NASA/TM—2003-212516

Strength, Fracture Toughness, Fatigue, and Standardization Issues of Free-Standing Thermal Barrier Coatings

Sung R. Choi
Ohio Aerospace Institute, Brook Park, Ohio

Dongming Zhu
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Robert A. Miller
Glenn Research Center, Cleveland, Ohio

July 2003

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301–621–0134
- Telephone the NASA Access Help Desk at 301–621–0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2003-212516

Strength, Fracture Toughness, Fatigue, and Standardization Issues of Free-Standing Thermal Barrier Coatings

Sung R. Choi
Ohio Aerospace Institute, Brook Park, Ohio

Dongming Zhu
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Robert A. Miller
Glenn Research Center, Cleveland, Ohio

Prepared for the
27th Annual Cocoa Beach Conference and Exposition on
Advanced
Ceramics and Composites
sponsored by the American Ceramic Society
Cocoa Beach, Florida, January 26–31, 2003

National Aeronautics and
Space Administration

Glenn Research Center

July 2003

Acknowledgments

This work was supported by the Ultra-Efficient Engine Technology (UEET) program, NASA Glenn Research Center, Cleveland, Ohio. Thanks to R. Pawlik for mechanical testing and G. Leissler for the preparation of thermal barrier coating material.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Strength, Fracture Toughness, Fatigue, and Standardization Issues of Free-Standing Thermal Barrier Coatings

Sung R. Choi, Dongming Zhu, and Robert A. Miller
NASA Glenn Research Center, Cleveland, OH

Presented at the 27th Annual Cocoa Beach Conference on Advanced Ceramics and Composites
January 26-31, 2003
Cocoa Beach, Florida

[Paper Number: ECD-S2-14-2003 (Invited)]

Abstract

Strength, Fracture Toughness, Fatigue, and Standardization Issues of Free-Standing Plasma-Sprayed Thermal Barrier Coatings

Sung R. Choi, Dongming Zhu, and Robert A. Miller
NASA Glenn Research Center, Cleveland, OH 44135

Strength, fracture toughness and fatigue behavior of free-standing thick thermal barrier coatings of plasma-sprayed ZrO_2-8wt% Y_2O_3 were determined at ambient and elevated temperatures in an attempt to establish a database for design. Strength, in conjunction with deformation (stress-strain behavior), was evaluated in tension (uniaxial and trans-thickness), compression, and uniaxial and biaxial flexure; fracture toughness was determined in various load conditions including mode I, mode II, and mixed modes I and II; fatigue or slow crack growth behavior was estimated in cyclic tension and dynamic flexure loading. Effect of sintering was quantified through approaches using strength, fracture toughness and modulus (constitutive relations) measurements. Standardization issues on test methodology also was presented with a special regard to material's unique constitutive relations.

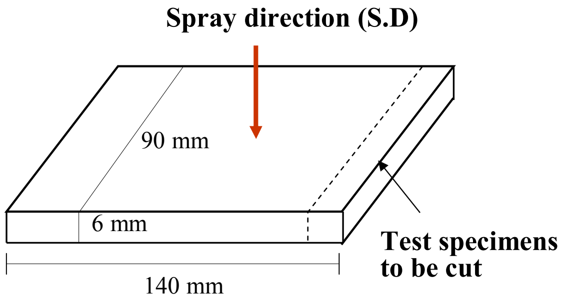
Contents

I. Backgrounds

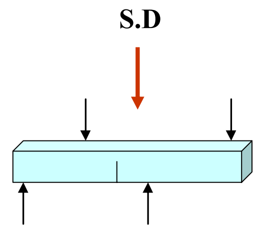
- **Thermal Barrier coatings (TBCs), ZrO_2-8 wt% Y_2O_3 – important coating materials due to low thermal conductivity, high thermal expansivity, and unique microstructure**
- **Somewhat anisotropic nature of porosity, microcracks and splat structure - a challenge in routine mechanical testing and data interpretation**
- **Mechanical testing for TBCs performed to characterize strength, fracture toughness, fatigue, and deformation, and also to establish database**
- **Results of mechanical testing presented and discussed, and related issues discussed**

II. Material Processing

- **ZrO_2-8 wt% Y_2O_3 powder** with an average particle size of 60 μm
- Plasma sprayed on a steel or graphite substrate
- SULZER-METCO ATC-1 plasma coating system with a 6-axes industrial robot used
- **Free standing** TBC billets fabricated
- Test specimens machined from billets with appropriate configurations
- Typical billets:

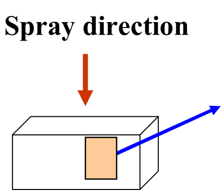


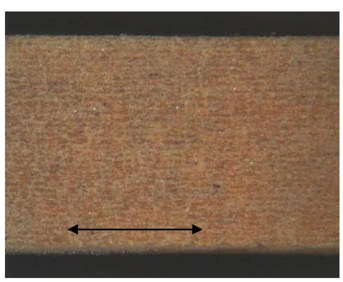
Billet



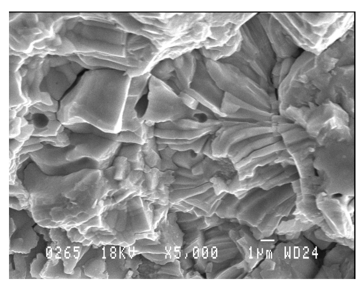
Test Specimen

Unique Microstructure of TBCs

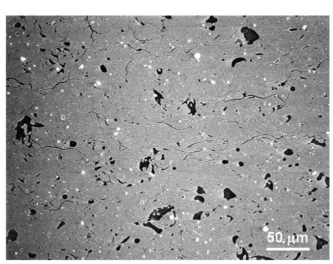




'side' view



fracture surface

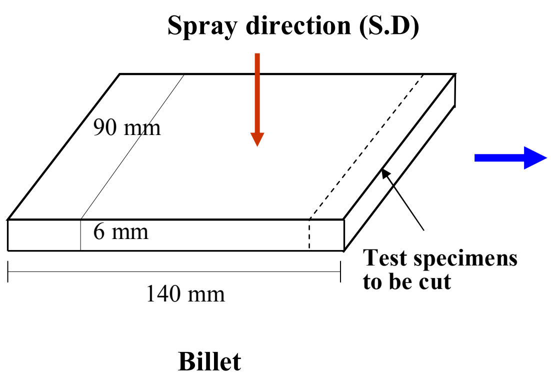


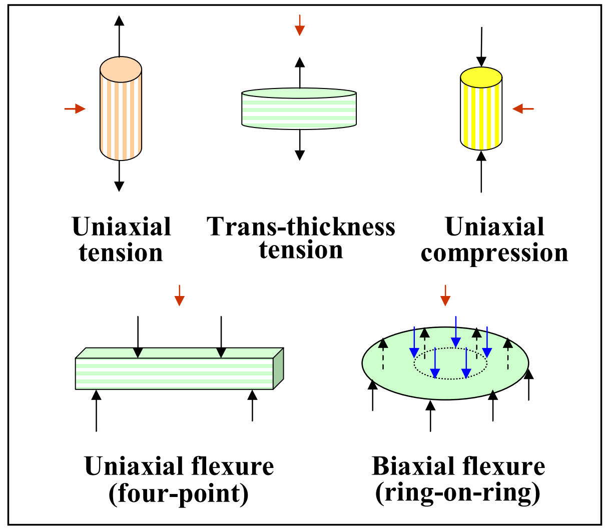
polished surface

- Layered, porous, microcracked, and splat (platelet) structure

III. Strength Testing

Types of Testing/Test Specimens/Orientations

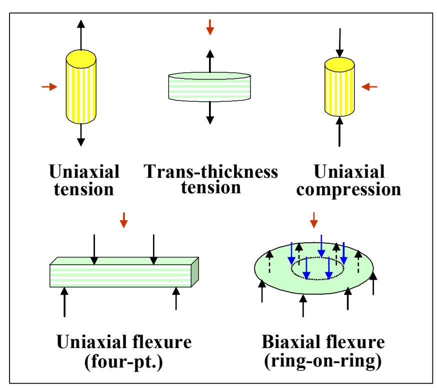




↓ indicates spray direction

Test Matrix (strength)

