Advanced Materials for Lightweight Valve Train Components

OVT Annual Merit Review
Final Program Review
February 26, 2008

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Project Manager :	Jeff Jensen (CAT)
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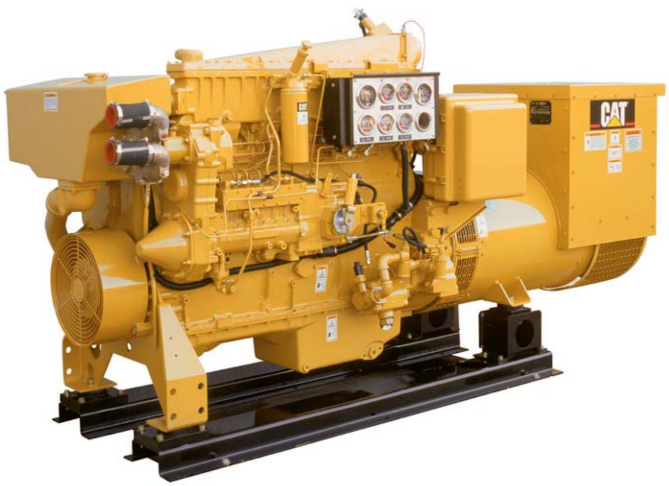
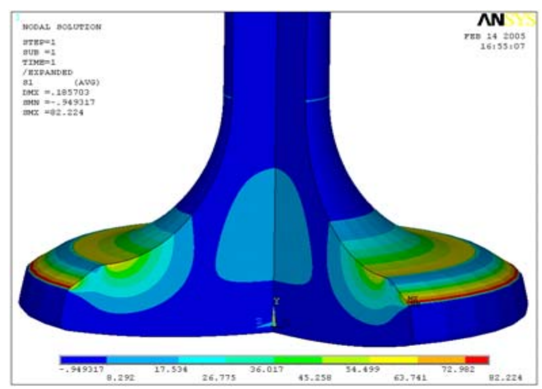
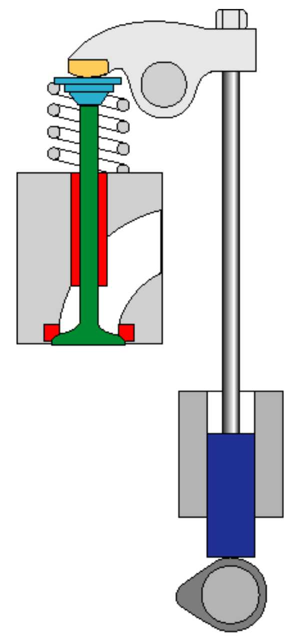






*This presentation does not contain any proprietary or confidential information

Program Objectives

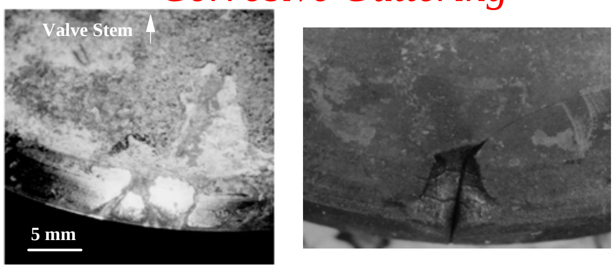
Overall Objective: Design and fabricate engine valves from high temperature advanced materials that:

- are 30% lighter than steel valves.
  - ✓ *Ceramics*
  - ✓ *Intermetallics*
- provide a 200% increase in service lifetime.
  - ✓ *Valve wear*
  - ✓ *Corrosion*
  - ✓ *Oxidation*
- provide a 5% increase in fuel efficiency.
  - ✓ *Less energy required to reciprocate valves*
  - ✓ *Enable operation in extreme combustion environments*
  - ✓ *Permit higher overspeed operation which allows more efficient engines to operate in more demanding regimes*

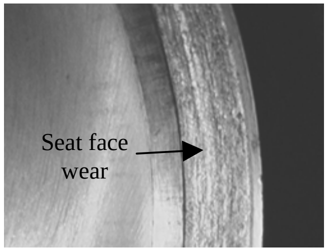
Barriers for lightweight valve train components

Premature life failure modes from current valve materials

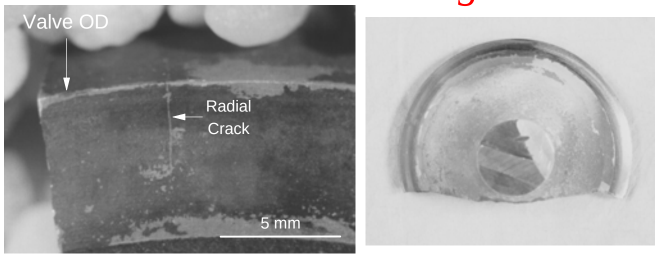
Corrosive Guttering



Excessive Wear



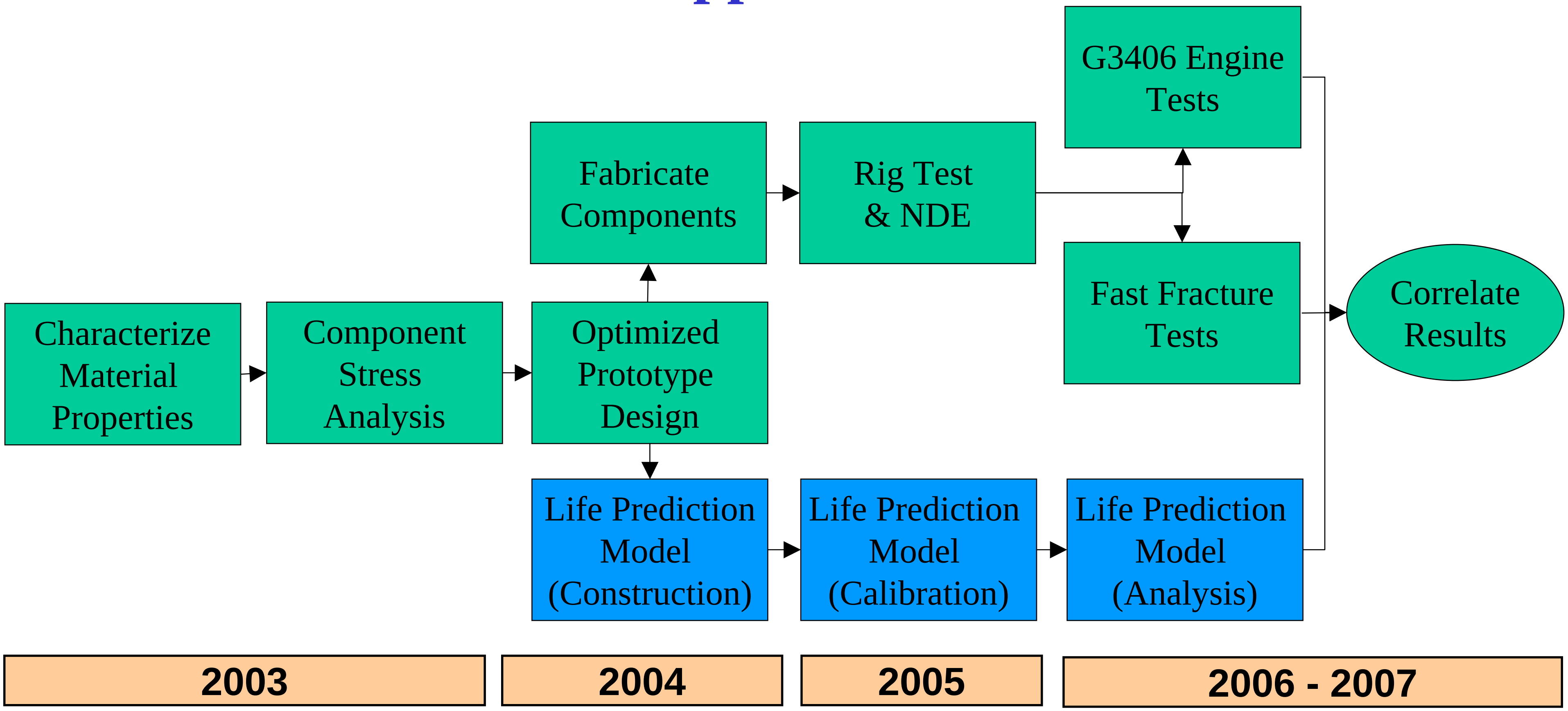
Radial cracking



The primary barriers that have traditionally limited intermetallics and ceramics for consideration in gas and diesel engines include:

- ✓ ***High cost of fabrication and machining***
- ✓ ***Unproven methodologies for advanced material component designs***
- ✓ ***Durability and reliability***

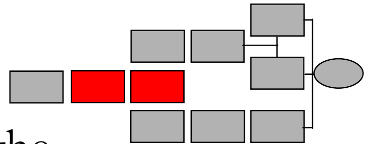
Approach



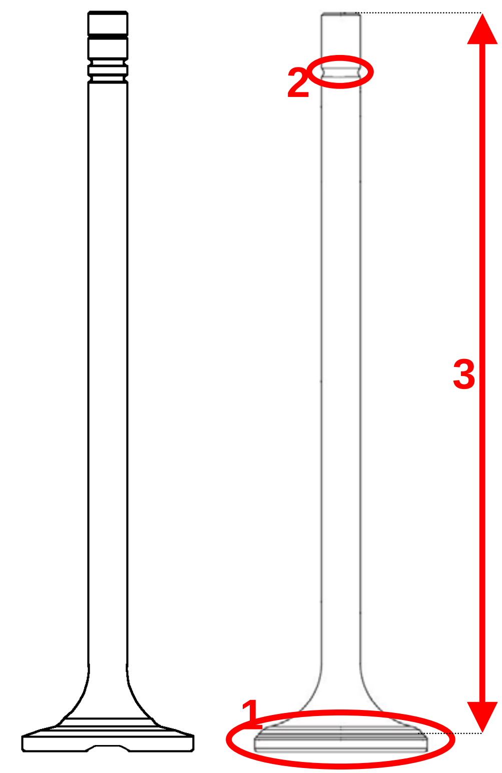
TiAl and Si_3N_4 are excellent candidate materials for valve train applications since they offer better corrosion/oxidation resistance, excellent wear resistance, and higher strengths at elevated temperatures.

Valve Design Changes

G3406 Exhaust & Intake Valves

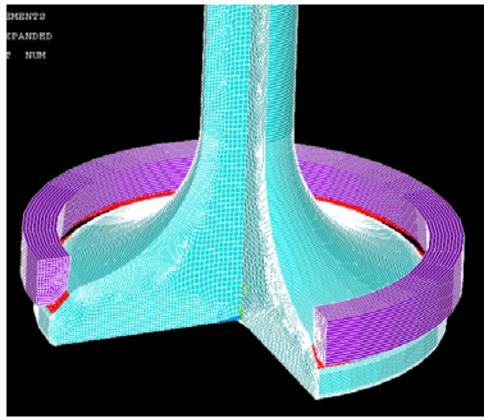


Task Objective: Optimize valve design through FEA by accounting for the brittle nature of ceramics and intermetallics.



Production Design

“Advanced” Design



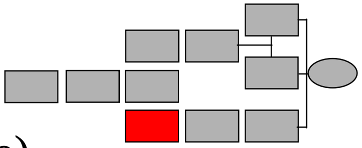
Component Stress Analysis

Valve Design Changes

1. Head
   - Intake contact angle 70° → 45°
   - Face to datum increased 3.56mm → 4.36mm
   - Add fillet breaks to all corners
2. Keeper
   - Single groove at same height as lower groove
   - Groove radius increased 0.8mm → 1.35mm
3. Datum to Tip Length
   - Shortened from 177.8mm → 175.9mm

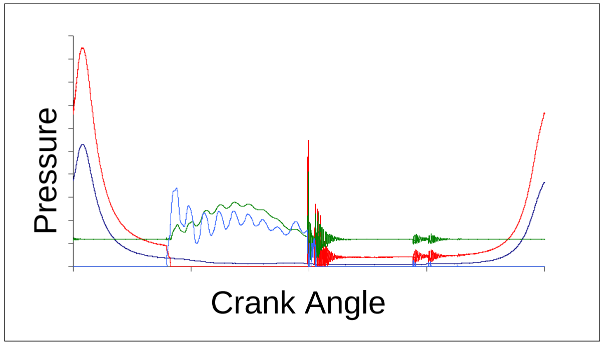
Life Prediction Model

Overview

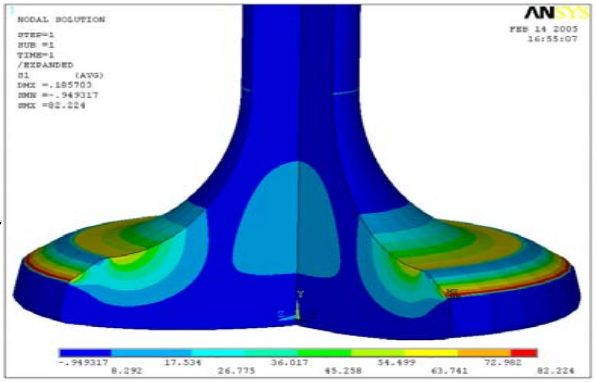


Task Objective: Develop FEA-based life prediction model (CARES/Life) that will generate life prediction curves for advanced valve materials.

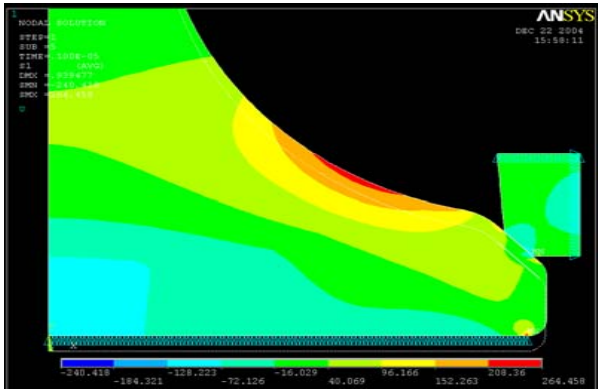
Collaborator: Jadaan Engineering & Consulting (Platteville, WI)



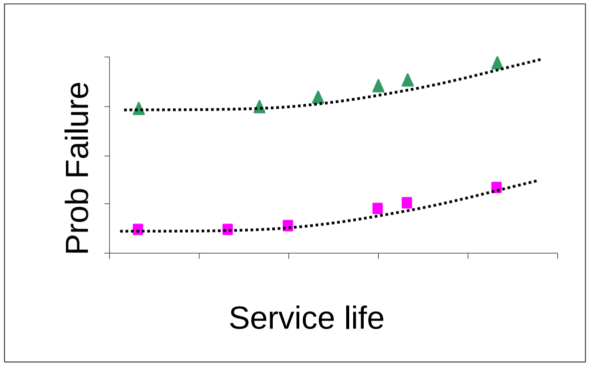
Thermo-mechanical Bound. Cond.



