Effect of Material Parameters on Mechanical Performance of Environmental Barrier Coatings

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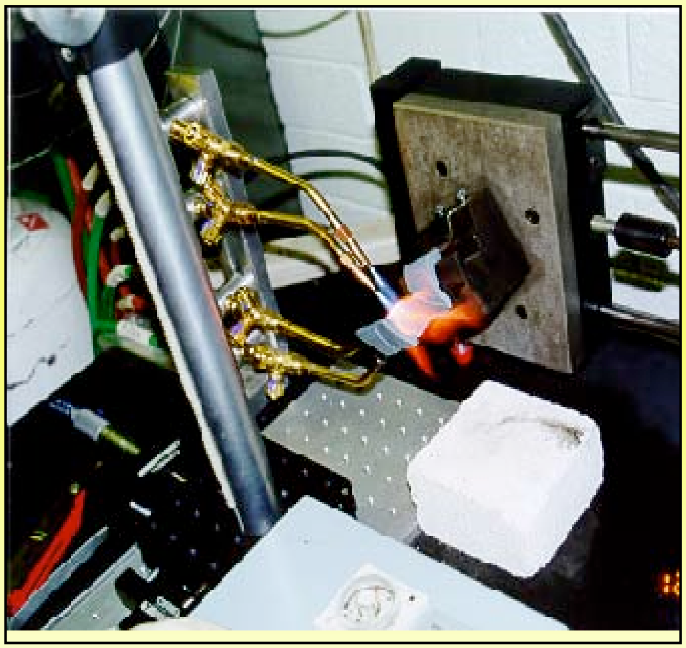
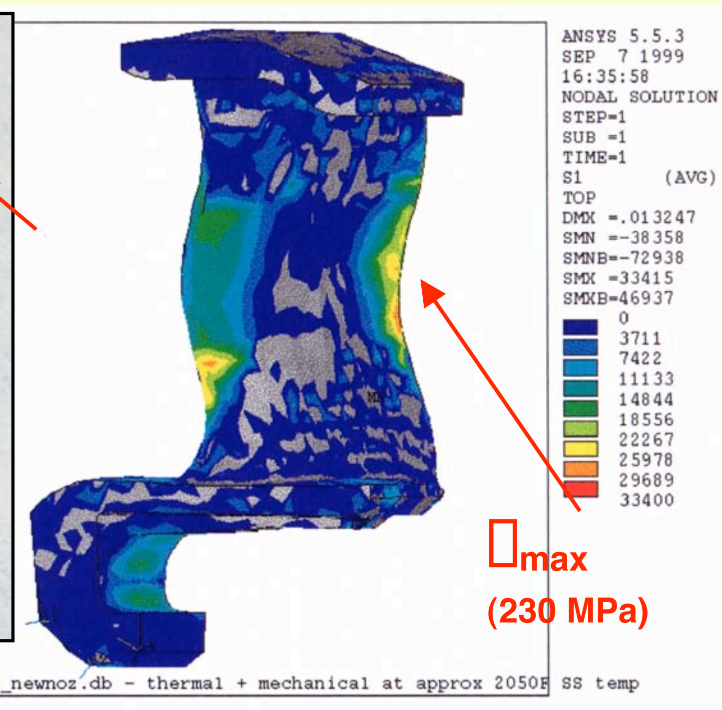
Study was Motivated by Fracture of EBC-SN282 Nozzle During Thermal Shock Proof Test at Solar Turbines



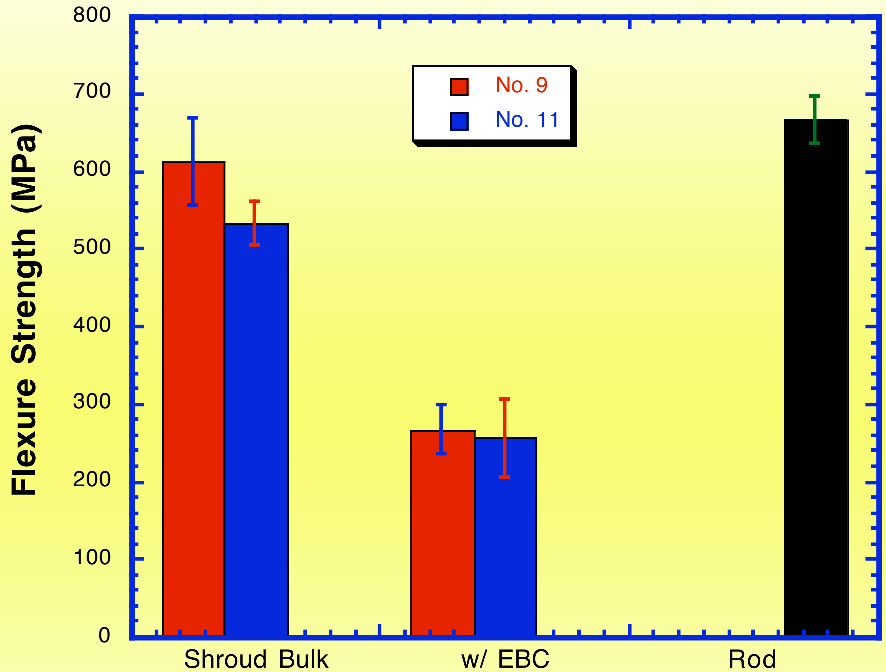
Solar SN282_11
2072°F, 28.6 s

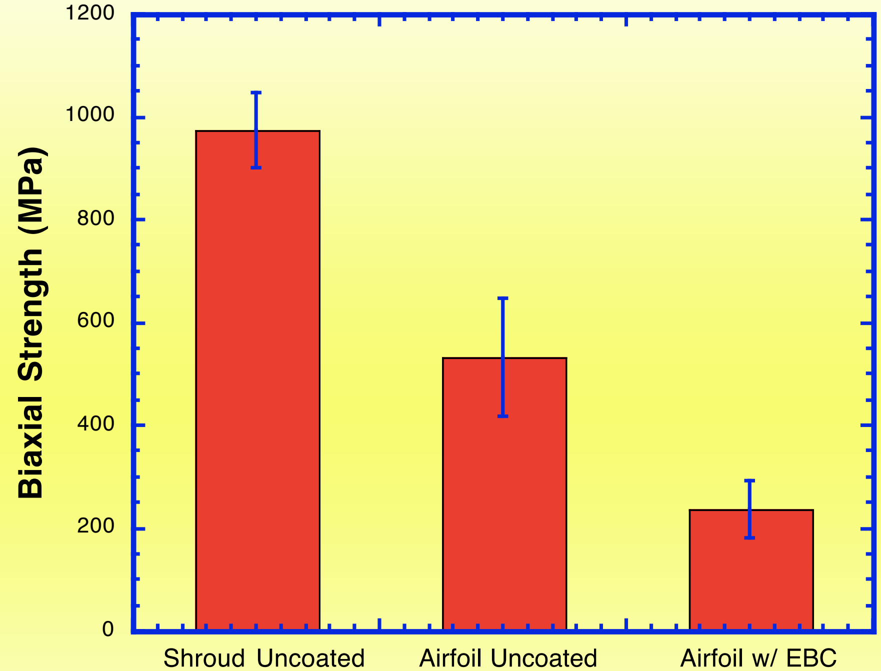


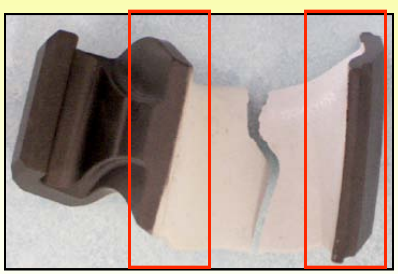
Suction side

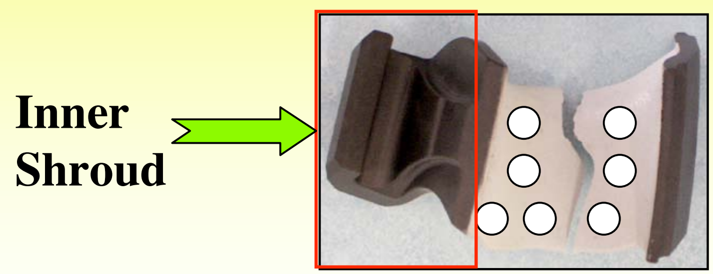
The first stage nozzle is designed for Centaur 50S Gas Turbine

Significant Strength Degradation Observed in EBC SN282 Samples Extracted from Nozzles



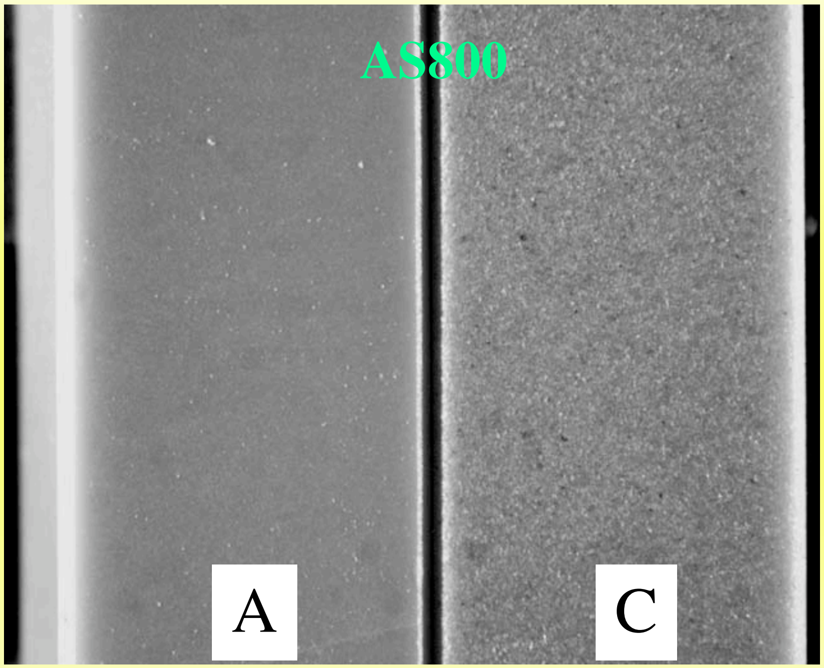




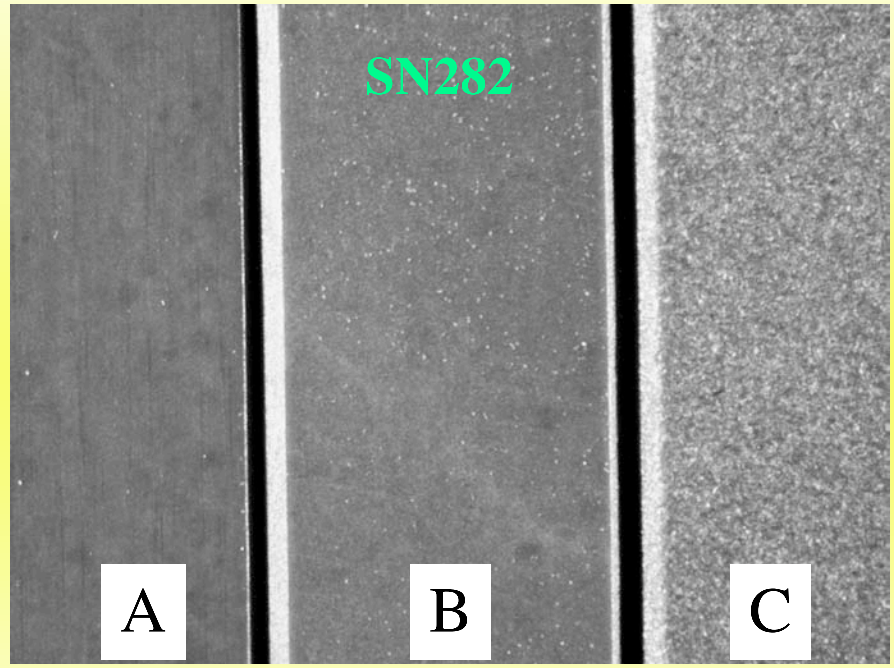


The strength of bend bars from inner shroud region is comparable to those obtained from production rods