Type of tests	Specimen geometry	No. of test specimens	Direction of fracture*
Uniaxial tension	15mm x 5mm$^{\phi}$	10	P
Trans-thickness Tension	15 mm x 3 mm (t) (diameter x thick.)	10	N
Uniaxial compression	10mm x 5mm$^{\phi}$	10	P
Uniaxial flexure (four-point)	3mm x 4mm x 25mm [10/20 mm spans]	30	P
Biaxial flexure (ring-on-ring)	25mm x 3mm (t) [11/22 mm rings]	10	P



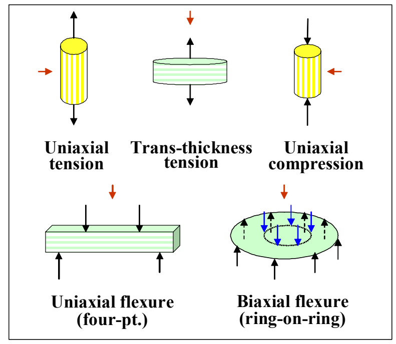
↓ indicates spray direction

* indicates the direction of fracture w.r.t plasma-spray direction.
Test temperature: ambient temperature in air.

Experimental Results (strength)

Type of tests	No. of test specimens valid	Direction*	Average strength (MPa)#	Weibull modulus
Uniaxial tension	3	P	15(1)	-
Trans-thickness Tension	10	N	11(1)	13
Uniaxial compression	10	P	300(77)	4
Uniaxial flexure (four-point)	30	P	33(7)	6
Biaxial flexure (ring-on-ring)	10	P	40(4)	12

* indicates fracture direction w.r.t plasma-spray direction:
N: normal; P: parallel
\# represents ±1.0 standard deviation



↓ indicates spray direction

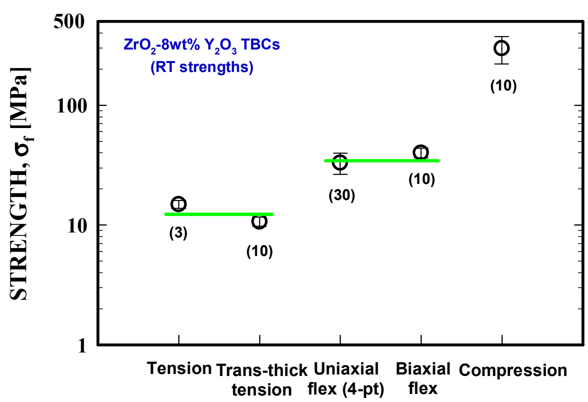
A basic assumption in strength calculation: a **continuum mechanics** (isotropic and linear-elastic)

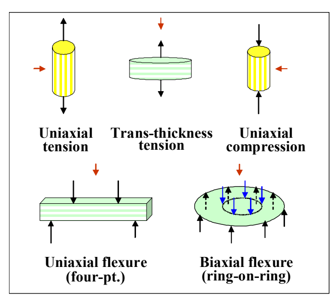
σ_f = 10-15 MPa in tension
= 30-40 MPa in flexure
= 300 MPa in compression

Choi, Zhu, and Miller ('98,'99,'00,'01)

Experimental Results (strength)

Strength *vs* Type of Tests





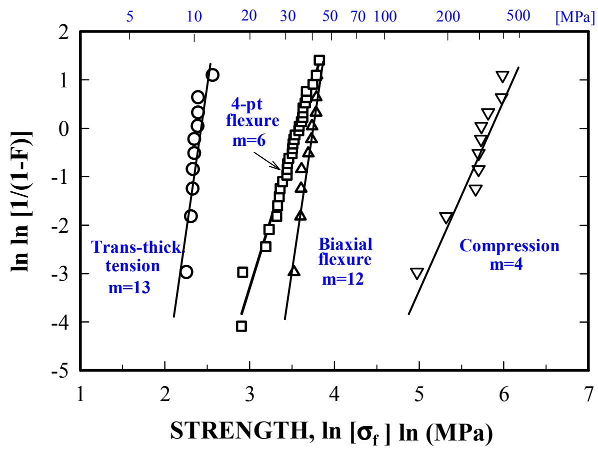
↓ indicates spray direction

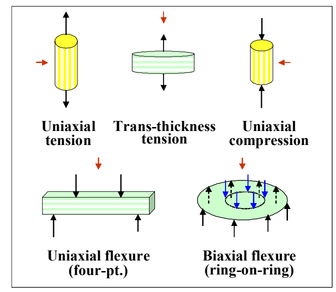
σ_f = 10-15 MPa in tension
= 30-40 MPa in flexure
= 300 MPa in compression

The numbers indicates the number of specimens tested valid

Experimental Results (strength)

Weibull Strength Distributions





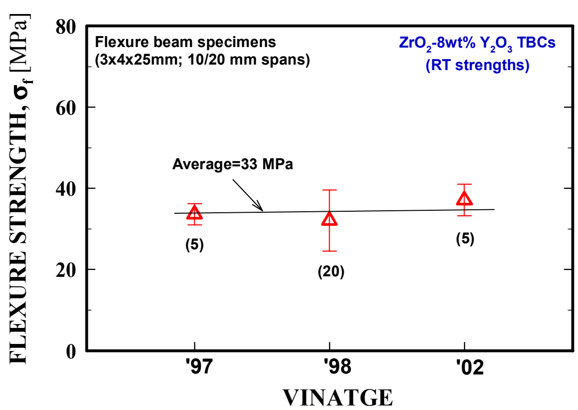
↓ indicates spray direction

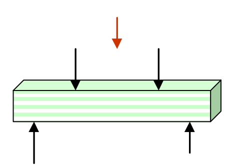
• Weibull moduli of m=5-15, a typical range for many commercial or in-house (dense) monolithic ceramics

Choi, Zhu, and Miller ('98,'99,'00,'01)

Experimental Results (strength)

Flexure Strength *vs* Vintage





↓ indicates spray direction

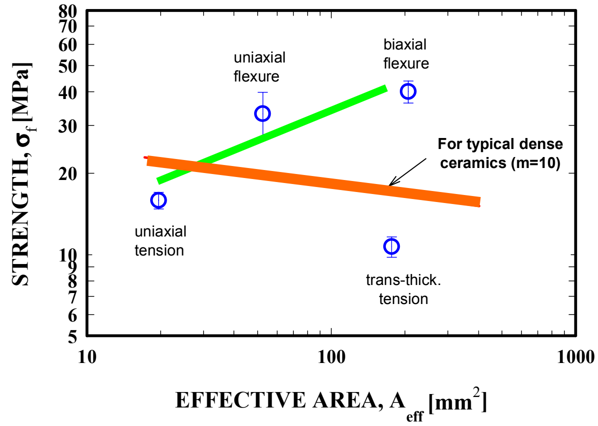
• Flexure strength – less influence by vintage, indicating consistency in plasma-spray processing over the years

Choi, Zhu, and Miller ('98,'99,'03)

The numbers indicates the number of specimens tested valid

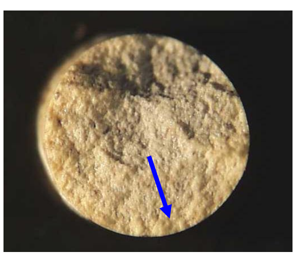
Strength vs. Effective Area – Size Effect

Strength-Effective Area (Weibull PIA model)



• **No reasonable agreement** in size effect between data and Weibull analysis (e.g., PIA); inconsistency in flaw populations (?)