Thermal Stress Evaluation



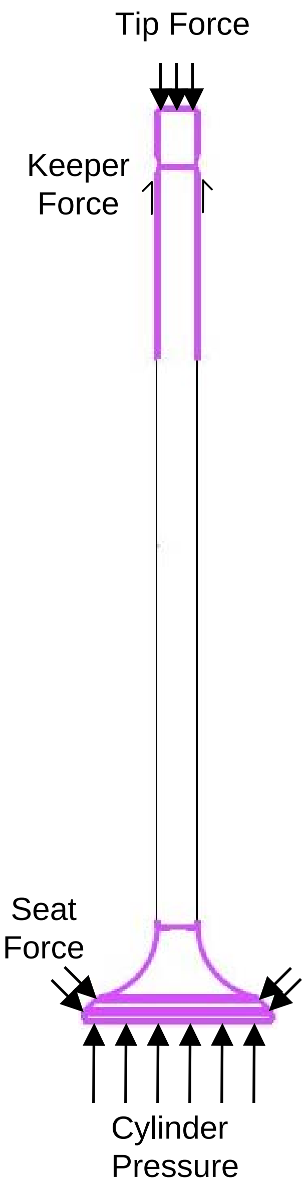
Contact Stress Evaluation

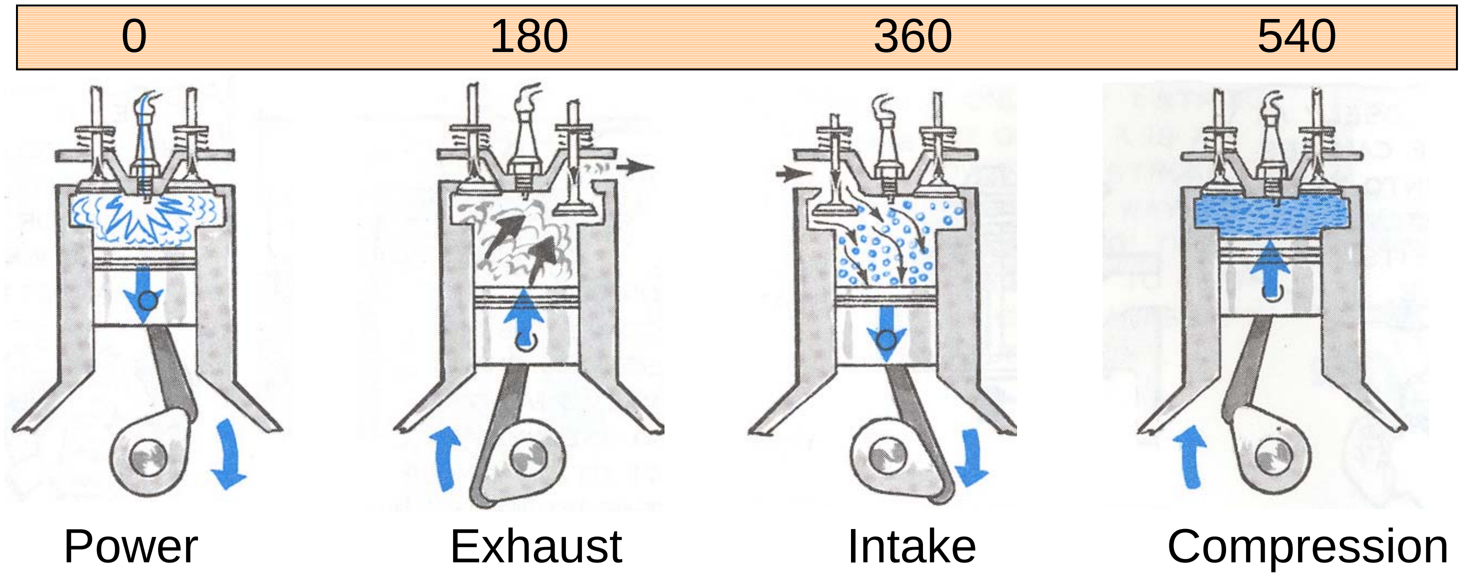


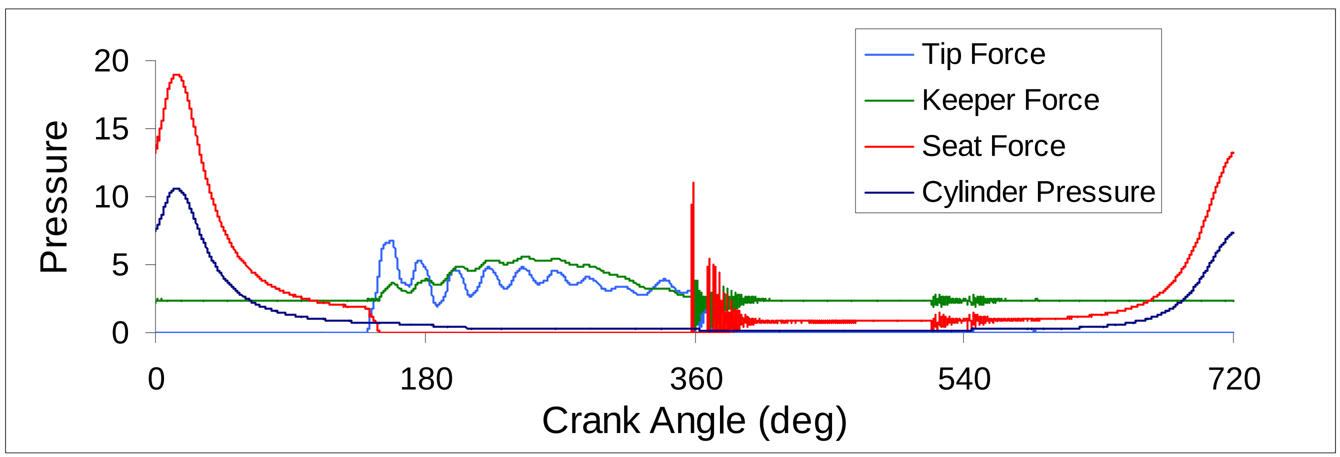
Life Prediction Curve

Life Prediction Model

Boundary Conditions

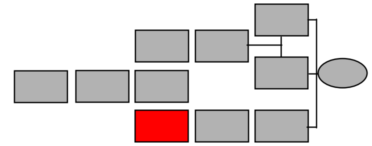


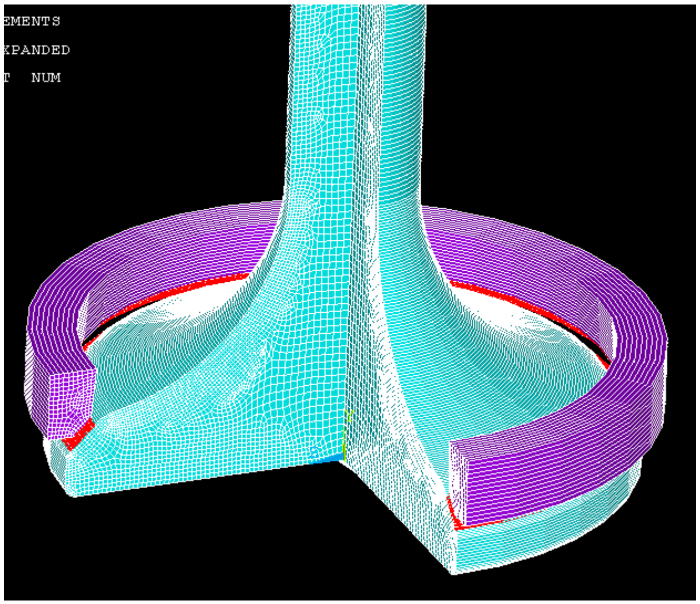




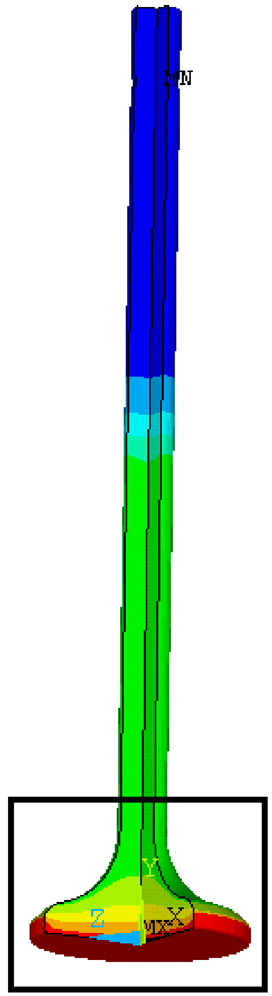
Life Prediction Model

Thermal Stresses

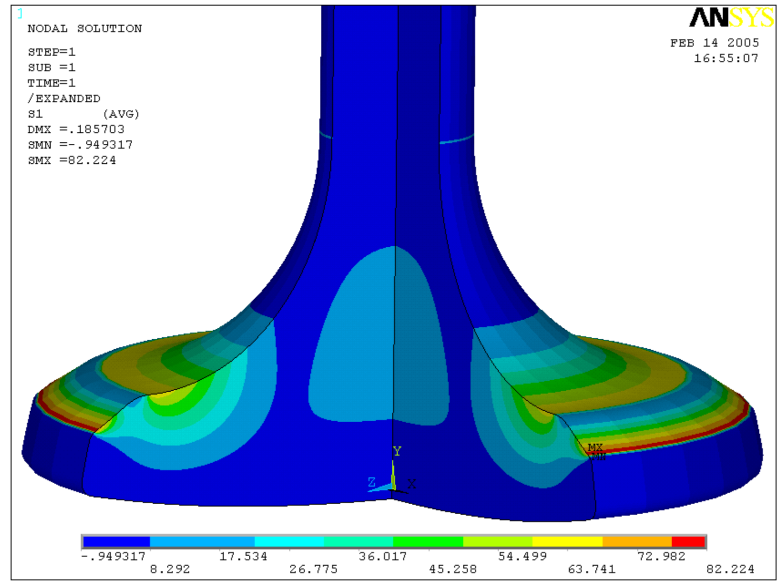




Axisymmetric FEA Model



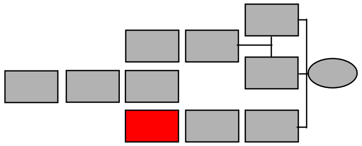
Temperature Distribution



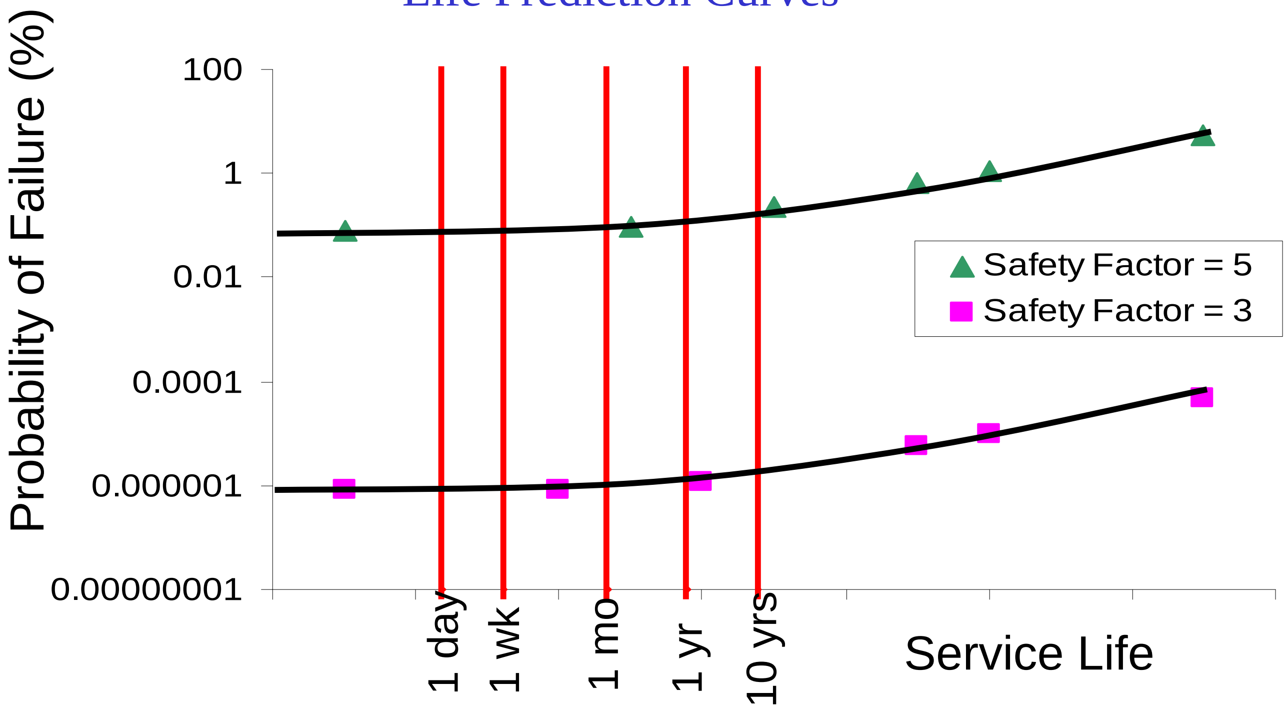
Thermal Stress Profile
(deformation exaggerated 200x)

➢ Similar "pringle-shaped" deformations have recently been seen on heavy-duty diesel engine valves.

Life Prediction Model

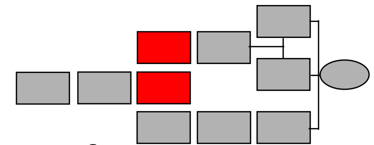


Life Prediction Curves



- **This life prediction curve demonstrates the model's capabilities using a transient load cycle boundary condition approach.**