Grit Blast Conditions Employed for Surface Preparation Result in Different Surface Morphology of Substrate



~50 μm **~100 μm**



~50 μm **~27 μm** **~100 μm**

Grit blast step was carried out prior to the EBC coating process to ensure a better mechanical adhesion

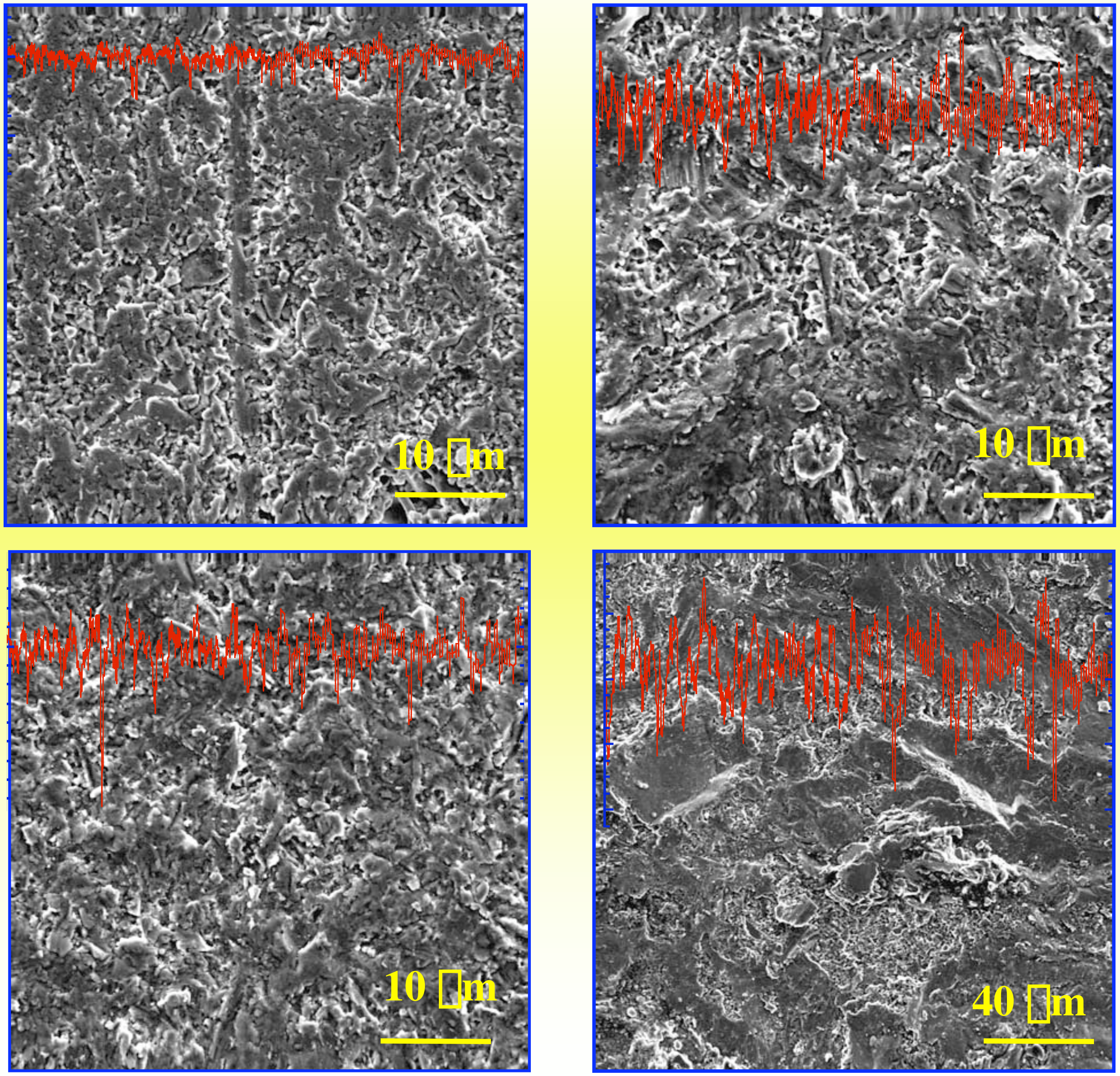
Grit Blast Conditions Employed Could Introduce Substantial Surface (and Subsurface) Damages

As-machined

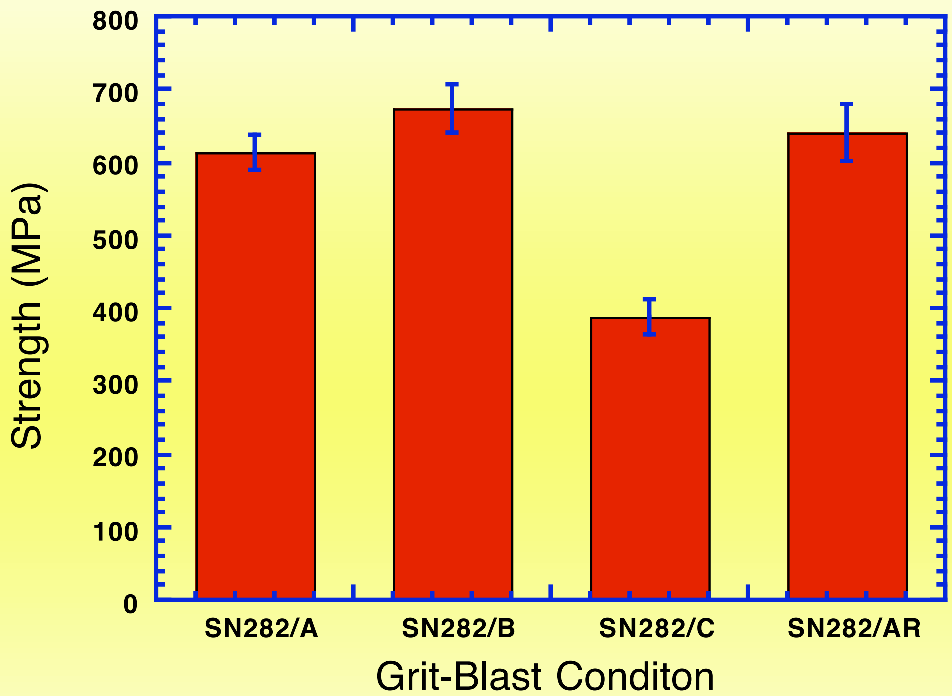
Condition "A" (~ 50 μm)

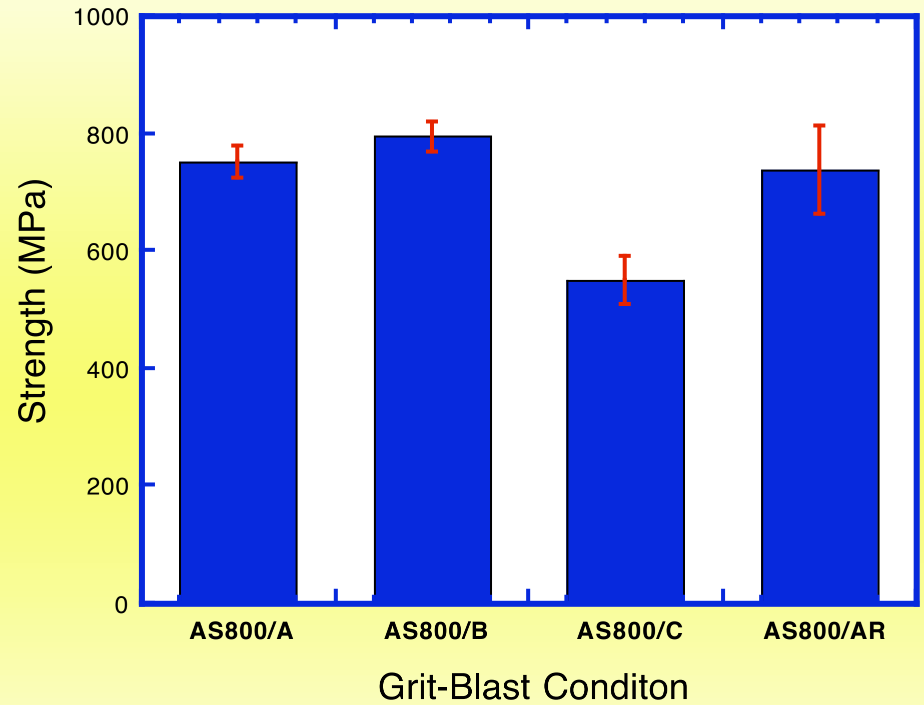
Condition "B" (~ 27 μm)

Condition "C" (~ 100 μm)



Grit Blast Conditions Employed for Surface Preparation Could Influence the Mechanical Property of Airfoils