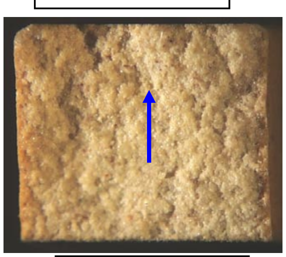
Fractography (strength)



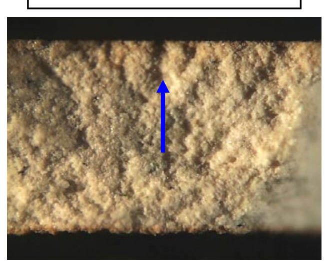
Uniaxial tension

Trans-thickness tension

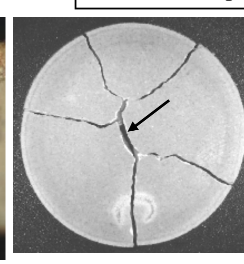
Uniaxial compression



Uniaxial flexure



Fracture surface



Top view of biaxial Flexure specimen

Biaxial flexure

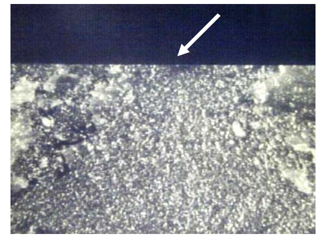
• **Very difficult to locate fracture origins and to analyze their nature**

Choi, Zhu, and Miller ('98,'99,'00,'01)

Fractography – A Great Challenge

Four-point flexure

TBCs **Dense Ceramics**



ZrO_2-8wt% Y_2O_3 **Toughened Si_3N_4** **ZrO_2-10 mol% Y_2O_3**

Fracture mirror size (r_m):
- **TBCs - 3-40 mm (estimated)**
- **Dense ceramics – 50-500 μm**

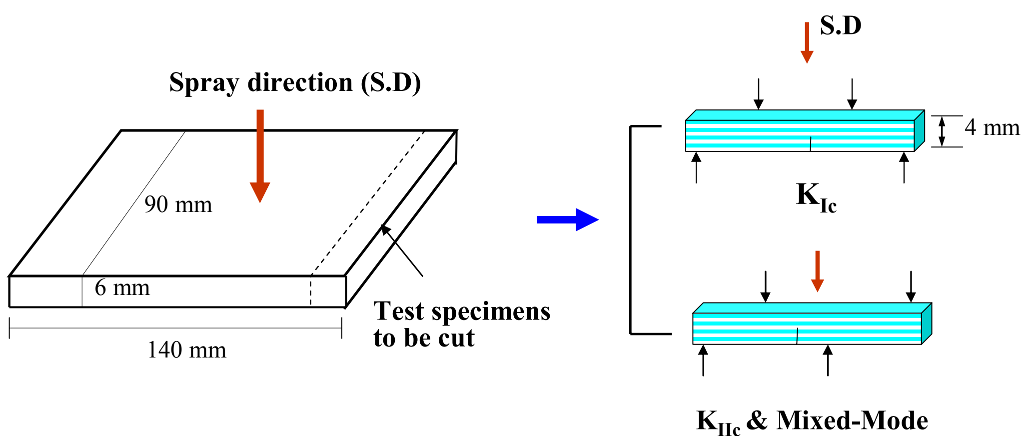
$$\sigma_f r_m^{1/2} = A$$

• Big mirror size & porous/microcracked nature of TBCs
→ An enormous challenge in fractogrphy

Choi, Zhu, and Miller ('00,'01)
Choi ('02); Choi and Narottam ('02)

IV. Fracture Toughness Testing
(Mode I, Mode II and Mixed Mode)

Types of Testing/Test Specimens/Orientations

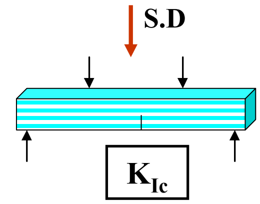


Billet

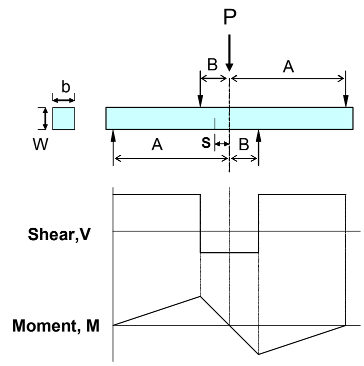
Test specimens
(4mm x 3 mm x 25-50 mm)

Experimental (fracture toughness)
(Mode I, Mode II and Mixed Mode)

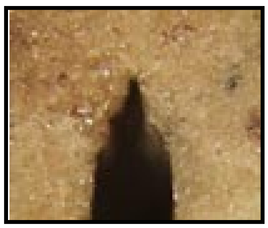
Types & Procedures



- **Sharp precracks generated**
  - Single edge v-notched beam (**SEVNB**) method: Saw-notched → a sharp V-notch generated with a razor blade with diamond paste, $a/W \approx 0.5$
- **Test fixture configurations**
  - A/B=10/5 (typical); s=0-3.6 mm in mixed mode
  - 10/20 or 20/40 mm spans in K_{Ic}
- **Test temperatures**
  25 and 1316 °C in air
- **Number of test specimens**: typically ≥4



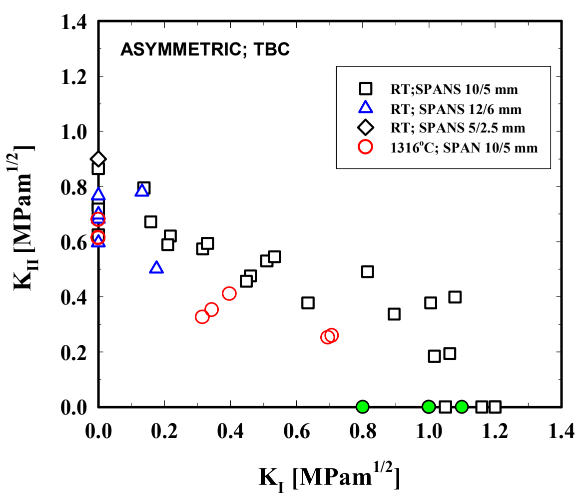
K_{IIc} & Mixed-Mode -asymmetric flexure-



A typical, sharp SEVNB precrack (root radius ≤30 µm)

Experimental Results (fracture toughness)