- **Using the maximum load, rather than a transient load, yielded a higher and possibly more realistic probability of failure, but higher standard deviation. For a load factor of 1, the probability of failure deviated from 4.45E-7 to 4.00E-15 for Si_3N_4 and similarly for TiAl.**

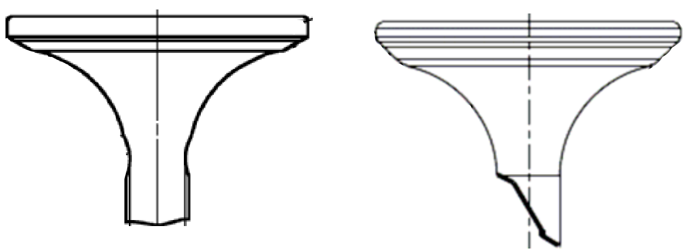
Valve Fabrication



Task Objective: Generate a valve design that accounts for the brittle nature of high temperature materials; Fabricate valves (cast, weld, rough & finish machine).
Suppliers: Kyocera, Howmet, Supfina, Erwin Junker

Valve Design

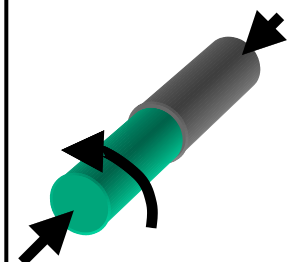
(M.J. Andrews)



Production Design | Ceramic/Intermetallic Design

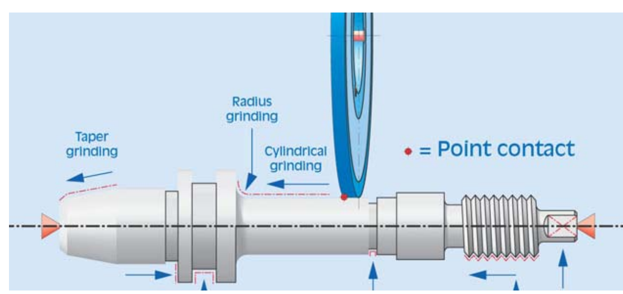
Friction Welding

(TiAl only)



Ti-6-4 shaft | TiAl head

Finish Machining

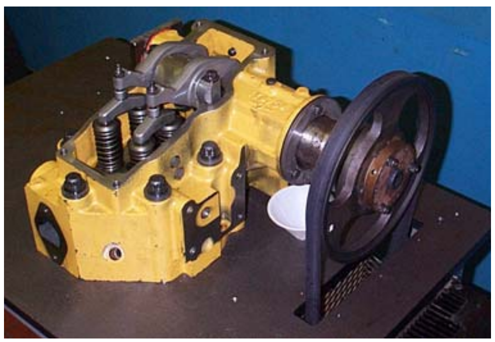


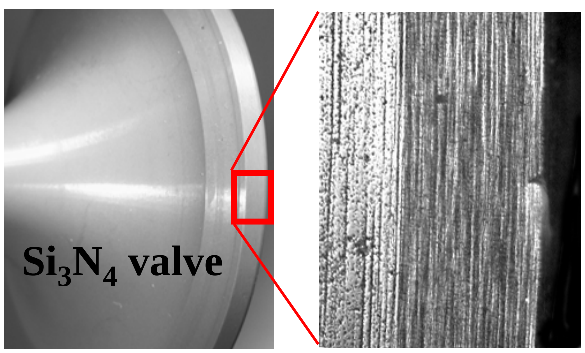
Junker's "Quickpoint" superfinish technique

Rig Test

Task Objective: Perform bench test evaluation of prototype valves to detect early-life failure modes before engine test.