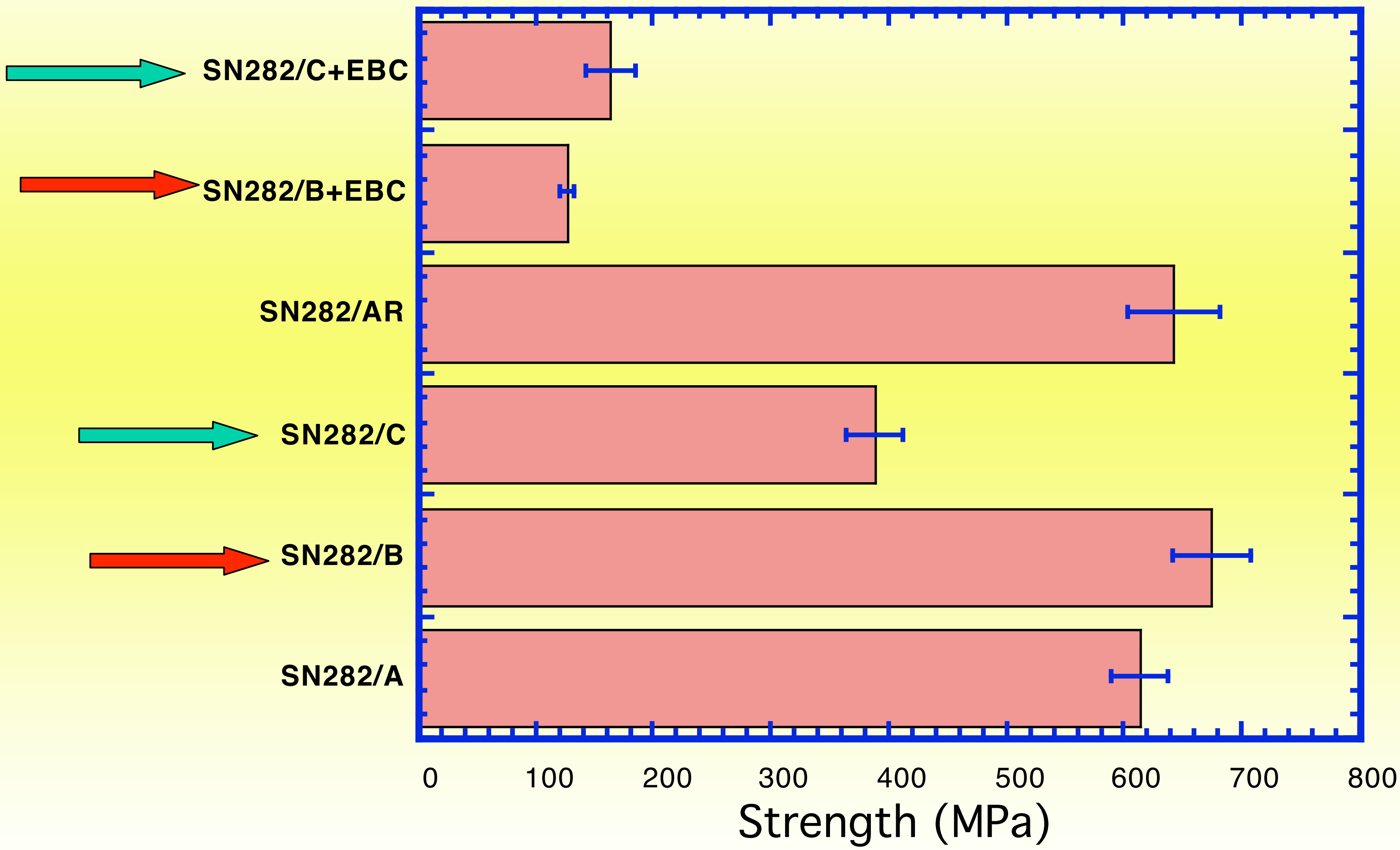


K_{IC} (SN282):
6 MPa√m 40% decrease

K_{IC} (AS800):
8.5 MPa√m 26% decrease

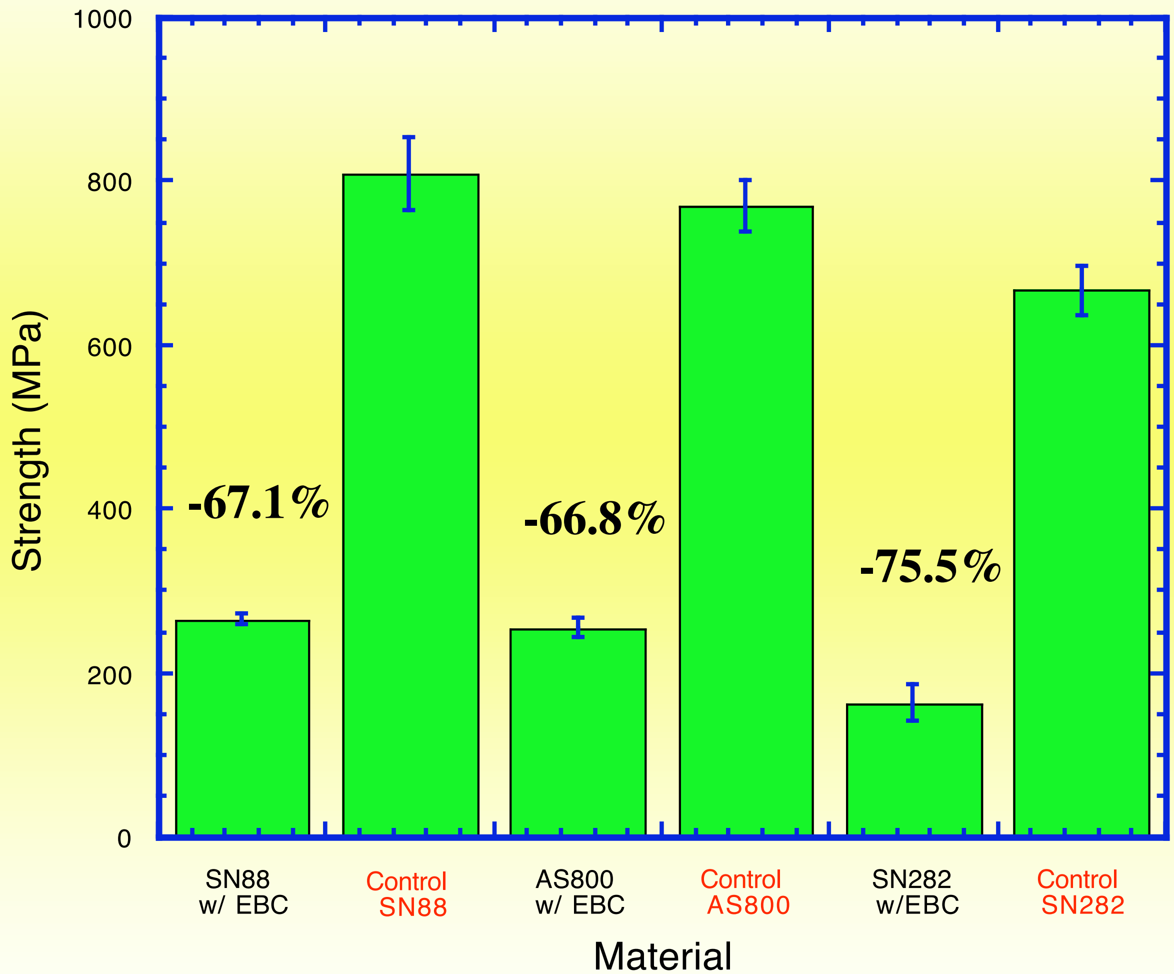
The extent of strength degradation is related to the material toughness (damage tolerance) and also hardness

Mechanical Strength of SN282 Samples is Significantly Decreased After Deposition of BSAS EBC System



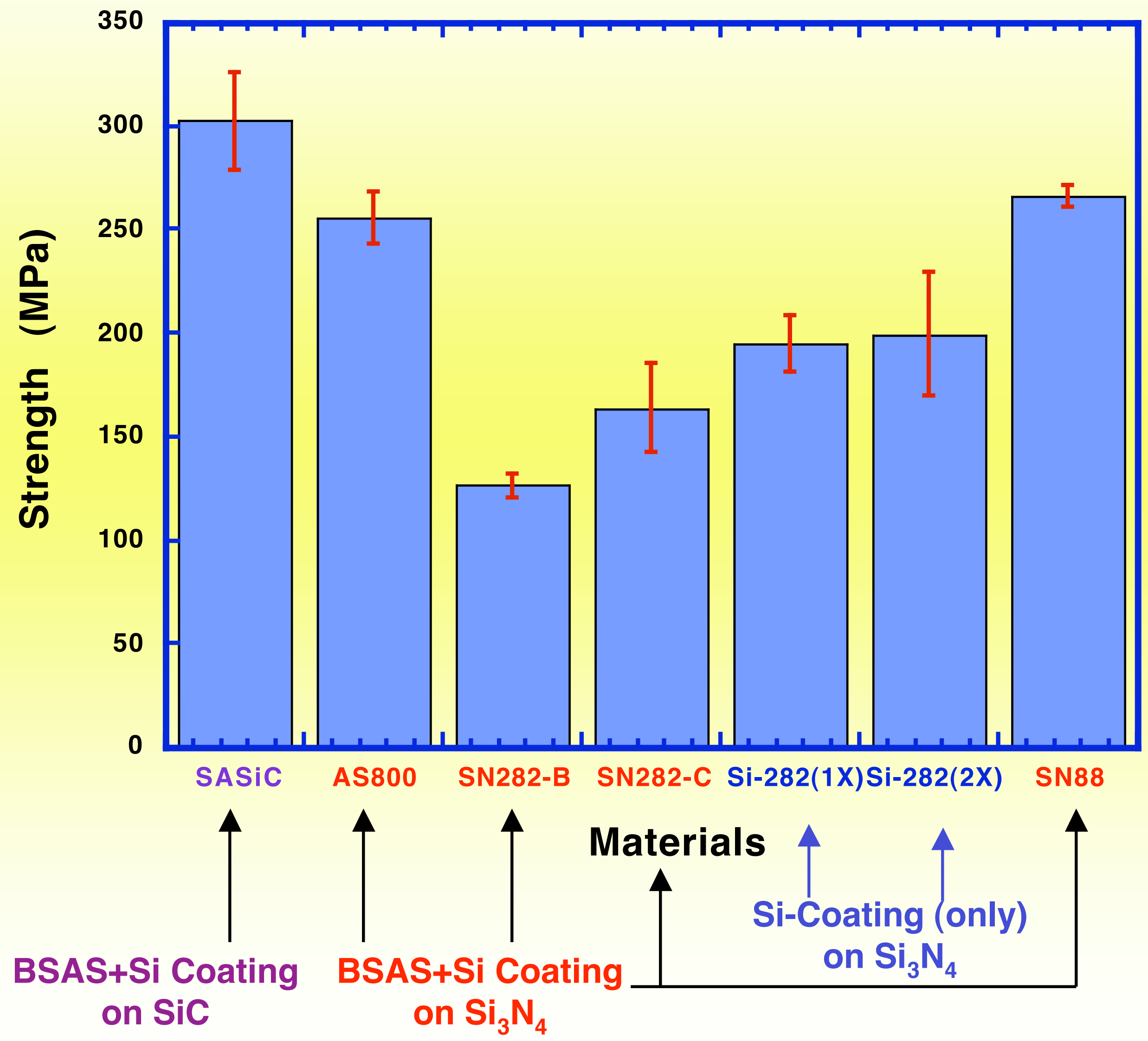
Strength degradation of EBC Si_3N_4 is independent upon grit blast condition

Substantial Strength Degradation Occurred in all EBC-Coated Commercially Available Advanced Silicon Nitrides



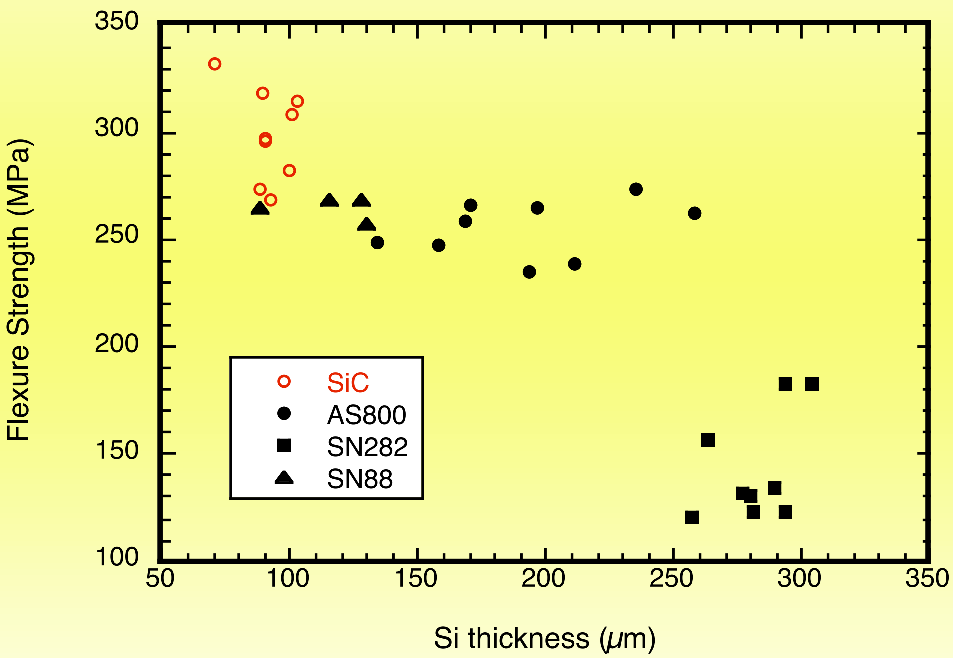
Extent of strength degradation is independent of mechanical properties (strength & toughness) of substrates