- **Mode I, Mode II, and Mixed Mode (25 and 1316 °C)**



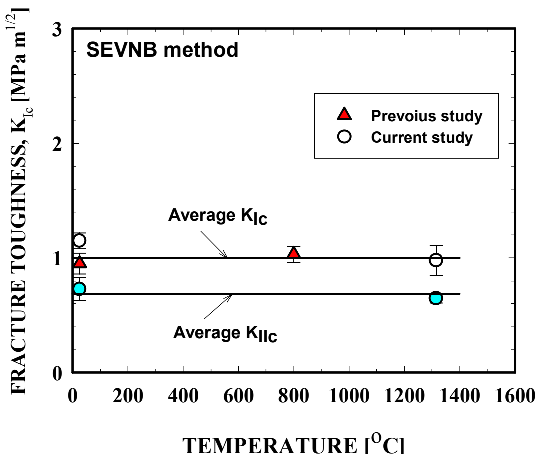
Test Temp(°C)	No. of specimens used	K_{Ic} (MPa√m)	K_{IIc} (MPa√m)
25	4 in K_{Ic} 9 in K_{IIc}	1.15(0.07)	0.73(0.10)
1316	4 each	0.98(0.13)	0.65(0.04)

- **$K_{Ic} > K_{IIc}$** → K_{IIc}/K_{Ic}=0.64 & 0.66 (at 25 & 1316 °C)
- K_{Ic} and K_{IIc} at 25 °C ≥ K_{IC} and K_{IIc} at 1316 °C
- **Elliptical relation** between K_I and K_{II}
- Test spans **independent**

Choi, Zhu, and Miller ('03)

Experimental Results (fracture toughness)

- **Fracture Toughness vs. Temperature**

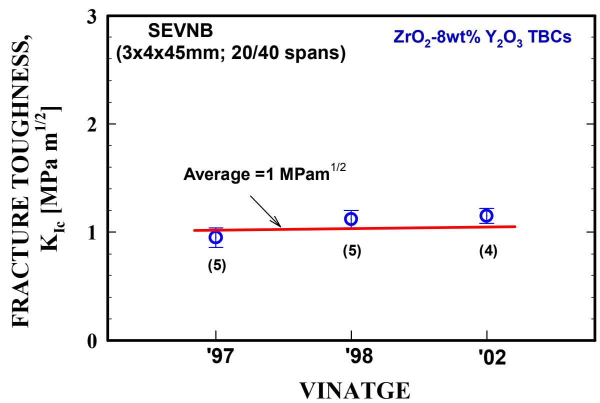


- **Temperature insensitive in K_{Ic} and K_{IIc}**
  $\rightarrow K_{Ic} \approx 1$ and $K_{IIc} \approx 0.65$ MPa$\sqrt{m}$
- **$K_{IIc}/K_{IC} \approx 0.65$**

Choi, Zhu, and Miller ('98,'03)

Experimental Results (fracture toughness)

- **Fracture Toughness (RT) vs. Vintage**

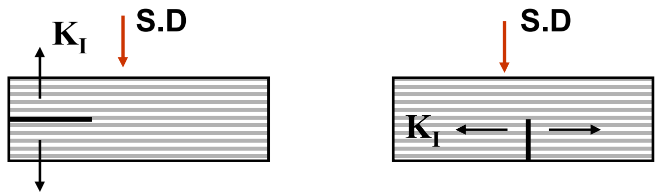


- **Fracture toughness (K_{Ic}) – less influence by vintage (similar to strength), indicating consistency in plasma-spray processing over the years**

Choi, Zhu, and Miller ('98,'03)

Experimental Results (fracture toughness)

Fracture Toughness vs. Orientation



DCB specimens

SEVNB specimens

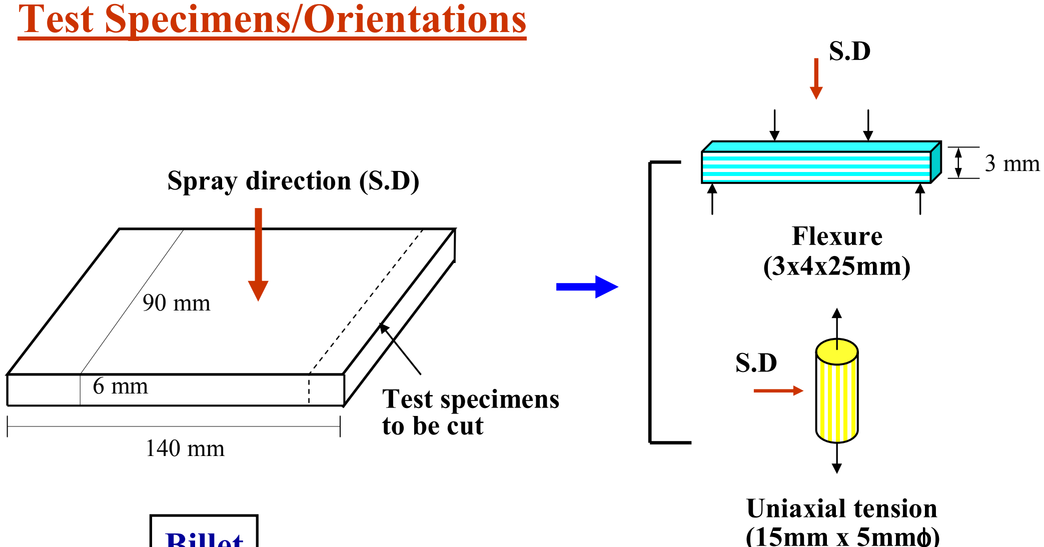
Direction of crack	Fracture Toughness K_{IC} (MPa$\sqrt{m}$)	Method
Parallel to plasma spray direction	**1.15±0.07**	SEVNB (regular method)
Normal to plasma spray direction	**1.04±0.05**	DCB (Double Cantilever Beam)

- **No significant difference in K_{Ic}-- Little directionality effect on K_{Ic}**

Choi, Zhu, and Miller ('98,'03)

V. Fatigue/Slow Crack Growth

Test Specimens/Orientations



Billet

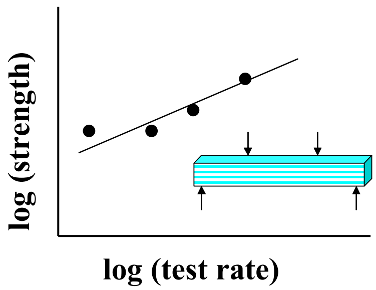
Test specimens

Experimental (fatigue)

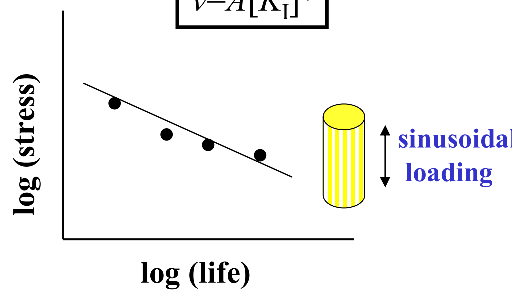
Test Types and Conditions

- **Dynamic fatigue (ASTM C1425)**
  800 °C in air; 3 test rates in flexure
- **Tensile cyclic fatigue**
  RT in air; sinusoidal; R= 0.1; f=10 Hz

