N^{(4)} = \frac{1}{2}(e_1 + e_2) \otimes (e_1 + e_2) \\
N^{(2)} = e_2 \otimes e_2 & N^{(5)} = \frac{1}{2}(e_1 + e_3) \otimes (e_1 + e_3) \\
N^{(3)} = e_3 \otimes e_3 & N^{(6)} = \frac{1}{2}(e_2 + e_3) \otimes (e_2 + e_3) \\
 & N^{(7)} = \frac{1}{2}(e_1 - e_2) \otimes (e_1 - e_2) \\
 & N^{(8)} = \frac{1}{2}(e_1 - e_3) \otimes (e_1 - e_3) \\
 & N^{(9)} = \frac{1}{2}(e_2 - e_3) \otimes (e_2 - e_3)
\end{array} \tag{3}$$

- We avoid operating with ε^+

DAMAGED MATERIAL BEHAVIOR

- Linear elastic behavior with constant damage $\Rightarrow \psi$ quadratic with ε_{ij}
- Elastic energy decreases with progressing damage $\Rightarrow \psi$ linear in D_{ij}
- Helmholtz free energy is chosen as

$$\rho\psi_1 = \alpha\varepsilon_{ij}\varepsilon_{jk}D_{ki} = \alpha\sum_a d^{(a)}\varepsilon_{ij}\varepsilon_{jk}N_{ki}^{(a)} \tag{4}$$

based on Bargellini et al. (2005) & Challamel et al. (2005).

MICROCRACK CLOSURE EFFECT

- Microcrack closure condition for crack with orientation N_{ij}:

$$g(\varepsilon_{ij}, N_{kl}^{(a)}) = M_{ij}^{(a)} \varepsilon_{ij} = 0, \tag{5}$$

where

$$M_{ij}^{(a)} = C_{ijkl}^{0} N_{kl}^{(a)} = \left(\lambda \delta_{ij} \delta_{kl} + 2\mu \delta_{ik} \delta_{jl}\right) N_{kl}^{(a)} \tag{6}$$

- Continuity and conservation of energy requirements are satisfied if

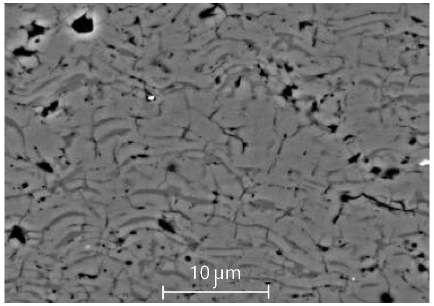
$$\rho \psi_2 = \beta \sum_{a} d^{(a)} H(-\varepsilon_{ij} M_{ij}^{(a)})(\varepsilon_{ij} M_{ij}^{(a)})^2 \tag{7}$$

- If non-zero compressive stress needed for closure:

$$\rho \psi_2 = \beta \sum_{a} d^{(a)} H(-\varepsilon_{ij} M_{ij}^{(a)} + \gamma)(\varepsilon_{ij} M_{ij}^{(a)} - \gamma)^2, \tag{8}$$

REPRESENTATIVE EXAMPLE CASE

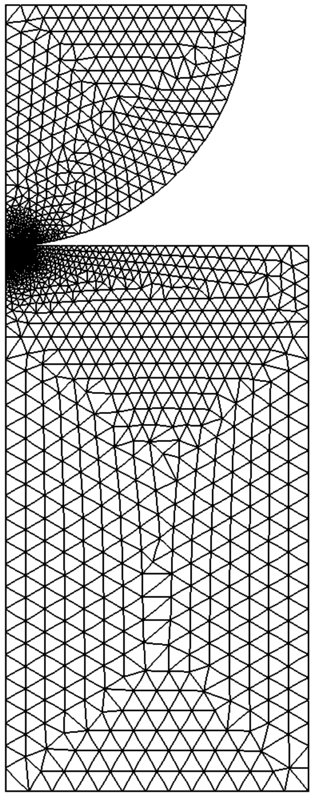
- Al_2O_3 coating produced with HVOF method by VTT.