Flexural Strength Comparison of BSAS EBC Coated Silicon Nitride Ceramic Samples

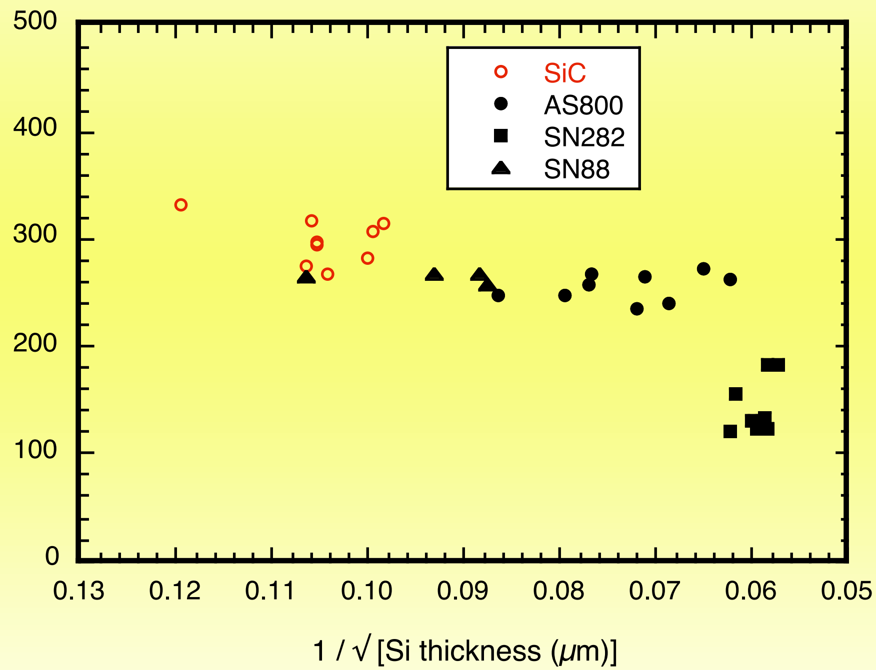


Dependence of BSAS EBC/Si_3N_4 Strength on Si Bond Coat Thickness Appears to be Very Subtle

Strength as a Function of Si Thickness



Strength as a Function of 1 / √ (Si Thickness)



$$K_{IC} = \sigma_a Y \sqrt{a}$$

There Was no Conclusive Dependence of Si/Si_3N_4 Strength on Si Thickness

Specimen ID	Max Stress (MPa)	Si coating thickness (µm)	Ra (µm)	Rq (µm)	Rp (µm)	Rv (µm)	Rt (µm)	Rz (µm)
1X-4	172.9	168	7.51	9.47	22.18	20.97	55.78	43.15
1X-3	193.0	93	7.76	9.92	26.97	20.14	61.15	47.11
1X-5	197.3	113	7.82	9.97	24.39	22.40	64.26	46.79
1X-1	201.6	133	9.49	11.81	27.51	24.42	64.99	51.93
1X-2	209.9	145	8.05	9.57	19.65	19.32	45.86	38.96
Ave	**194.9**	**130.4**	**8.13**	**10.15**	**24.14**	**21.45**	**58.41**	**45.59**
Std Dev	**13.8**	**28.9**	**0.79**	**0.95**	**3.30**	**2.01**	**7.90**	**4.84**
2X-6	175.5	264	7.29	9.19	19.52	20.26	60.00	39.78
2X-8	177.1	221	7.27	8.95	20.66	18.73	45.99	39.39
2X-7	189.9	290	8.52	11.01	33.58	21.69	73.05	55.27
2X-9	208.8	298						
2X-10	247.0	269	7.87	9.60	23.39	19.22	53.81	42.61
Ave	**199.7**	**268.4**	**7.74**	**9.69**	**24.29**	**19.98**	**58.21**	**44.26**
Std Dev	**29.6**	**30.0**	**0.59**	**0.92**	**6.40**	**1.31**	**11.43**	**7.48**

Flexure strength was essentially the same even though coating thickness was doubled

There May Appear to be Some Dependence of Si/Si_3N_4 Strength on Si Roughness Thickness (Ra & Rq)

Specimen ID	Max Stress (MPa)	Si coating thickness (μm)	Ra (μm)	Rq (μm)	Rp (μm)	Rv (μm)	Rt (μm)	Rz (μm)
1X-4	172.9	168	7.51	9.47	22.18	20.97	55.78	43.15
1X-3	193.0	93	7.76	9.92	26.97	20.14	61.15	47.11
1X-5	197.3	113	7.82	9.97	24.39	22.40	64.26	46.79
1X-1	201.6	133	9.49	11.81	27.51	24.42	64.99	51.93
1X-2	209.9	145	8.05	9.57	19.65	19.32	45.86	38.96
Ave	**194.9**	**130.4**	**8.13**	**10.15**	**24.14**	**21.45**	**58.41**	**45.59**
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Std Dev	**29.6**	**30.0**	**0.59**	**0.92**	**6.40**	**1.31**	**11.43**	**7.48**

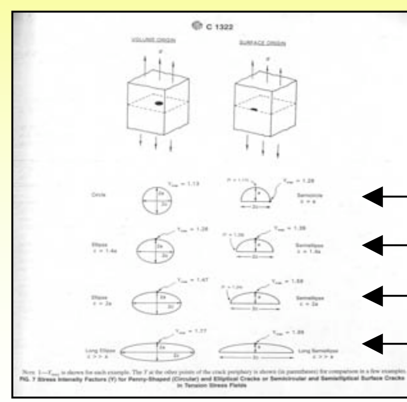
When the roughness parameters shown above are used to "back-calculate" the crack geometry correction factor, Y, there is good correlation with Ra and Rq and surface-located, elliptical, strength-limiting flaws shown below

	1x	2x	
Ra	1.80	1.80	Good Correlation
Rq	1.61	1.61	
Rp	1.05	1.02	No physical meaning
Rv	1.11	1.12	
Rt	0.67	0.66	
Rz	0.76	0.75	

$$S = \frac{K_{Ic}}{Y\sqrt{c}}$$

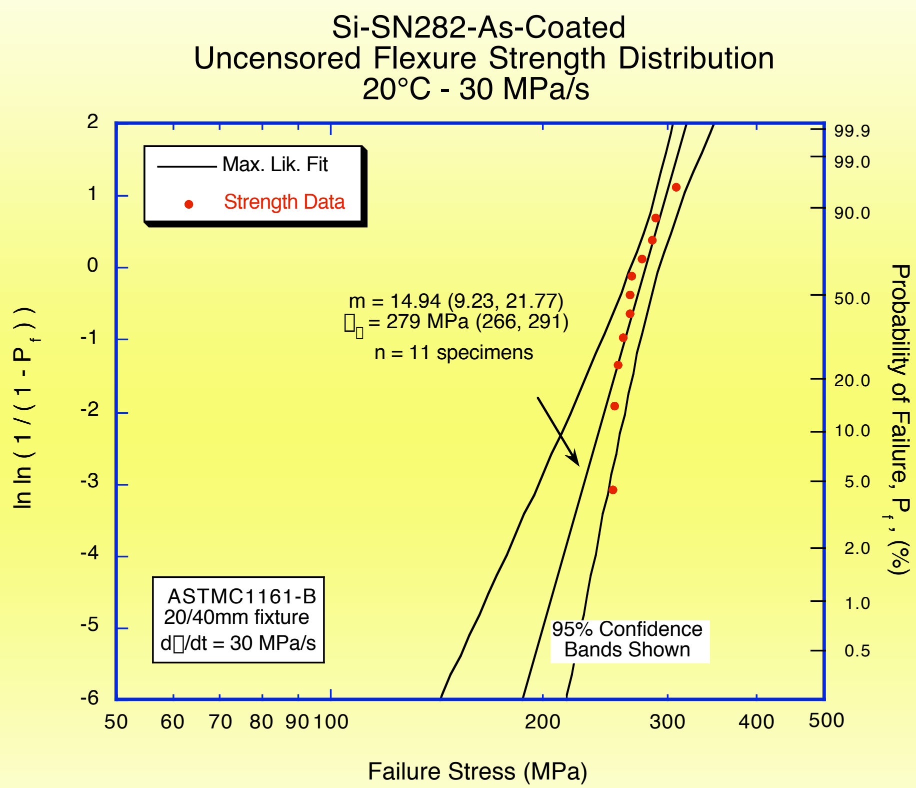
or

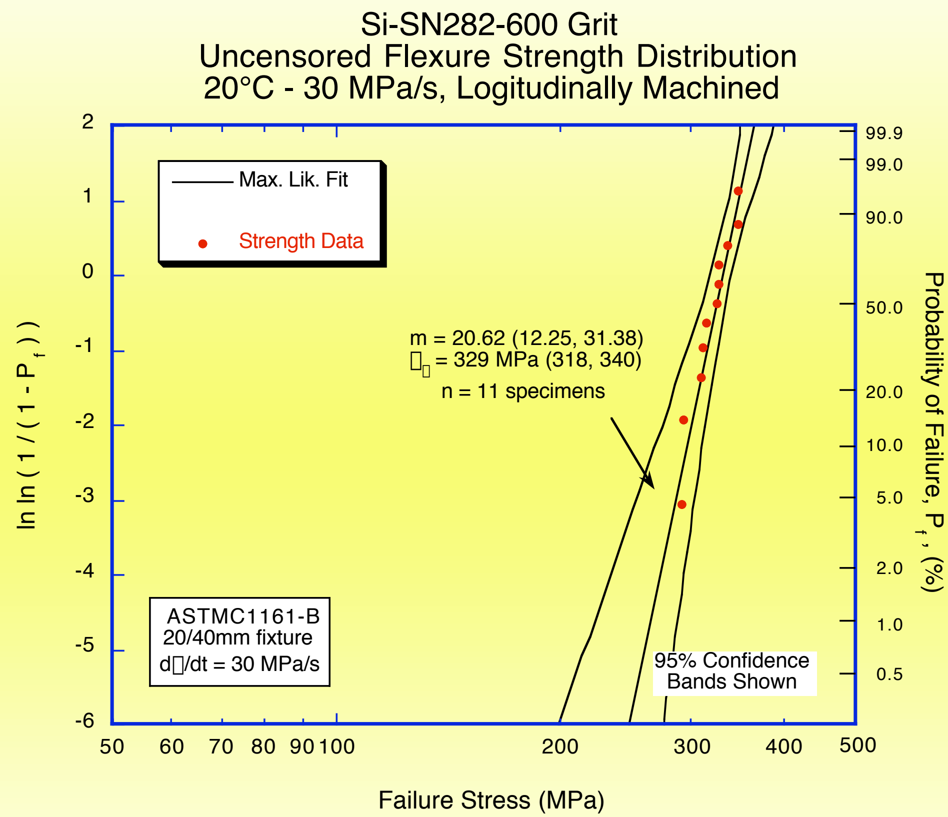
$$Y = \frac{K_{Ic}}{S\sqrt{c}}$$



Y = 1.29
Y = 1.39
Y = 1.59
Y = 1.99

However, Si-SN282 Strength Results Seems to Exclude the Hypothesis of "Si" Surface Roughness Effect