$\boxed{v = A[K_I]^n}$



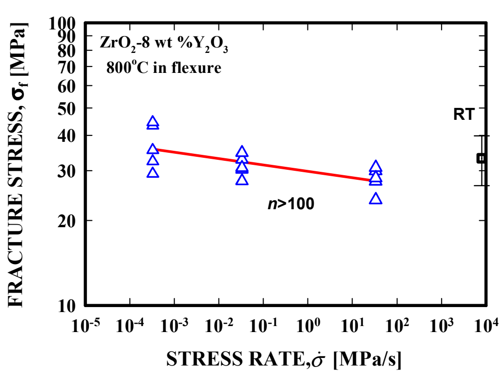
Dynamic fatigue



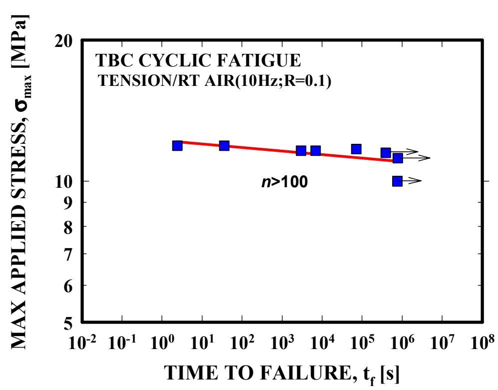
Tensile cyclic fatigue

Experimental Results (fatigue/SCG)

Dynamic fatigue



Tensile cyclic fatigue



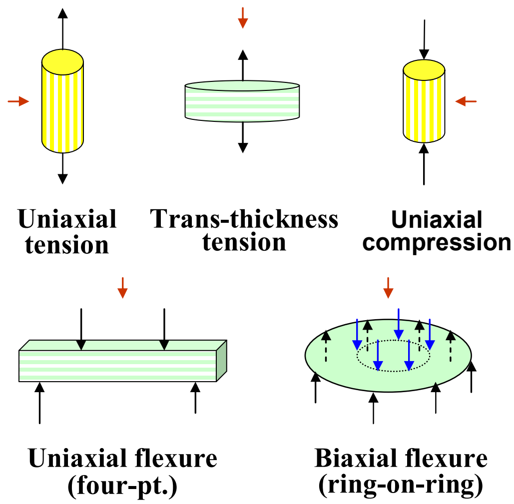
$\boxed{v = A[K_I]^n}$

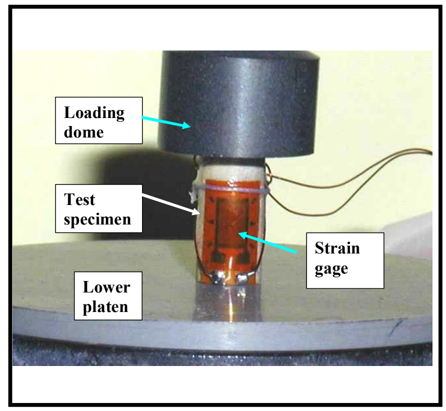
- Slow crack growth (SCG) parameter n:
  $n > 100$ in both dynamic and tensile cyclic fatigue –
  Little susceptibility to SCG (fatigue)

Choi, Zhu, and Miller ('98,'99,'01)

VI. Deformation (Stress-Strain) Behavior

5 Specimen/Loading Conditions Considered



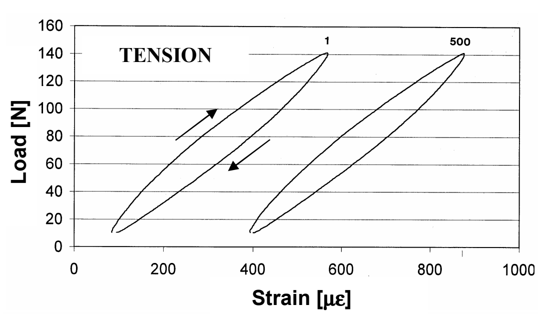


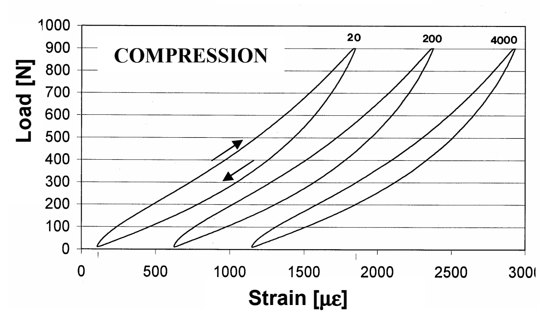
Test Setup (strain gaging)

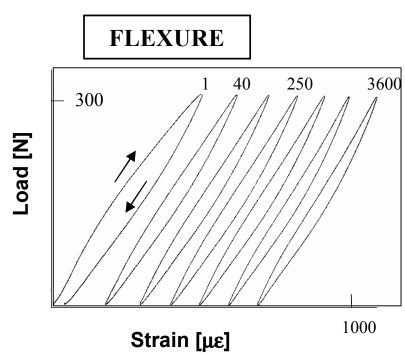
↓ indicates spray direction

Experimental Results (deformation)

Typical Load-Strain Curves





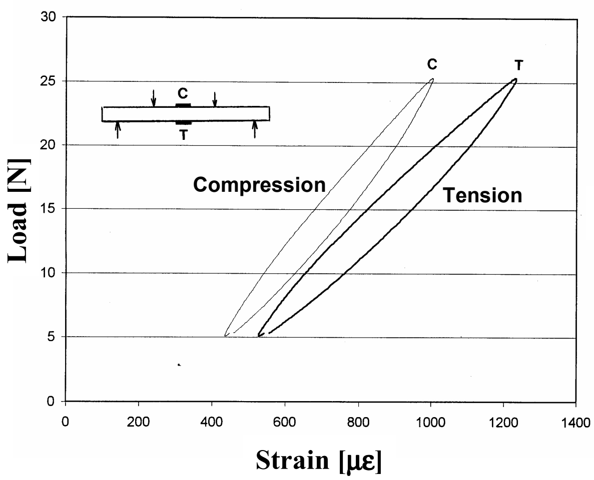


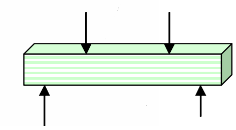
- **Non-linearity** with **hysteresis** but **elastic**
  -desirable in TBCs but difficulty in analysis
- Independent of the number of cycles and test rate (not-viscoelastic)

Choi, Zhu, and Miller ('00,'01)

Experimental Results (deformation)

Four-Point Flexure



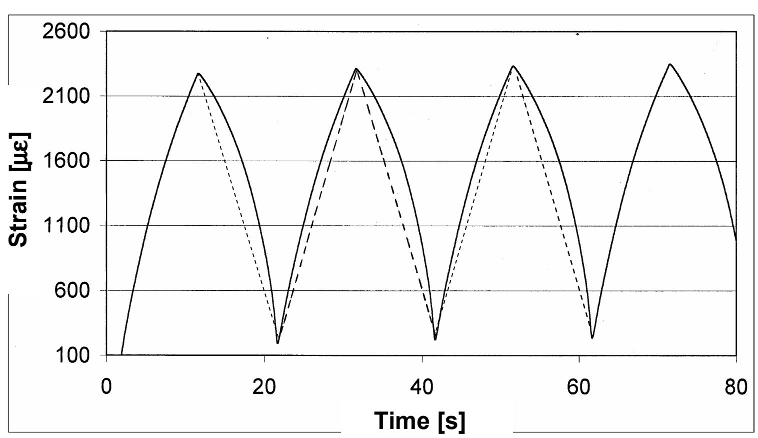


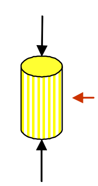
- **Different response of strain** in compression and tension
- A possible **neutral axis shift** due to different elastic modulus
- Flexure stress calculation – complex