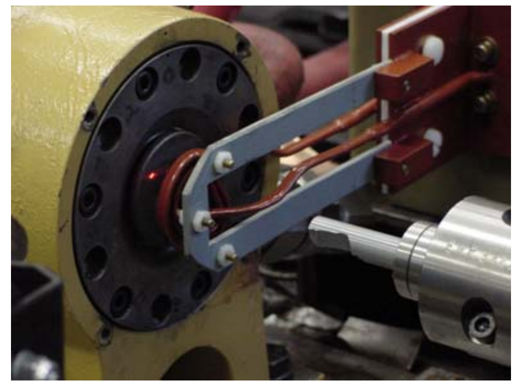
SCOTE impact test rig





Early life "polish" wear

"Buettner" Thermo-mechanical rig



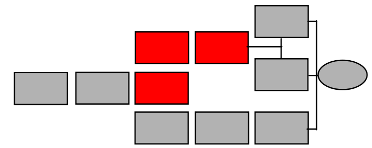
Features

- Induction coil simulates temp
- Load pin simulates combustion pressure
- Easily accommodates various size valves

Analysis Capabilities

- Ability to separate valve wear from seat insert wear
- Capable of measuring wear over short intervals of time

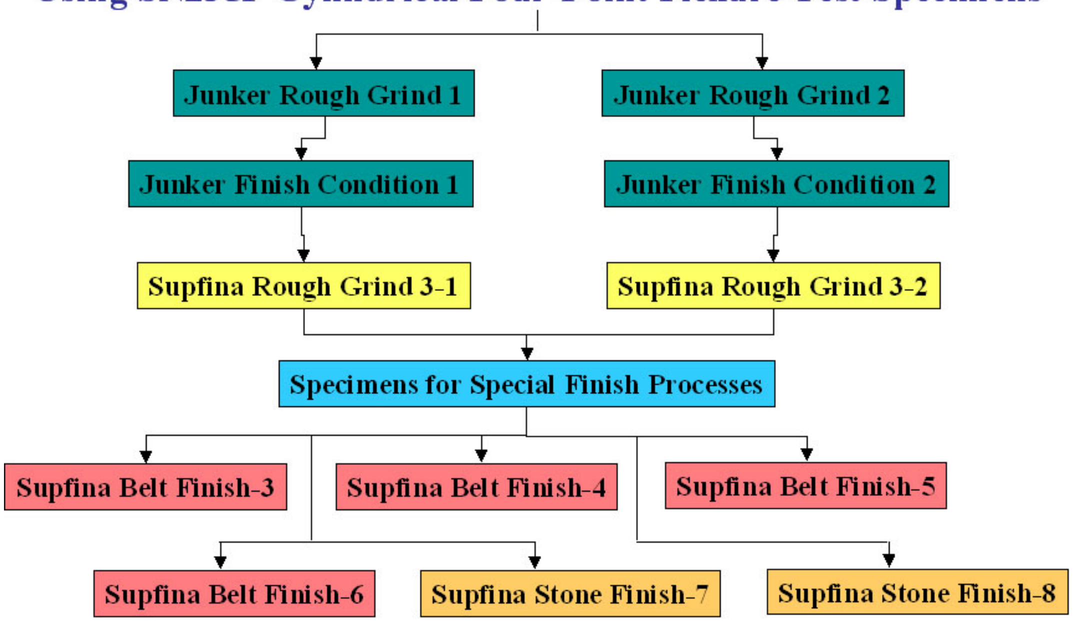
Effect of Machining Procedures on the Strength of Ceramics

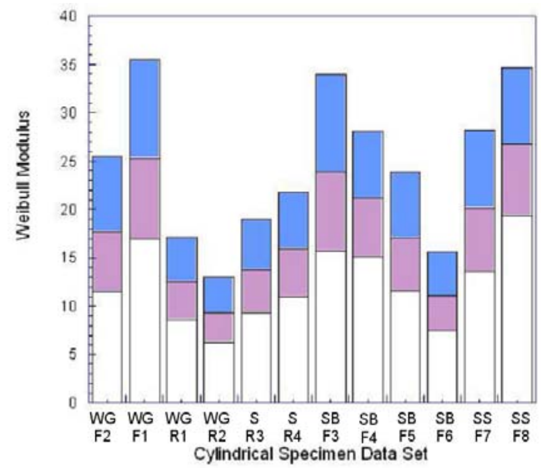


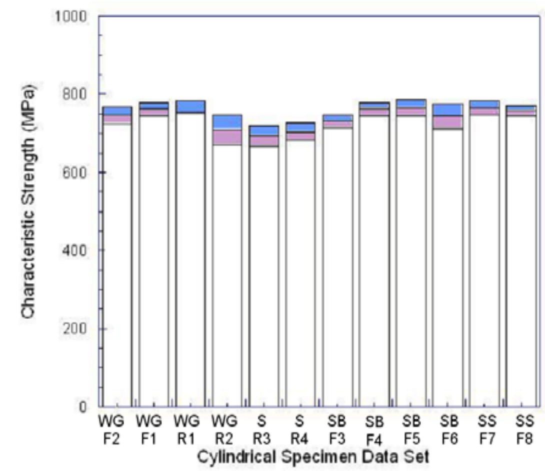
Task Objective: Determine a cost-effective machining process to improve the optimal performance and extended life and reliability of advanced ceramic components

Suppliers: Kyocera, Supfina, Erwin Junker

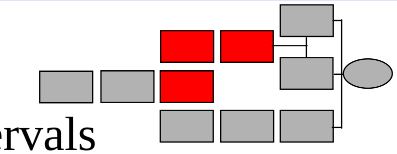
Machining Study Generated 12 Strength Data Sets
Using SN235P Cylindrical Four-Point Flexure Test Specimens







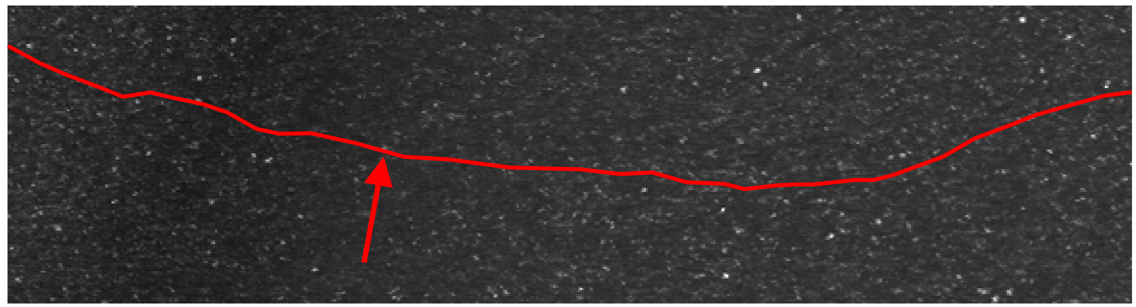
NDE – Laser Scatter



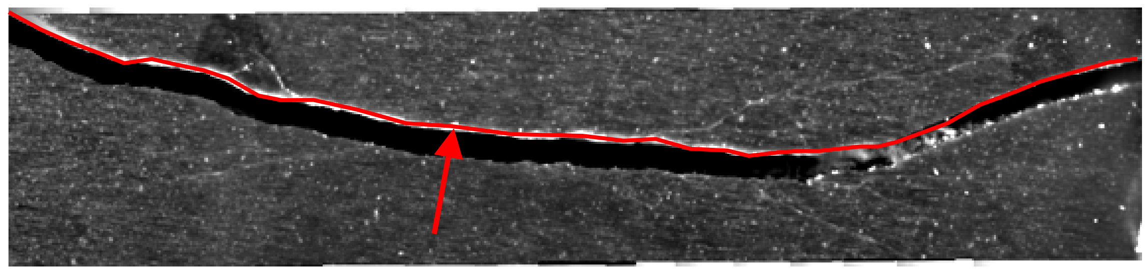
Task Objective: Scan valves to detect subsurface; perform scan at set intervals before, during and after engine testing to observe damage accumulation.

Collaborator: JG Sun (ANL)

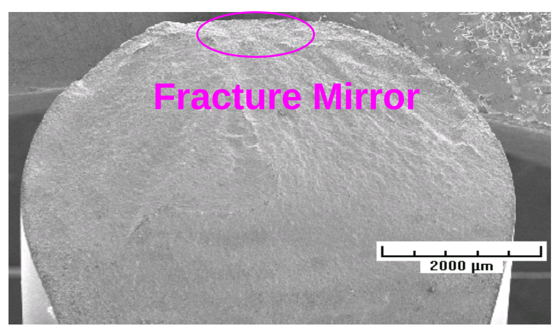
- Using a novel NDE technique (Elastic optical scattering), we can characterize subsurface material defects and machining damage.