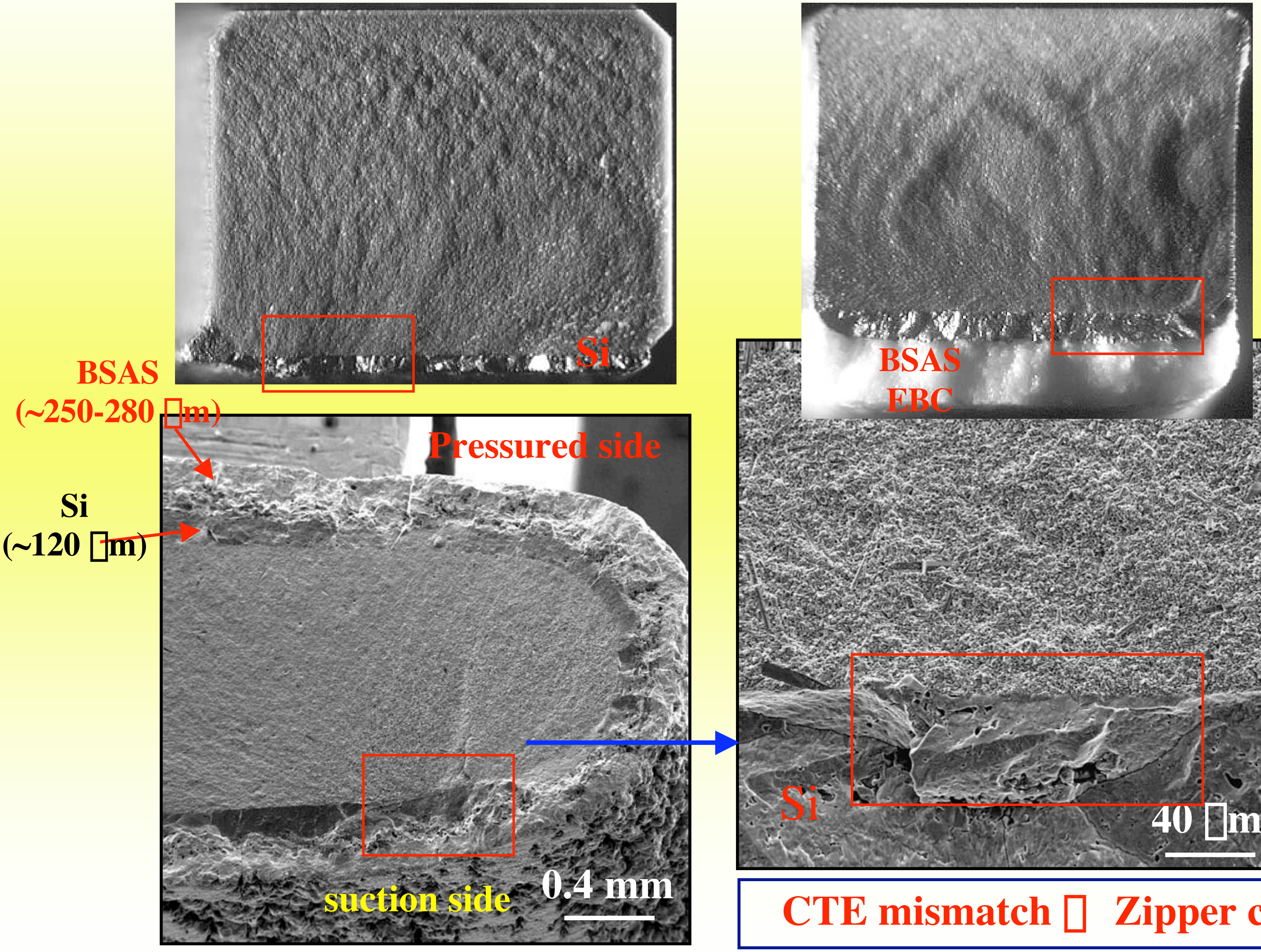


σ_{avg} = 253 ± 9.8 MPa

σ_{avg} = 270 ± 17.7 MPa

Fine surface finish (600 grit) of Si bond coat slightly improve strength and Weibull modulus

Zipper Crack Observed in all Si- and BSAS EBC-Coated Silicon Nitride Samples



Zipper crack observed on fracture surface

CTE mismatch → Zipper crack

Micro-FEA (Finite Element Analysis) Method

Input Microstructural Image Into Micro-FEA Program (a LabView™ Executable)

Specify Thermoelastic Properties of All Microstructural Constituents & μm/pixel Resolution

Micro-FEA Outputs an ANSYS™ Input File

Reconstruct Microstructure in ANSYS™ Using Input File

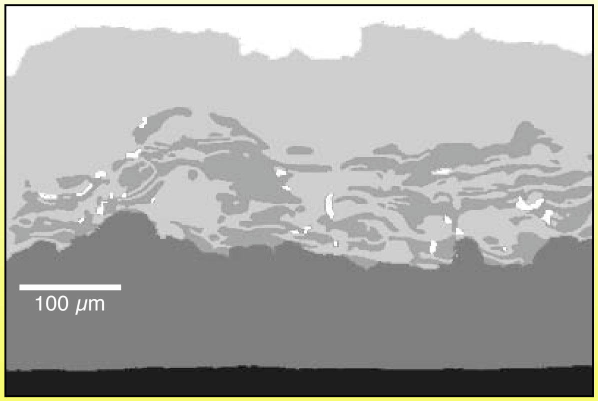
Apply Desired Boundary or Initial Conditions or Both

Determine Solution.
e.g., Residual Stress State,
Predict Microcracking,
Thermal Shock,
Contact-Induced Deformation,
Apparent Elastic Properties, Etc.

By Wereszczak & Ferber

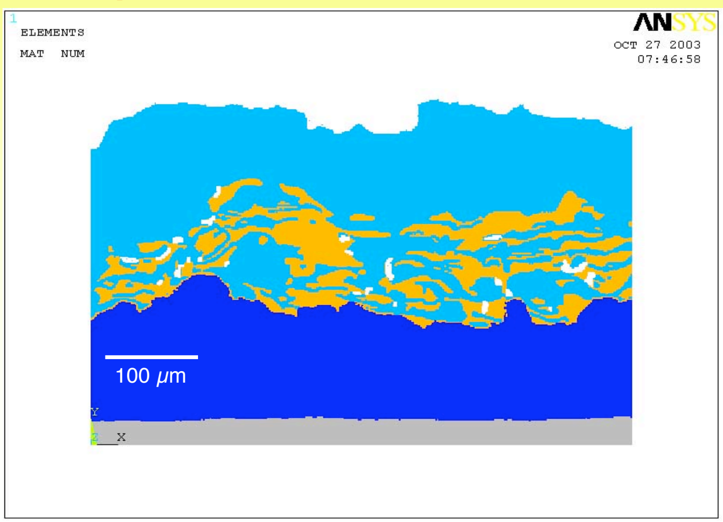
Micro-FEA of SN282 Bend Bar Coated with BSAS EBC

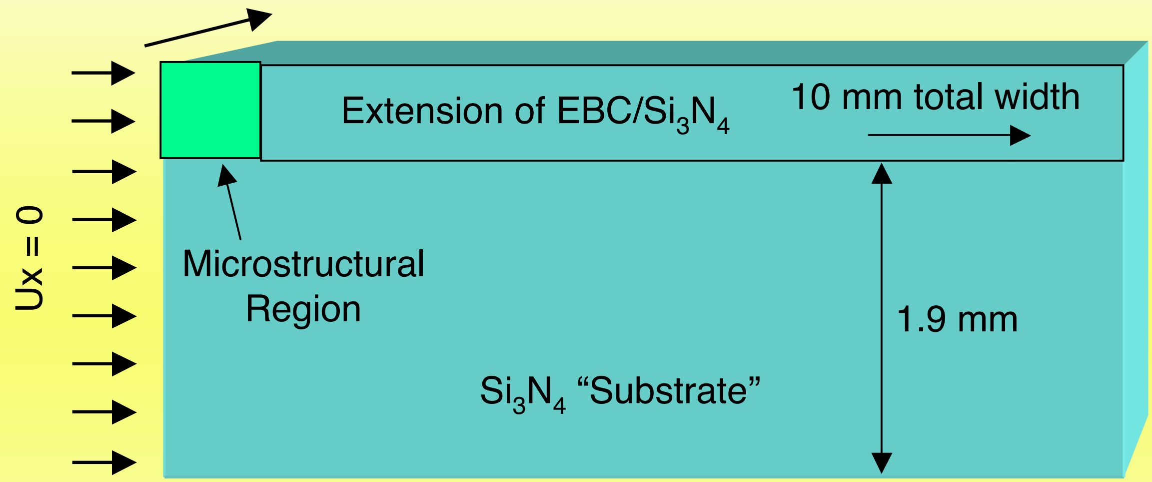
Microstructural Region



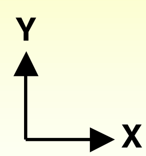
281 x 400 pixels
1.45 μm/pixel
407.45 x 580.00 μm

μ-FEA Reconstructed Model



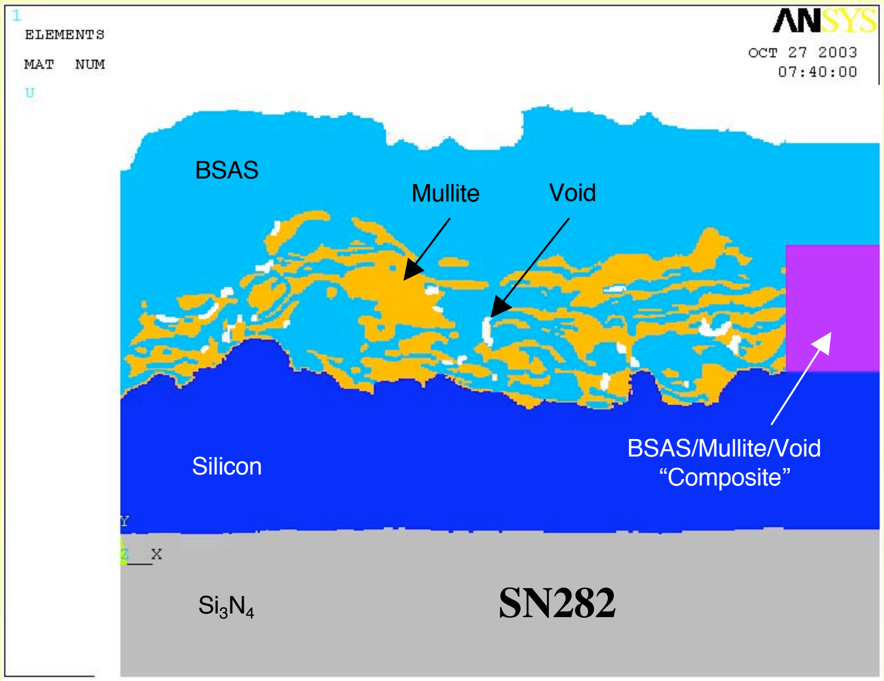


2.42 mm thickness (□ to slide)



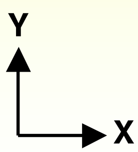
Thermoelastic Properties of BSAS EBC System and SN282 Silicon Nitride Substrate

μ-FEA Reconstructed Model



	E (GPa)		CTE (ppm/C)
Si_3N_4	315	0.29	2.9
Silicon	80	0.20	4.9
BSAS	80	0.24	5.0
Mullite	130	0.23	3.5
BSAS/Mullite	60	0.23	4.2

TREF = 1250C
TUNIF = 25C

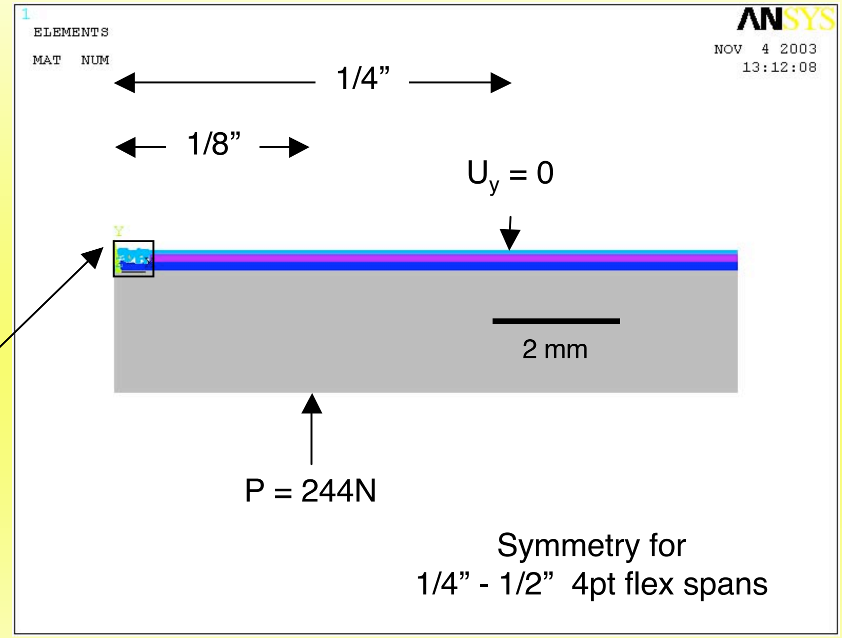


BSAS EBC properties by Tania Bhatia @ UTRC

Inclusion of a Semi-Infinite Field in the FEA Acts To Apply Appropriate BCs on the Micro-Modeled Region