Choi, Zhu, and Miller ('’01)

Experimental Results (deformation)

Response of Output Wave Form to Cyclic Compression Loading





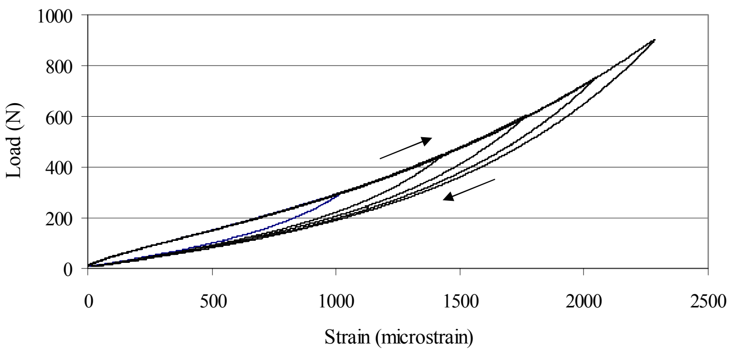
Triangular cyclic loading

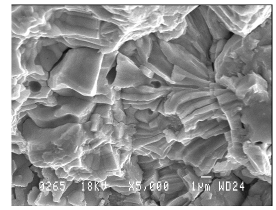
The output wave form - **distorted** from the input triangular wave form

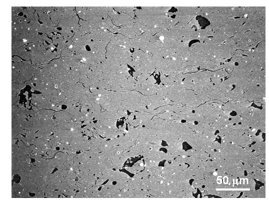
Choi, Zhu, and Miller ('01)

Deformation (Stress-Strain) Behavior

What is the cause of nonlinearity and hysteresis?







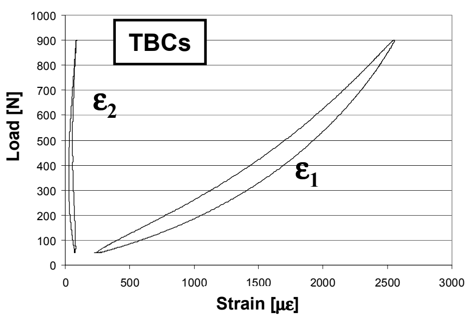
Major reason – **'loosely' connected open structure** due to pores and microcracks

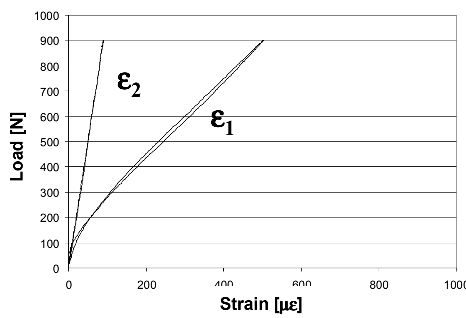
- Internal friction and densification
- Still overall elastic behavior

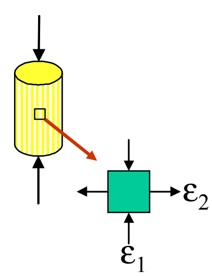
Eldridge, Morscher, and Choi ('02)

Deformation (Stress-Strain) Behavior

'Loosely-Connected Open' Structure – Poisson's Response







Poisson's ratio
$\nu = |\varepsilon_2/\varepsilon_1|$

Exhibits **no or little change** in lateral strain: Poisson's ratio not well defined

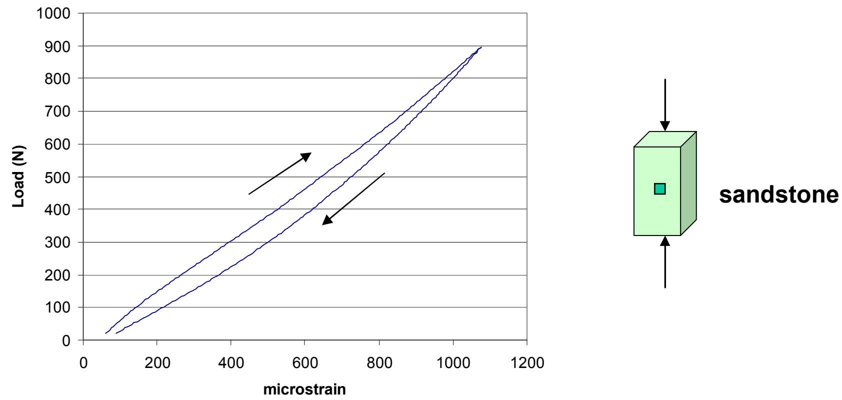
Open, loose structure

Exhibits a **linearly increasing** lateral strain: Poisson's ratio well defined

Dense structure

Experimental Results (deformation)

Sandstone – Another Example of Open Structure

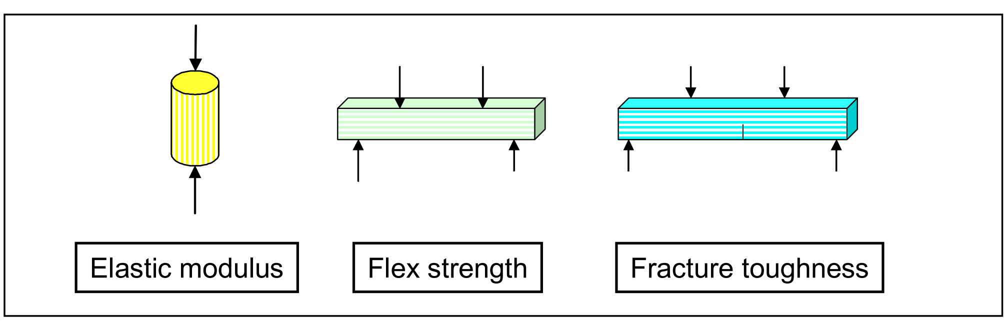


Open, loose structure: non-linearity with hysteresis
-- Similarity to TBCs

VII. Sintering – A Changer of Structure

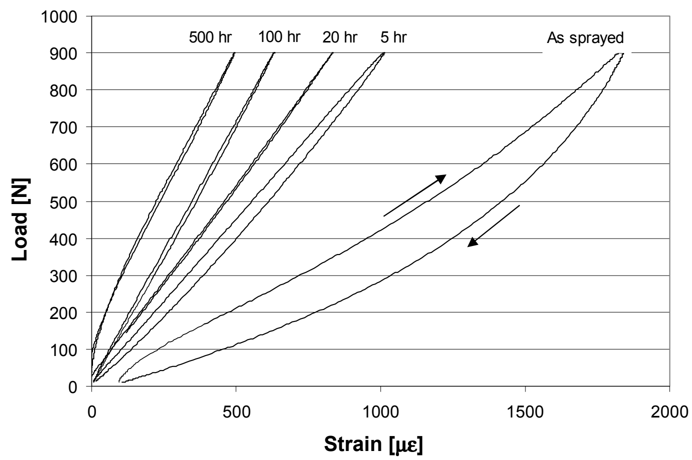
Sintering conditions:

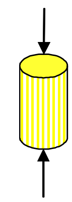
- Temperature/environment: 1316 °C/air
- Annealing time: 0, 5, 20, 100, and 500 h
- Determine as a function of anneal time:
  - Elastic modulus
  - Fracture toughness (K_{Ic})
  - Flexure strength
  - Thermal conductivity



Experimental Results (sintering)

Elastic Modulus





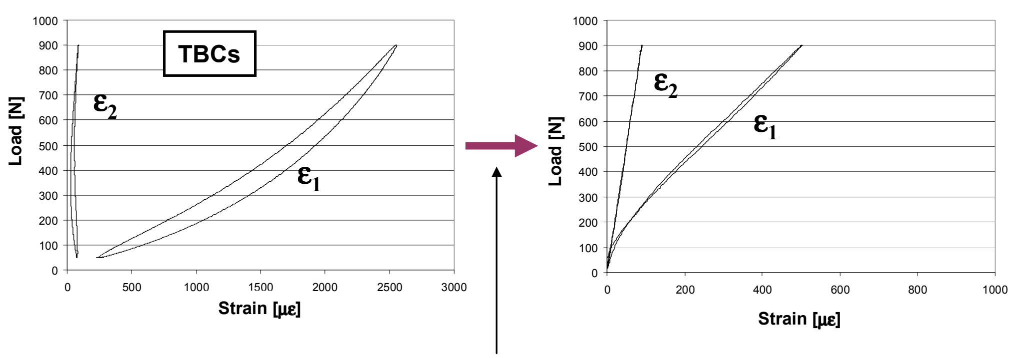
Compression

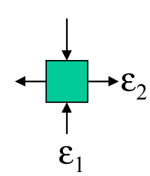
- **Slope (elastic modulus) increases** with anneal time
- **Linearity increases** with anneal time
- **Hysteresis decreases** with anneal time

→ Implies a change of microstructure from **'loosely'** connected to '**closely**' connected

Experimental Results (sintering)

Well-Developed Poisson's (Lateral Strain) Response





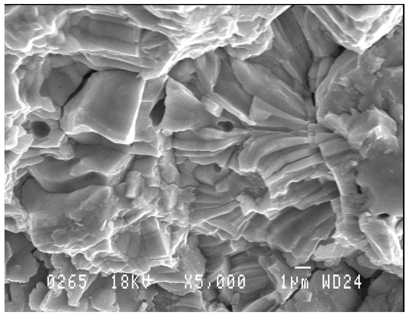
500 h annealing

Poisson's ratio
$\nu = |\varepsilon_1 / \varepsilon_2|$

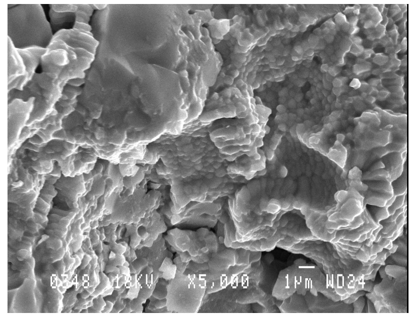
Open structure → More closely-connected structure

Experimental Results (sintering)

Microstructure



As-sprayed

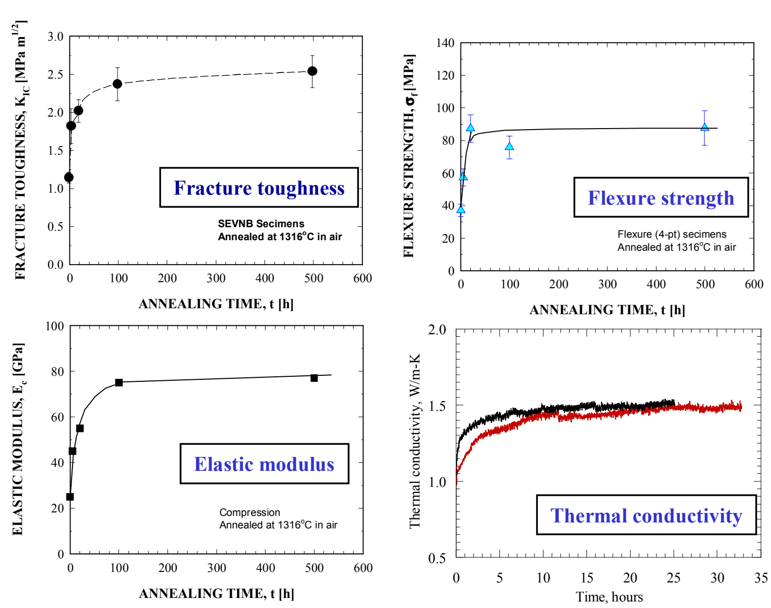


100 h annealed

- **As-sprayed** - Large amounts of **microcracks and pores** with a unique platelet (splat) structure presented
- **100 h annealing** - **Increased grain growth** at longer annealing time

Experimental Results (sintering)

- **Summary on elastic modulus, flexure strength, fracture toughness and thermal conductivity**



→ **Properties change exponentially with sintering time**

Choi, Zhu, and Miller ('03)

Standardization Issues

- **The most hindering factor** in establishing test methods for as-sprayed TBCs: **non-linearity** & **hysteresis** in the constitutive relations
  - Flexure testing (uniaxial and biaxial) maybe inappropriate due to difference in modulus between tension and compression
  - Poisson's ratio not well-defined
  - Impulse excitation technique maybe inappropriate

- Pure tension and compression testing – impose less problems

- Fracture toughness testing – maybe OK in view of low fracture loads

- Fractography – challenging

- Properties change with sintering/service conditions
  - requires to evaluate based on sinter/service conditions

Summary

- **Strength**:
  tension: 10-15 MPa; flexure: 30-40 MPa; compression: 300 MPa
  Weibull modulus: 5-15
- **Fatigue/Slow Crack Growth:**
  SCG parameter *n*>100
- **Fracture Toughness**:
  K_{Ic}=1.0 MPa$\sqrt{m}$ up to 1316 ^{o}C
  K_{IIc}=0.7 MPa$\sqrt{m}$ up to 1316 ^{o}C
- **Deformation**:
  nonlinear elasticity with hysteresis;
  imposes problems in continuum approach (*test standards*)
- **Sintering**:
  significant influence - a changer of most properties!