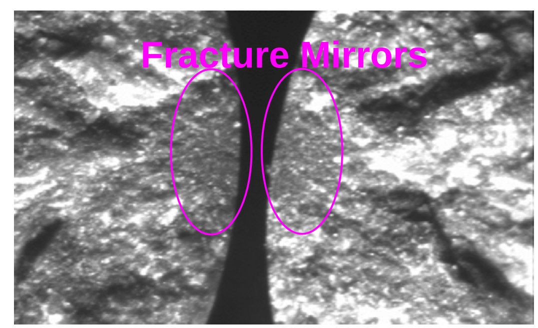


Valve before failure (Laser NDE scan)

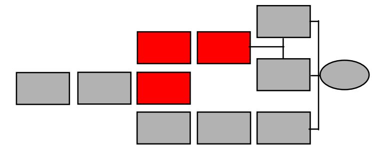


Valve after failure (Composite photomicrograph)

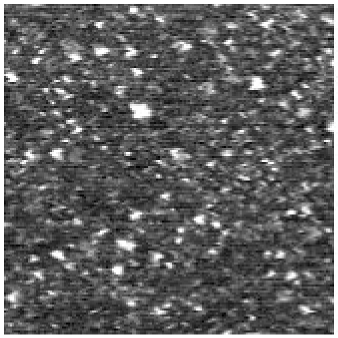




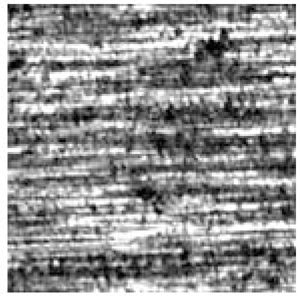
Effect of Machining Procedures on the Strength of Si_3N_4



Wheel Grinding Finish 1

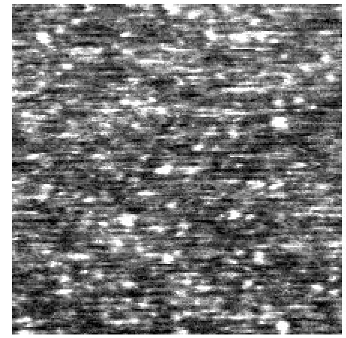


Laser Image

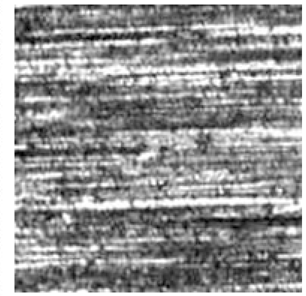


Optical Image 200x

Wheel Grinding Rough 2

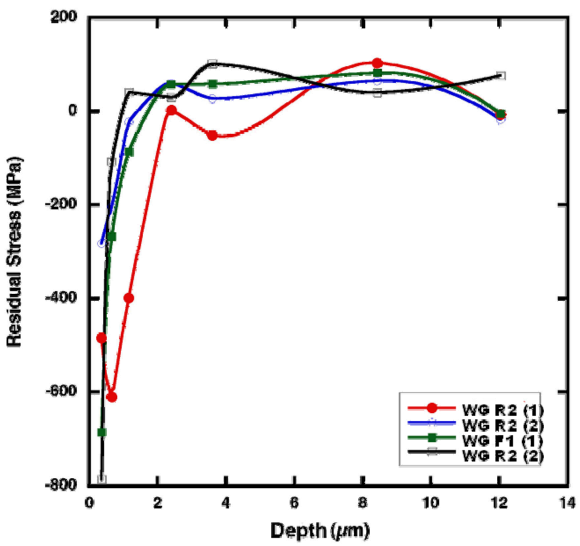


Laser Image



Optical Image 200x

Residual Stress Determination of Si_3N_4 Test Specimens
User Agreement with ORNL/HTML (Tom Watkins)



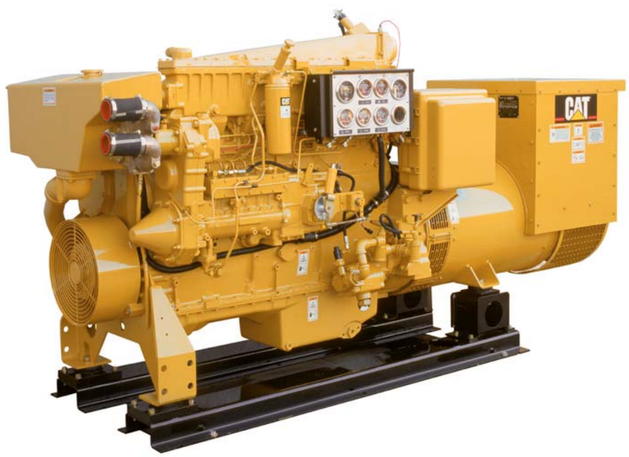
- **Characteristic strength results of machined rods are independent of surface finish**
- **Better surface finish reduces the population and size of flaws, resulting in a decreased probability of failure and increased Weibull Modulus**
- **Specimens with finished machining (Wheel Grinding Finish 1) have larger residual stress and the highest Weibull Modulus**
  - **Higher compressive stresses make it harder for cracks to propagate**
  - **Finished machining shears the material more than the rough grinding, creating a more deformed surface and possibly causing surface flaws to be more uniformly distributed. As a result, the Weibull Modulus would increase.**

G3406 Engine Test
Overview

Task Objective: Subject valves to realistic engine environment loading; evaluate valve wear and engine performance.

Collaborators: Tim Theiss, Mike Kass, Noberto Domingo (ORNL–NTRC)

- Valves will accumulate 1000 hrs. on a G3406:
  - 1800 rpm, 12.77 bar bmep, λ = 0.99-1.09
  - Three Phases
    - Phase I: 100 hours
    - Phase II: 500 hours
    - Phase III: 1000hours
- Valves to be tested:
  - 8 Si3N4 intake valves
  - 8 Si3N4 exhaust valves
  - 8 TiAl exhaust valves
  - Balance: production valves

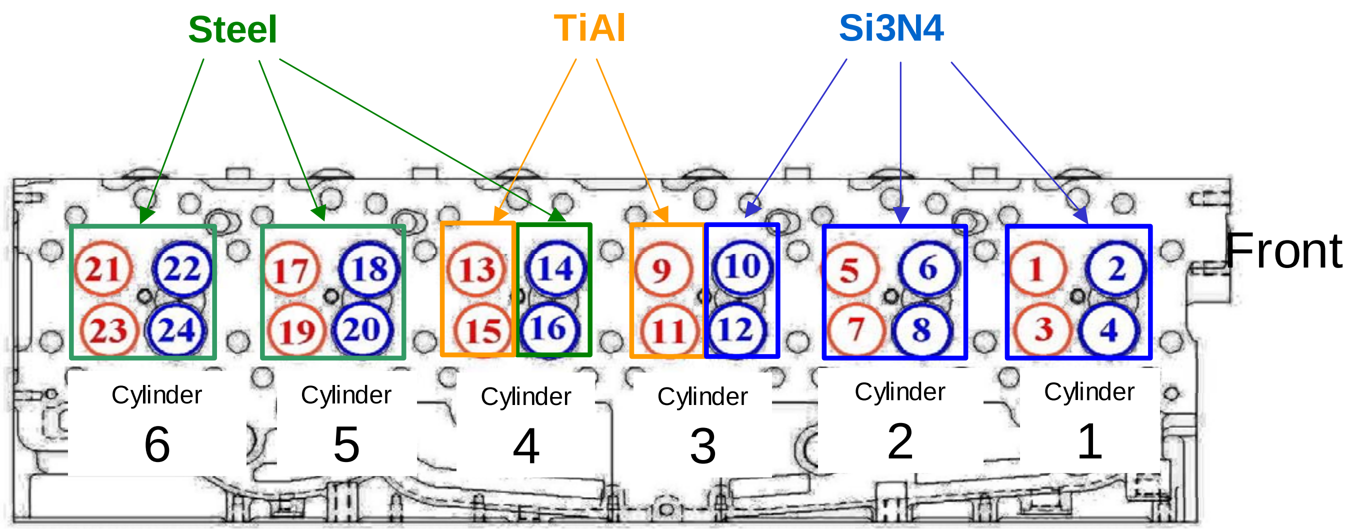


Caterpillar G3406 Engine

Break-in (SCOTE rig) → Laser NDE Characterization → Engine Test (accumulate X hours) → Fast fracture at HTML → Correlate to Life Prediction Model