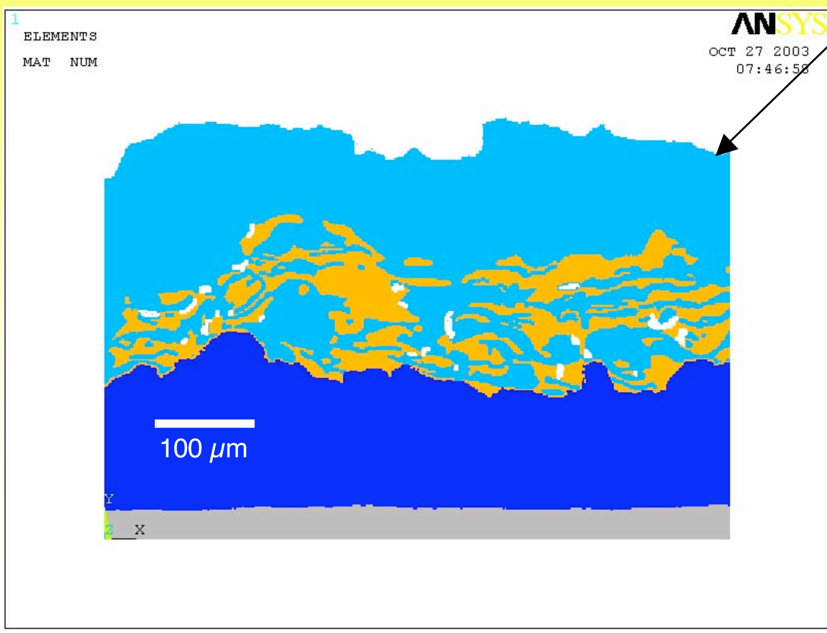
SEM micrograph taken from a polished cross section of bend bar extracted from EBC-SN282 nozzle

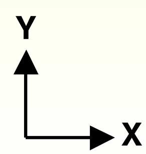
Whole Modeled Geometry



Detail

μ-FEA Reconstructed Model

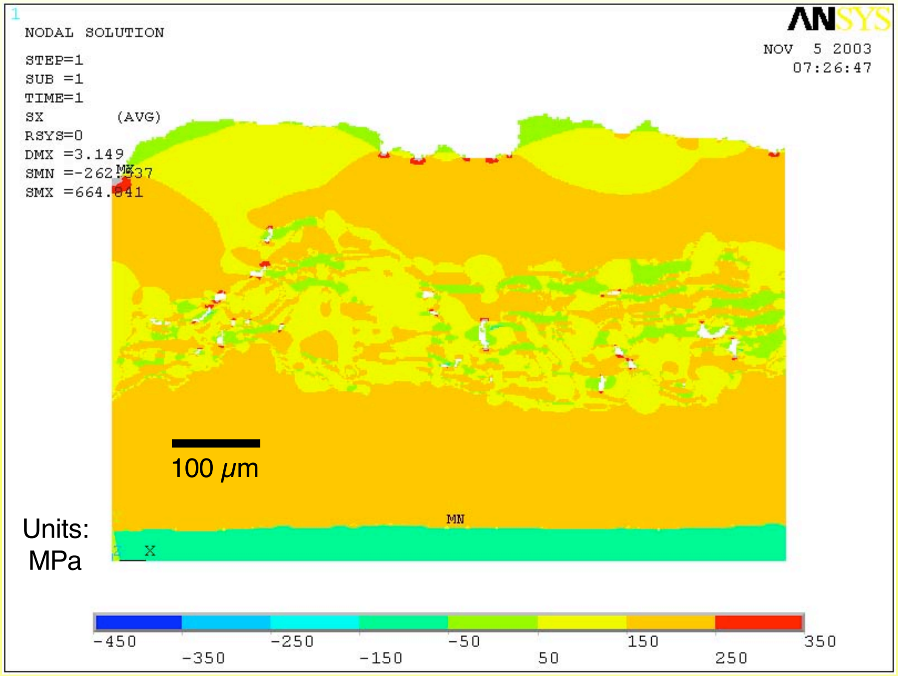




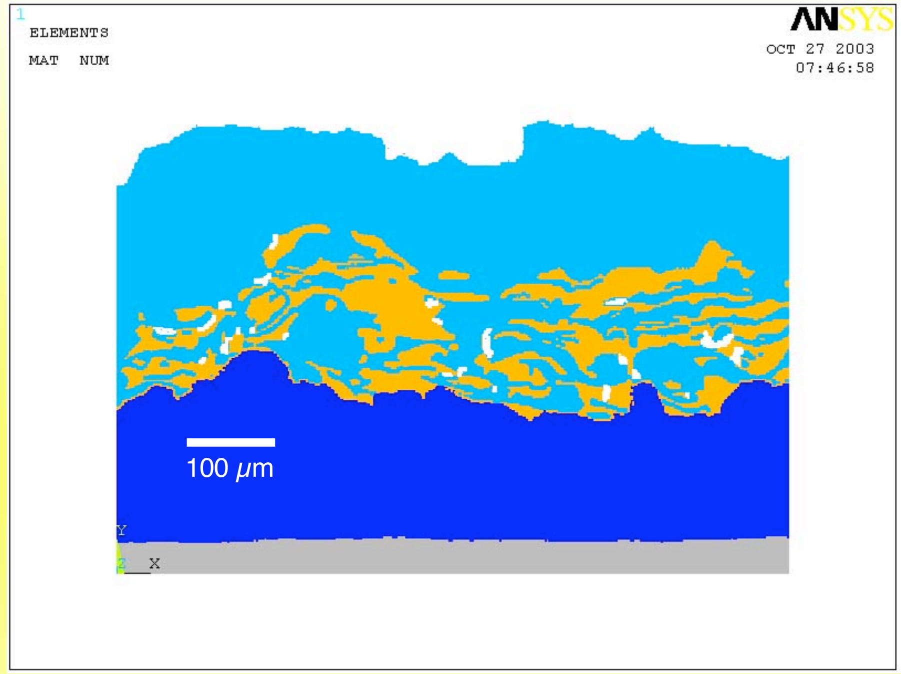
Case study was also carried out on ASTM standard MOR bar (20/40 mm loading spans)