Bibliography

1. **S. R. Choi, D. Zhu, and R. A. Miller, "High-Temperature Slow Crack Growth, Fracture Toughness and Room-Temperature Deformation Behavior of Plasma-Sprayed ZrO2-8 wt% Y2O3," *Ceram. Eng. Sci. Proc.*, 19[4] 293–301 (1998).**
2. **S. R. Choi, D. Zhu, and R. A. Miller, "Flexural and Compressive Strengths, and Room-Temperature Creep/Relaxation Properties of Plasma-Sprayed ZrO2-8wt% Y2O3," *Ceram. Eng. Sci. Proc.*, 20[3] 365-372 (1999).**
3. **S. R. Choi, D. Zhu, and R. A. Miller, "Deformation and Strength Behavior of Plasma-Sprayed ZrO2-8 wt% Y2O3 Thermal Barrier Coatings in Biaxial Flexure and Trans-Thickness Tension," *Ceram. Eng. Sci. Proc.*, 21[4] 653–661 (2000).**
4. **S. R. Choi, D. Zhu, and R. A. Miller, "Deformation and Tensile Cyclic Fatigue of Plasma-Sprayed ZrO2-8 wt% Y2O3 Thermal Barrier Coatings," *Ceram. Eng. Sci. Proc.*, 22[4] 427-43 (2001).**
5. **R. A. Miller, "Current Status of Thermal Barrier Coatings—An Overview," *Surface and Coating Technology*, 30, 1–11 (1987).**
6. **R. A. Miller, "Thermal Barrier Coatings for Aircraft Engines—History and Direction," pp. 17–34 in NASA CP–3312 (Ed. W.J. Brindley), National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (1995).**
7. **T. M. Yonushonis, "Thick Thermal Barrier Coatings for Diesel Components," NASA CR–187111, National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (1991).**
8. **Y. C. Tsui, T. W. Clyne, *Proc. 9th Nat. Thermal Spray Conf.*, Cincinnati, OH (1996).**
9. **L. L. Shaw, B. Barber, E. H. Jordan, and M. Gell, *Scr. Mater.*, 39 1427–1434 (1998).**
10. **G. Thurn, G. A. Schneider, H. A. Bahr, and F. Aldinger, "Toughness Anisotropy and Behavior of Plasma Sprayed ZrO2 thermal Barrier Coatings," *Surf. Coat. Tech.*, 123, 147–158 (2000).**
11. **K. F. Wesling, D. F. Socie, and B. Beardsley, "Fatigue of Thick Thermal Barrier Coatings," *J. Am. Ceram. Soc.*, 77[7] 1863–1868 (1994).**
12. **P. J. Callus and C. C. Berndt, "Relationship between the Mode II Fracture Toughness and Microstructure of Thermal Spray Coatings," *Surf. Coat. Tech.*, 114, 114–128 (1999).**
13. **S. R. Choi and N. P. Bansal, "Strength and Fracture Toughness of Zirconia/Alumina Composites for Solid Oxide Fuel Cells," *Ceram. Eng. Sci. Proc.*, 23[3] 741–750 (2002); "Processing and Mechanical Properties of Various Zirconia/Alumina Composites for Fuel Cells Applications," NASA/TM—2002-211580, National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (2002); also presented at CIMTEC 2002 Conference, paper no. G1:P03 (to be published in the proceedings), June 14–18, 2002, Florence, Italy.**

Bibliography (continued)

14. **D. Zhu and R. A. Miller, "Influence of High Cycle Thermal Loads on Thermal Fatigue Behavior of Thick Thermal Barrier Coatings," NASA Technical paper 3676 (also in Army Laboratory Technical Report ARL–TR–1341), National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (1997).**
15. **J. Kübler, (a) "Fracture Toughness of Ceramics Using the SEVNB Method: Preliminary Results," *Ceram. Eng. Sci. Proc.*, 18[4] 155–162 (1997); (b) "Fracture Toughness of Ceramics Using the SEVNB Method; Round Robin," VAMAS Report No. 37, EMPA, Swiss Federal Laboratories for Materials Testing & Research, Dübendorf, Switzerland (1999).**
16. **ASTM C 1421 "Test Method for Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature," *Annual Book of ASTM Standards*, Vol. 15.01, American Society for Testing and Materials, West Conshohocken, PA (2002).**
17. **S. Suresh, C. F. Shih, A. Morrone, and N. P. O'Dowd, "Mixed-Mode Fracture Toughness of Ceramic Materials," J. *Am. Ceram. Soc.*, 73[5] 1257–1267 (1990).**
18. **K. J. Wang, H. C. Lin, and K. Hua, "Calculation of Stress Intensity Factors for Combined Mode Bend Specimens," pp. 123–133 in *Advances in Research on the Strength and Fracture of Materials*, Vol. 4, Edited by M. D. R. Taplin, ICF4, Waterloo, Canada (1977).**
19. **M. Y. He and J. W. Hutchinson, "Asymmetric Four-Point Crack Specimen," *J. Appl. Mech.*, 67, 207–209 (2000).**
20. **Y. Murakami (ed.), Stress Intensity Factors Handbook, Vol. 1, p. 16, Pergamon Press, New York (1987).**
21. **J. E. Srawley and B. Gross, "Side-Cracked Plates Subjected to Combined Direct and Bending Forces," pp. 559–579 in *Cracks and Fracture*, ASTM STP 601, American Society for Testing and Materials, Philadelphia (1976).**
22. **V. Tikare and S. R. Choi, "Combined Mode I and Mode II Fracture of Monolithic Ceramics," *J. Am. Ceram. Soc.*, 76[9] 2265–2272 (1993).**
23. **V. Tikare and S. R. Choi, "Combined Mode I-Mode II Fracture of 12-mol-%-Ceria-Doped Tetragonal Zirconia Polycrystalline Ceramic," *J. Am. Ceram. Soc.*, 80[6] 1624–1626 (1997).**
24. **D. Zhu and R. A. Miller, "Thermal Conductivity and Elastic Modulus Evolution of Thermal Barrier Coatings under High Heat Flux Conditions," NASA/TM—1999-209069, National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (1999).**
25. **J. J. Eldridge, G. N. Morscher, and S. R. Choi, "Quasistatic vs. Dynamic Modulus Measurement of Plasma-Sprayed Thermal Barrier Coatings," *Ceram. Eng. Sci. Eng.*, 23[4] 371-378 (2002).**
26. **S. R. Choi, D. Zhu, and R. A. Miller, "Mode I, Mode II, and Mixed-Mode Fracture of Plasma-Sprayed Thermal Barrier Coatings at Ambient and Elevated Temperatures," presented at the 8th International Symposium on Fracture Mechanics of Ceramics, February 25-28, 2003, Houston, TX; To be published in *Fracture Mechanics of Ceramics*, Vol. 14, Kluwer Academi/Plenum Publisher, New York (2004); also in NASA/TM-2003-212185, National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH (2003).**

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
July 2003

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Strength, Fracture Toughness, Fatigue, and Standardization Issues of Free-Standing Thermal Barrier Coatings

5. FUNDING NUMBERS
WBS–22–714–04–05

6. AUTHOR(S)
Sung R. Choi, Dongming Zhu, and Robert A. Miller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–14076

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2003-212516

11. SUPPLEMENTARY NOTES
Prepared for the 27th Annual Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites sponsored by the American Ceramic Society, Cocoa Beach, Florida, January 26–31, 2003. Sung R. Choi, Ohio Aerospace Institute, Brook Park, Ohio 44142; Dongming Zhu, U.S. Army Research Laboratory, NASA Glenn Research Center; and Robert A. Miller, NASA Glenn Research Center. Responsible person, Sung R. Choi, organization code 5920, 216–433–8366.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Strength, fracture toughness and fatigue behavior of free-standing thick thermal barrier coatings of plasma-sprayed ZrO_2-8wt % Y_2O_3 were determined at ambient and elevated temperatures in an attempt to establish a database for design. Strength, in conjunction with deformation (stress-strain behavior), was evaluated in tension (uniaxial and trans-thickness), compression, and uniaxial and biaxial flexure; fracture toughness was determined in various load conditions including mode I, mode II, and mixed modes I and II; fatigue or slow crack growth behavior was estimated in cyclic tension and dynamic flexure loading. Effect of sintering was quantified through approaches using strength, fracture toughness, and modulus (constitutive relations) measurements. Standardization issues on test methodology also was presented with a special regard to material's unique constitutive relations.

14. SUBJECT TERMS
Thermal barrier coatings; Strength; Fracture toughness; Fatigue; Deformation; Sintering effect

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	