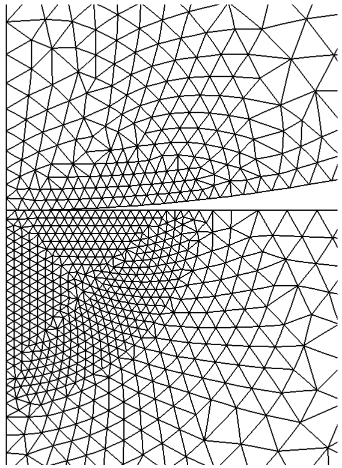


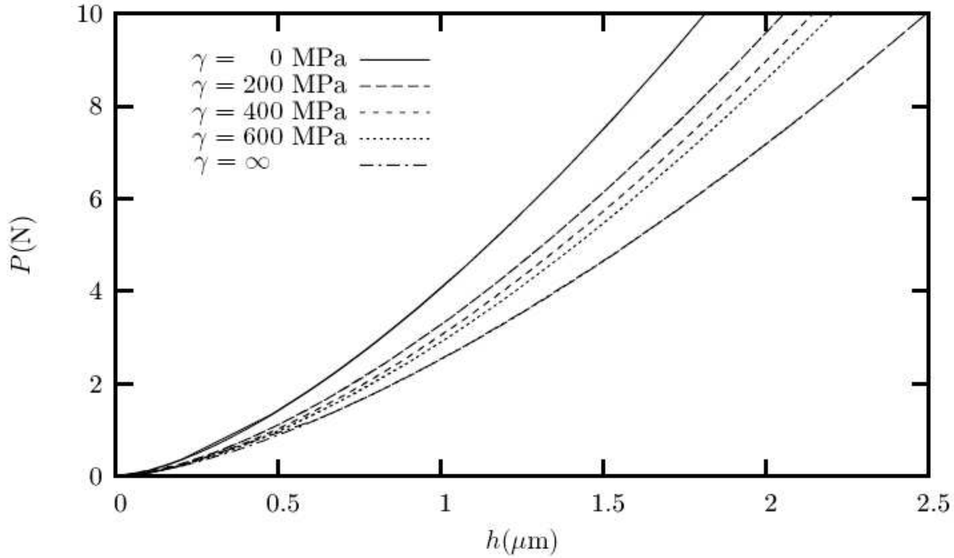
- In-plane Young's modulus by impulse excitation method: $E = 96$ GPa
  Indentation Young's modulus: $E = 96$ GPa.
- Globular porosity (5%) accounted for by lowering the base material properties to $E = 225$ GPa, $\nu = 0.185$
- Indentation maximum load was $P = 10$ N.
  Spherical tip radius $R = 0.794$ mm.

NUMERICAL SIMULATION

- Abaqus/Standard v6.4, axisymmetric model.
- Simulated load-displacement curve analyzed using standard analytical Oliver-Pharr method.
- Isotropic damage orientation distribution chosen for simplicity.
- Material parameters chosen based on measured values and base material properties.
- Microcrack closure stress unknown $\Rightarrow$ 3 different values used.







$\gamma =$ 0 MPa
$\gamma =$ 200 MPa
$\gamma =$ 400 MPa
$\gamma =$ 600 MPa
$\gamma = \infty$
P(N)
$h(\mu$m)
0
2
4
6
8
10
0
0.5
1
1.5
2
2.5

RESULTS

The influence of material parameter γ and the corresponding crack closure stress on indentation Young's modulus.

γ (MPa)	0	200	400	600	∞
$\sim p_c$ (MPa)	0	125	250	375	∞
E (GPa)	123	99	91	87	72

CONCLUSIONS

- Indentation Young's modulus increases due to MCE
- The size of the effect depends on the stress needed for microcrack closure
- In the example case studied:
  - Without MCE: $E = 72$ GPa
  - With MCE taken into account: $E \in (72, 123)$ GPa.
- Damage model formulated with the Helmholtz free energy does not yield orthotropic elastic material. Stress-based formulation using the Gibbs energy might do better?