Case 1: σ_x Residual Stress Field Only

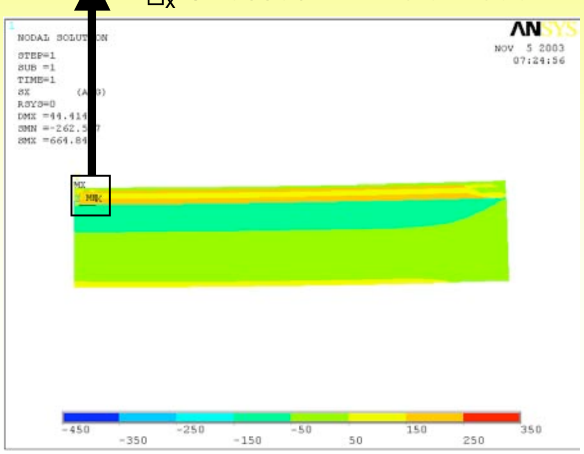
σ_x Stresses

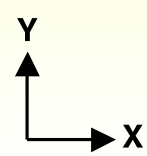


μ-FEA Reconstructed Model

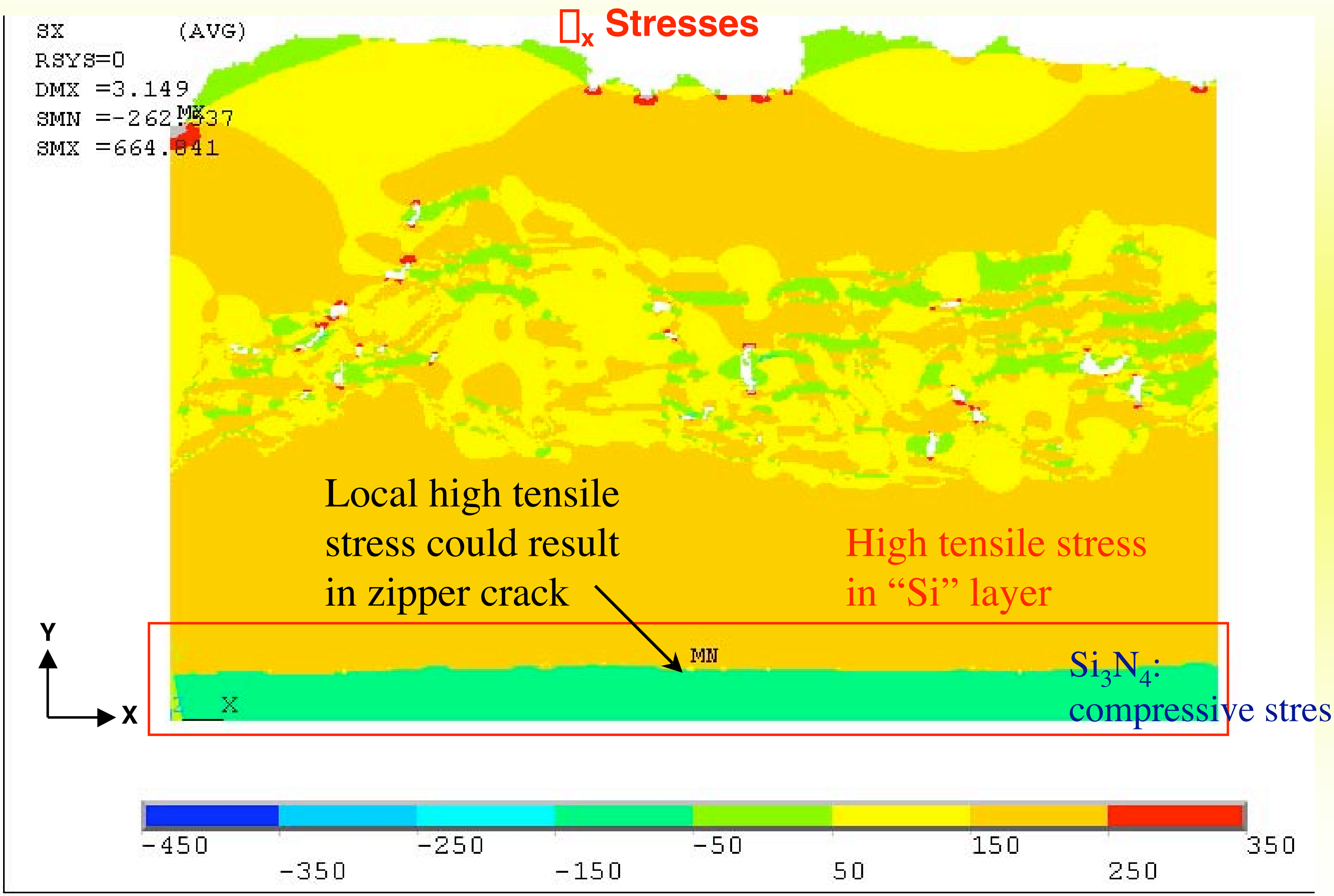


σ_x Stresses in Whole Model



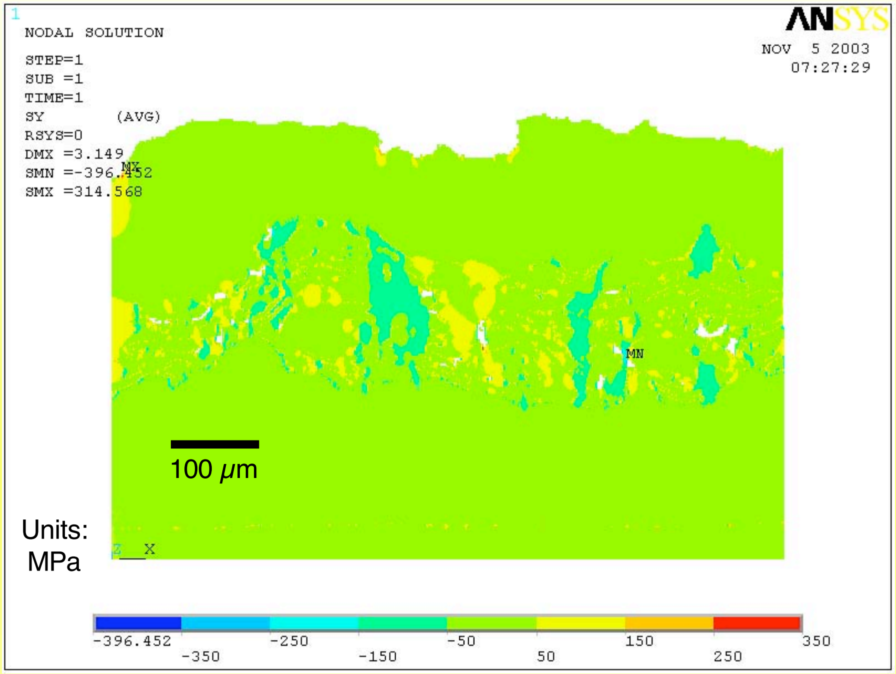


High Stress Concentration Observed at Si/Si_3N_4 Interface

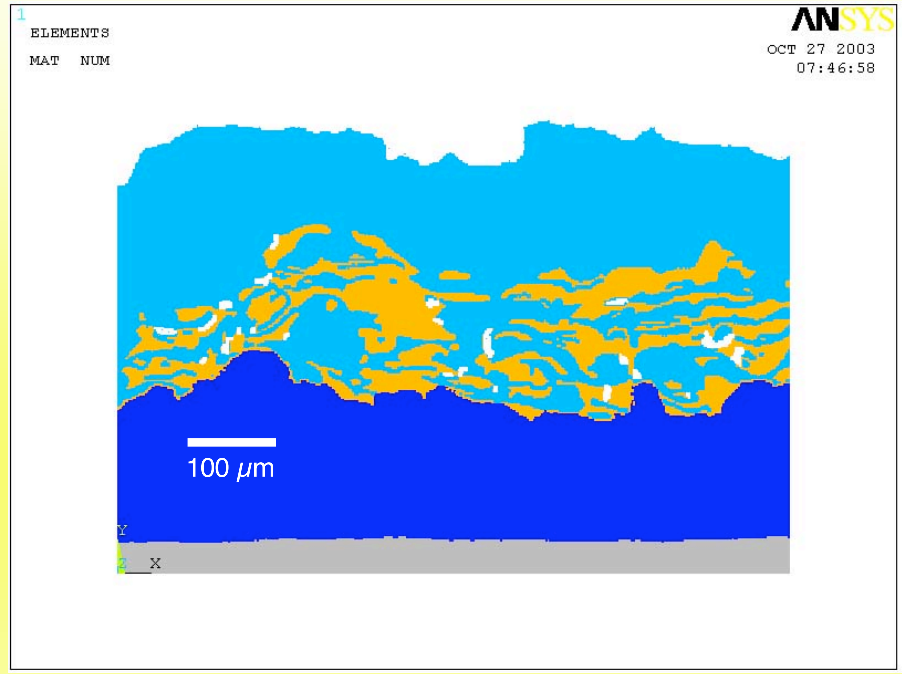


Case 1: σ_y Residual Stress Field Only

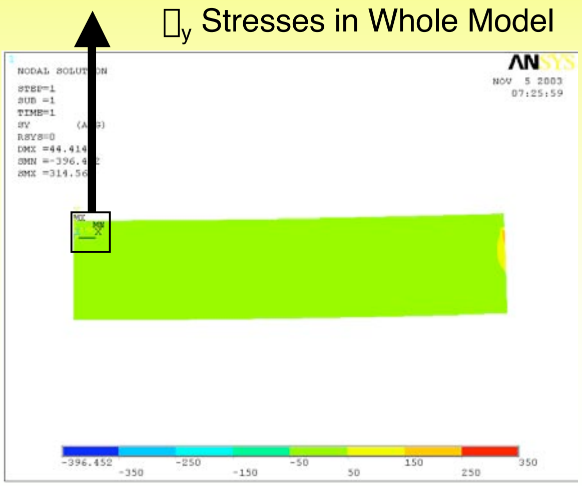
σ_y Stresses

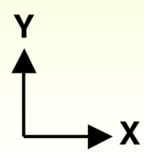


μ-FEA Reconstructed Model

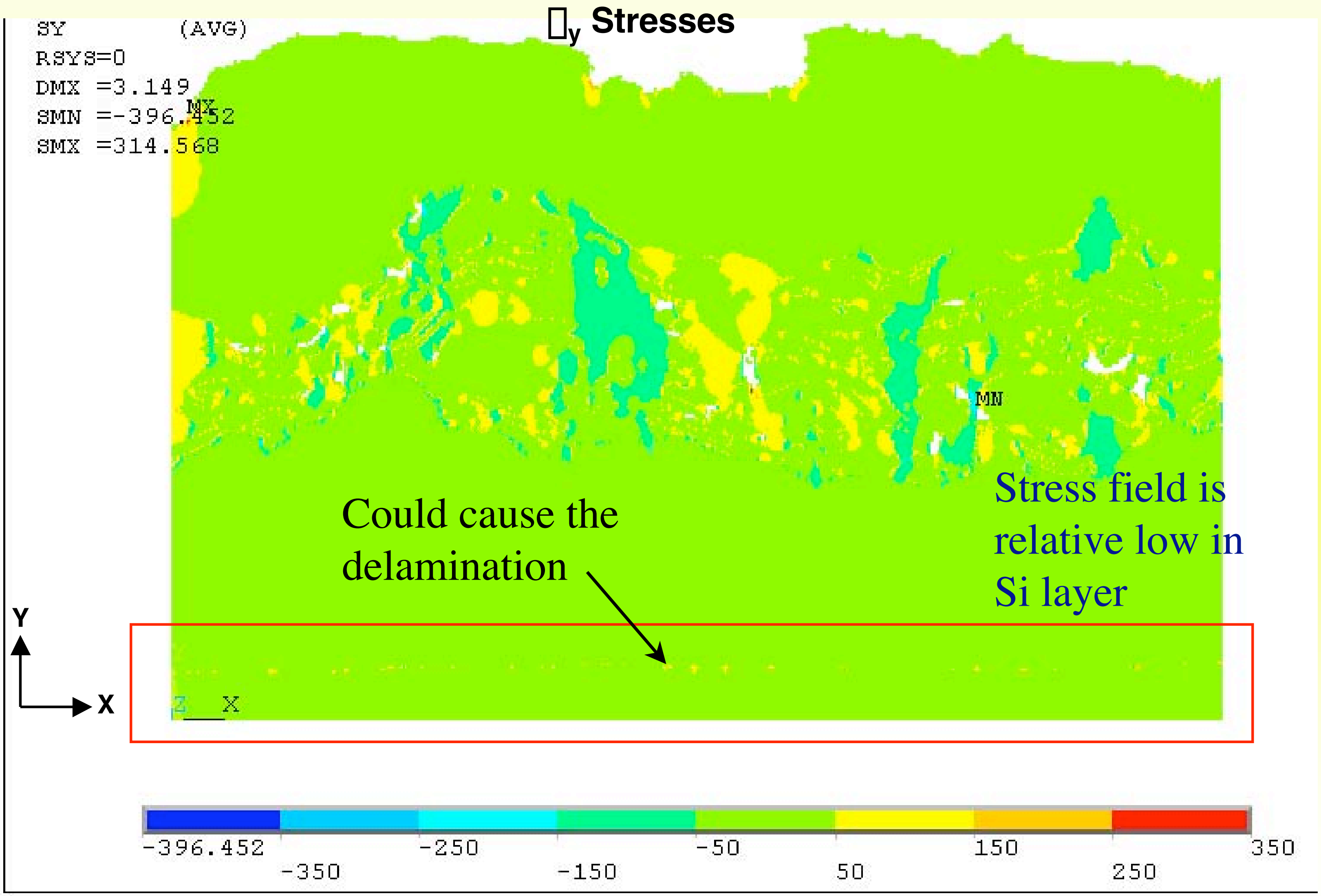


σ_y Stresses in Whole Model



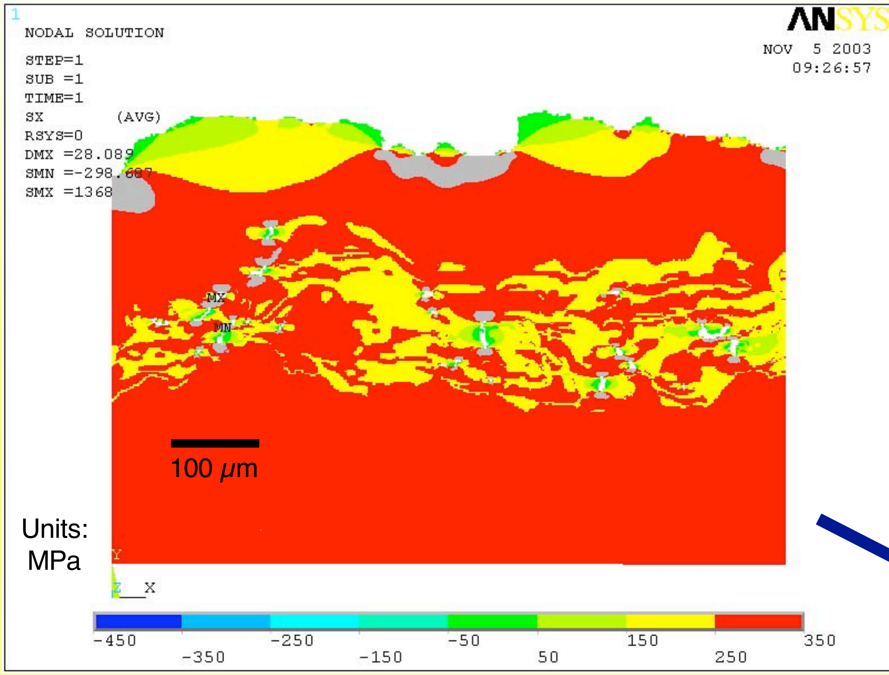


High Stress Concentration Observed at Si/Si_3N_4 Interface

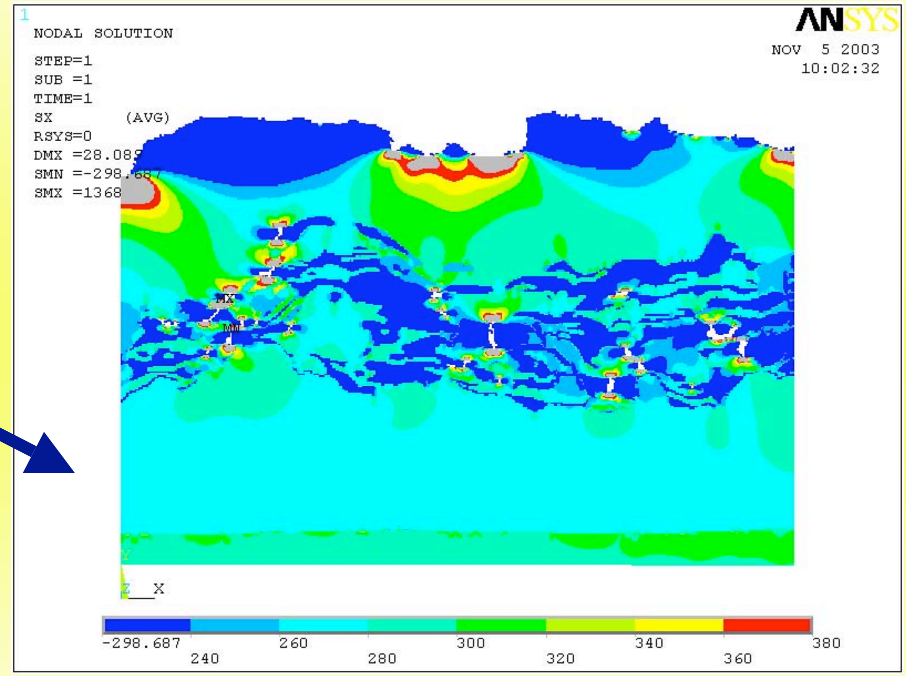


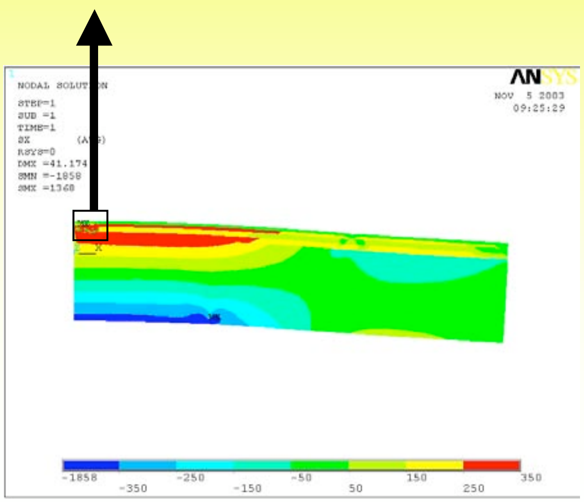
Case 2: Sum of σ_x Residual Stress Field + σ_x Bend Stress