G3406 Engine Test

Phase I and II Overview: 100 and 500 hours

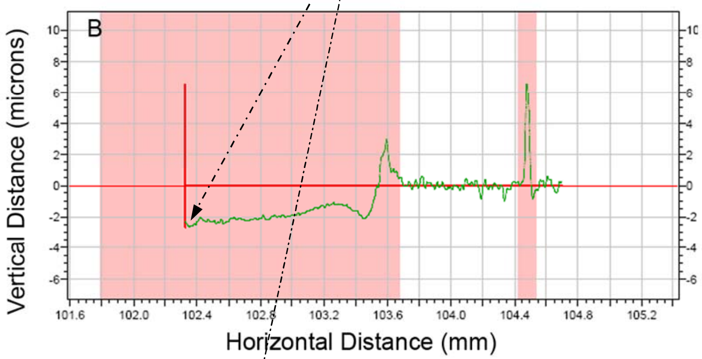


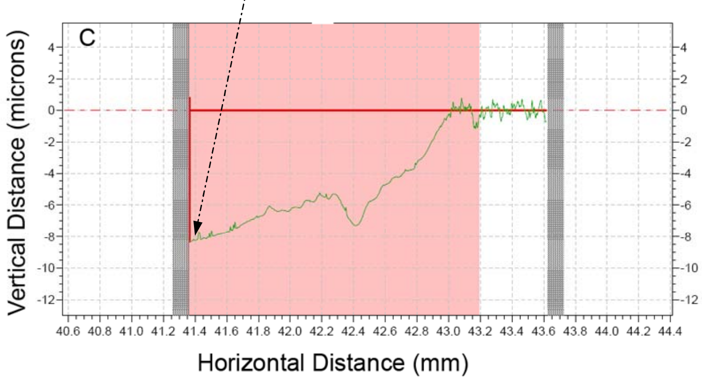
- First 500 hours of testing was performed at half-rated condition due to a “knocking” phenomenon in Cylinder 1
  - Rated condition: 235 kW
  - Condition for Phase I and II: 125 kW
- Cylinder 1 traditionally runs hotter than Cylinder 6. The valves in Cylinder 1 protruded from the engine head further than the production steel valves, since the head thickness for the Si_3N_4 valve was increased. This caused pre-ignition due to hot spots on the Si_3N_4 valves.

G3406 Engine Test

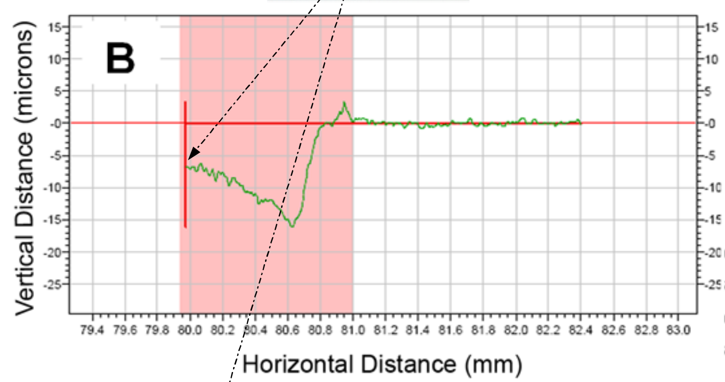
Phase I and II NDE: 100 and 500 hours

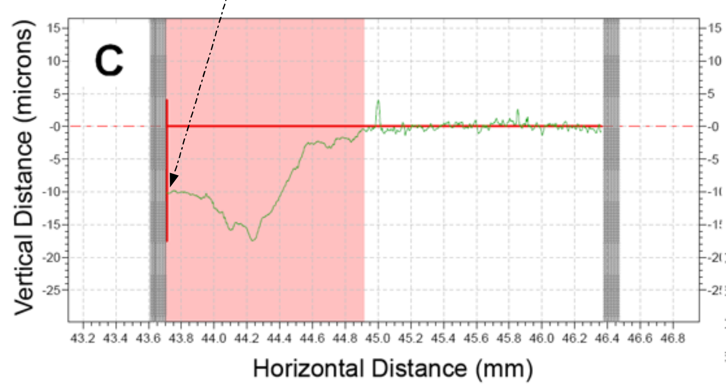
Si_3N_4 Exhaust





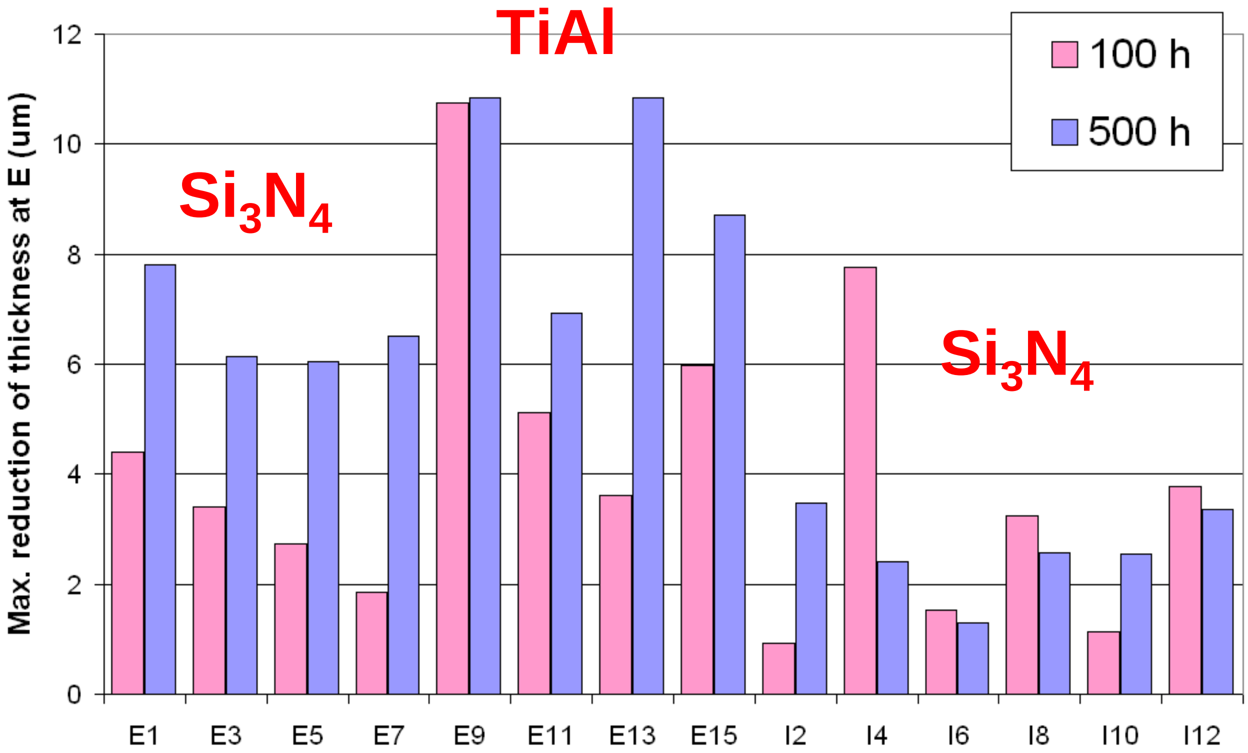
TiAl Exhaust





G3406 Engine Test

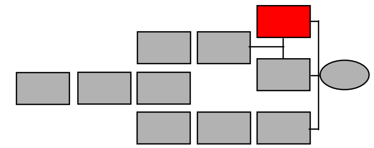
Phase I and II NDE: 100 and 500 hours



- Vast wear improvement in the seating region over production steel valves
  - ➢ Production steel intake valves showed between 30 and 40 microns of wear
  - ➢ Although production steel exhaust valve wear was not measured, typically it is significantly worse than wear on intake valves.