σ_x Stresses



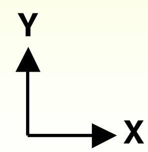
Refined View of σ_x Stresses



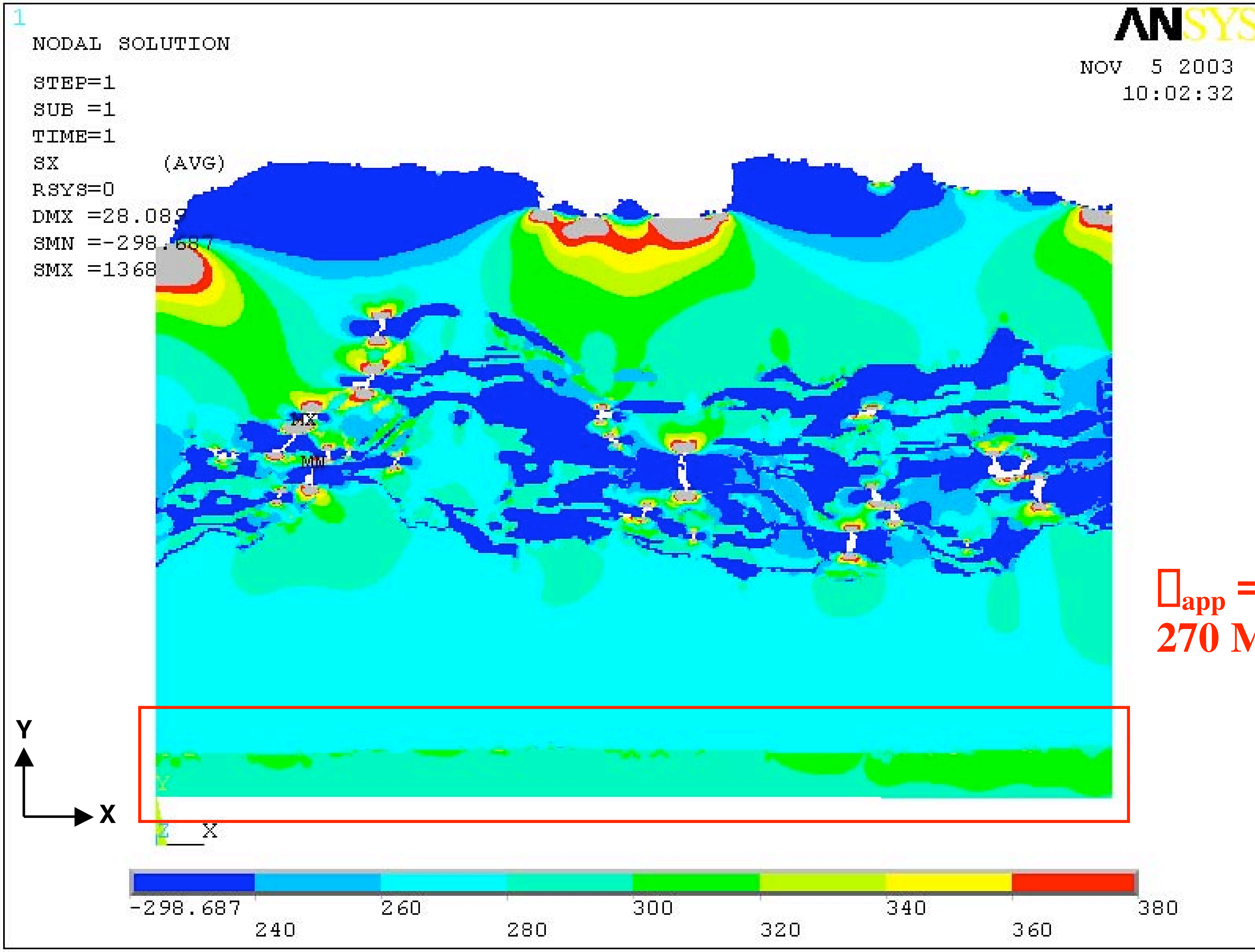


σ_{app} = 270 MPa Bend Stress

σ_x Stresses in Whole Model



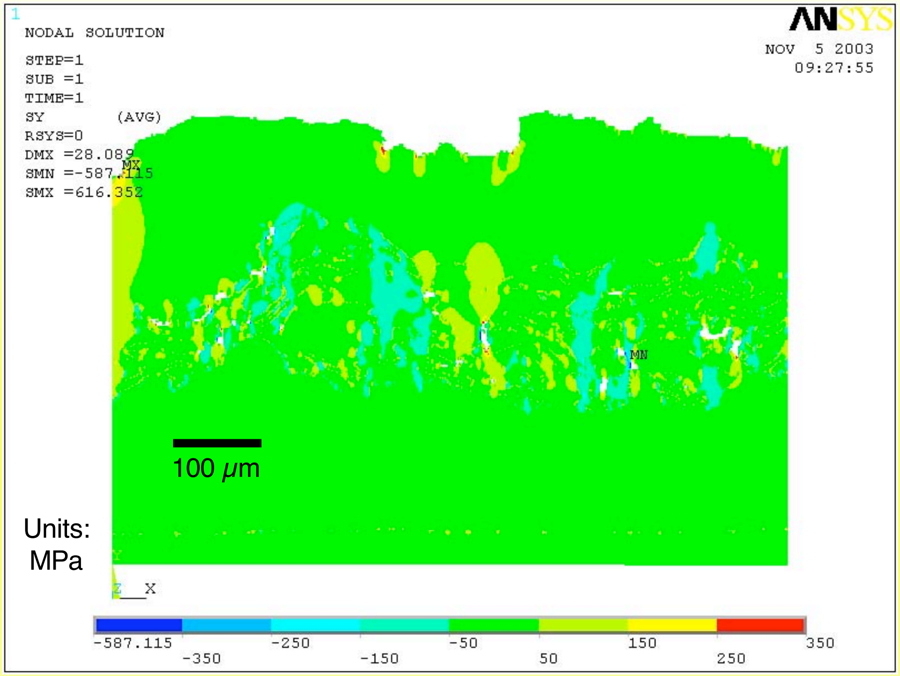
Externally Applied Stress Augments the Residual Stress Field



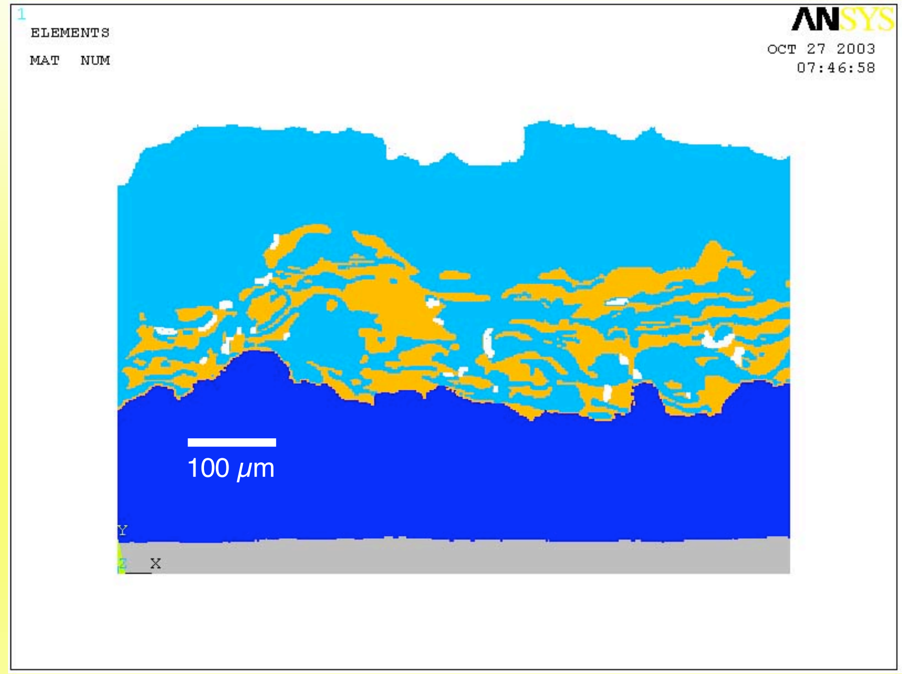
σ_{app} = 270 MPa

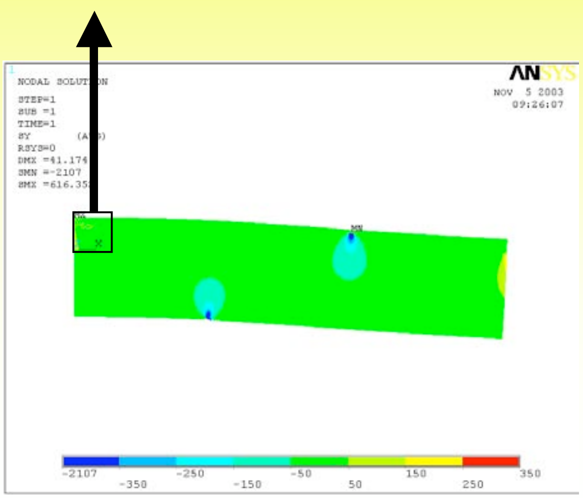
Case 2: Sum of σ_y Residual Stress Field + σ_y Bend Stress

σ_y Stresses

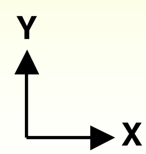


μ-FEA Reconstructed Model





σ_y Stresses in Whole Model



Summary

- Grit blast conditions employed to prepare the component surface could impact the mechanical performance of materials (especially for low toughness ones).

- The biaxial disks and flexure MOR bars with EBC exhibited 67-75% low strength than those obtained from non-coated samples. Subsequent test and analysis suggests that strength degradation is less dependent on the thickness as well as surface roughness of Si bond coat.

- Observations of zipper cracks evident in Si_3N_4 substrates, suggestive failure initiation (and strength degradation) could be possibly associated with CTE mismatch between EBC and Si_3N_4 substrates.

- μ-FEA results showed high residual stress field present in Si bond coat (~150-250 MPa) and Si/Si_3N_4 interface (~50-150 MPa).

- Externally applied stress would augment the residual stress field and cause the premature fracture of ECB samples.