G3406 Engine Test

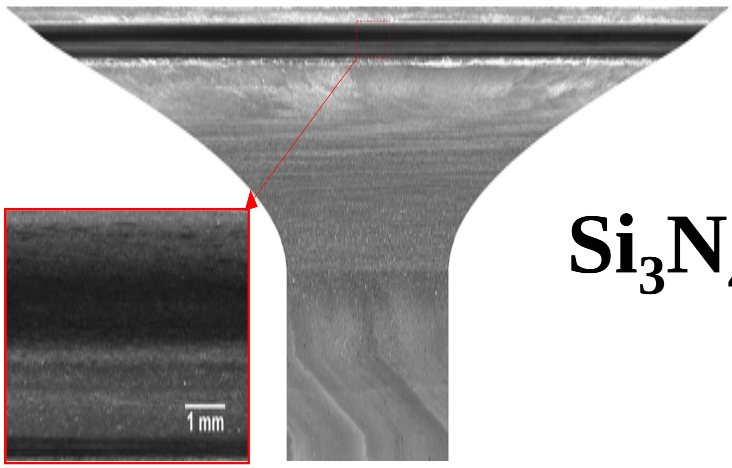
Phase I and II NDE: 100 and 500 hours

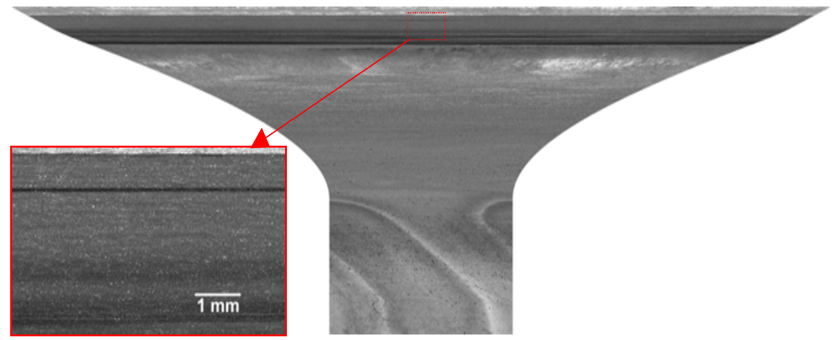


100 hours

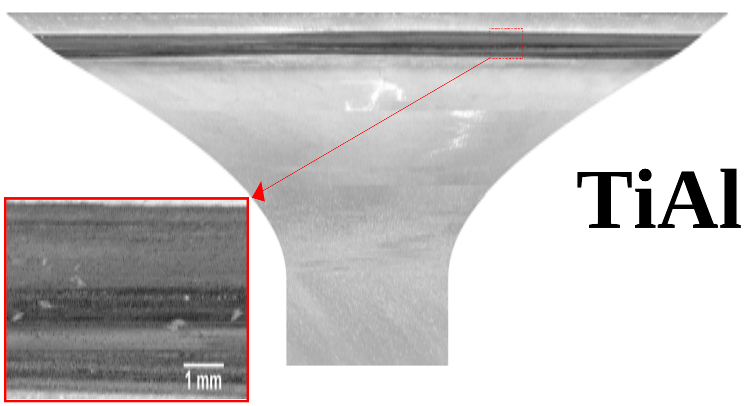
500 hours

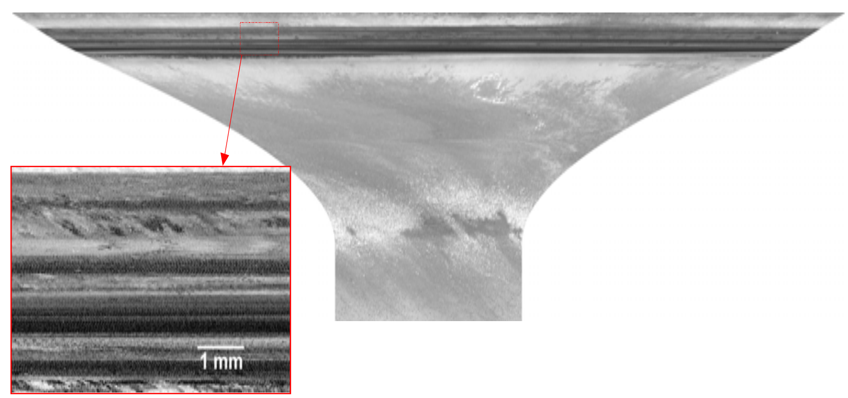
Si_3N_4





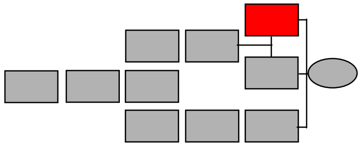
TiAl



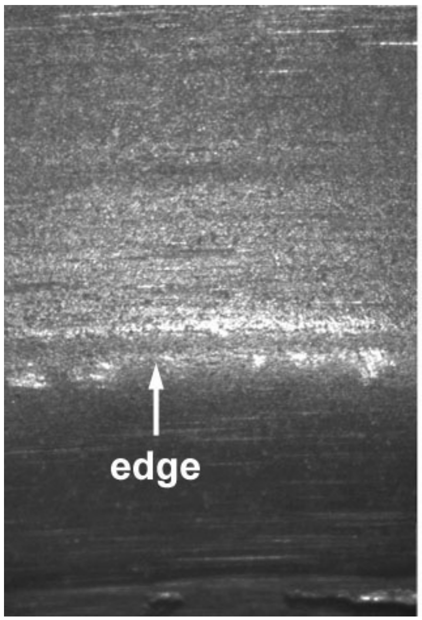


G3406 Engine Test

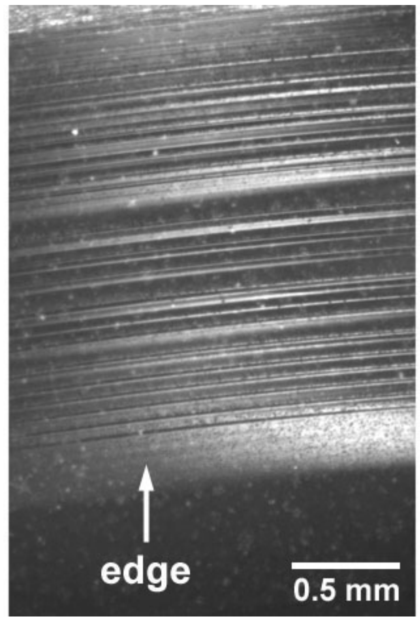
Phase I and II NDE: 100 and 500 hours



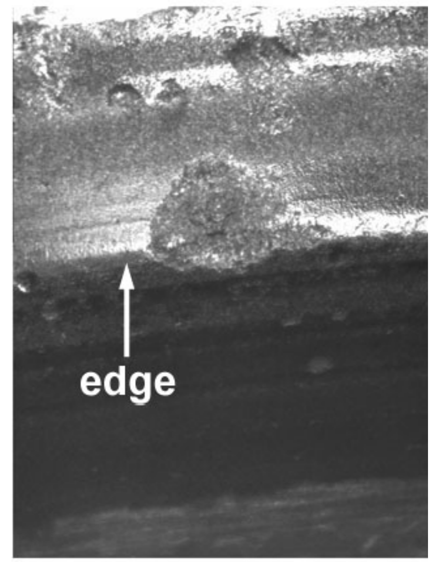
Si_3N_4 I2



Si_3N_4 E1



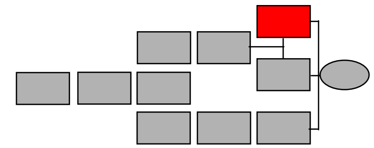
TiAl E9



- Si_3N_4 intake valves show significant scoring that is typical valves that have inadequate lubrication at the seating interface
- Si_3N_4 exhaust valves show signs of impact wear. The fine grooves are created as a result of the valve trying to align itself against the seat insert during high impact.
- TiAl exhaust valves show significant impact wear in the form of pitting/material pullout and alignment grooves.

G3406 Engine Test

Phase III: 1000 hours

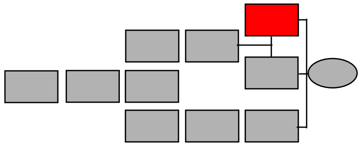


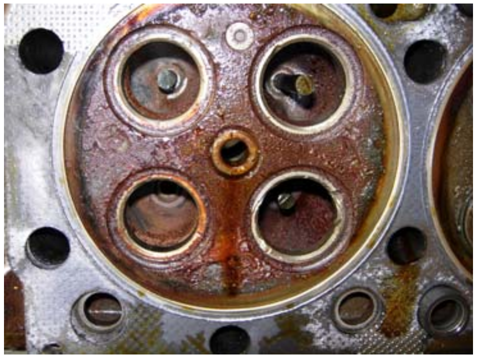
	0 – 500 hours		500 – 1000 hours	
Cylinder	**Intake**	**Exhaust**	**Intake**	**Exhaust**
1	Si_3N_4	Si_3N_4	Production Steel	Production Steel
2	Si_3N_4	Si_3N_4	Si_3N_4	Si_3N_4
3	Si_3N_4	TiAl	Si_3N_4	TiAl
4	Production Steel	TiAl	Production Steel	TiAl (1 new)
5	Production Steel	Production Steel	Production Steel	Production Steel
6	Production Steel	Production Steel	Si_3N_4 (new)	Si_3N_4 (new)

- Due to the previously described pre-ignition complications from Phases I and II, the Si_3N_4 valves from Cylinder 1 were removed for remaining strength determination and replaced with production steel valves.
- New Si_3N_4 valves were inserted into Cylinder 6
- The TiAl valve from Cylinder 4 was removed for destructive testing and replaced with a new valve
- It was determined that as a result of the change in valve set-up, the engine could run at fully rated conditions (235 kW) without pre-ignition.

G3406 Engine Test

Phase III: Engine Failure

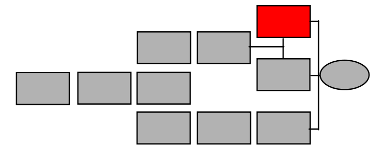


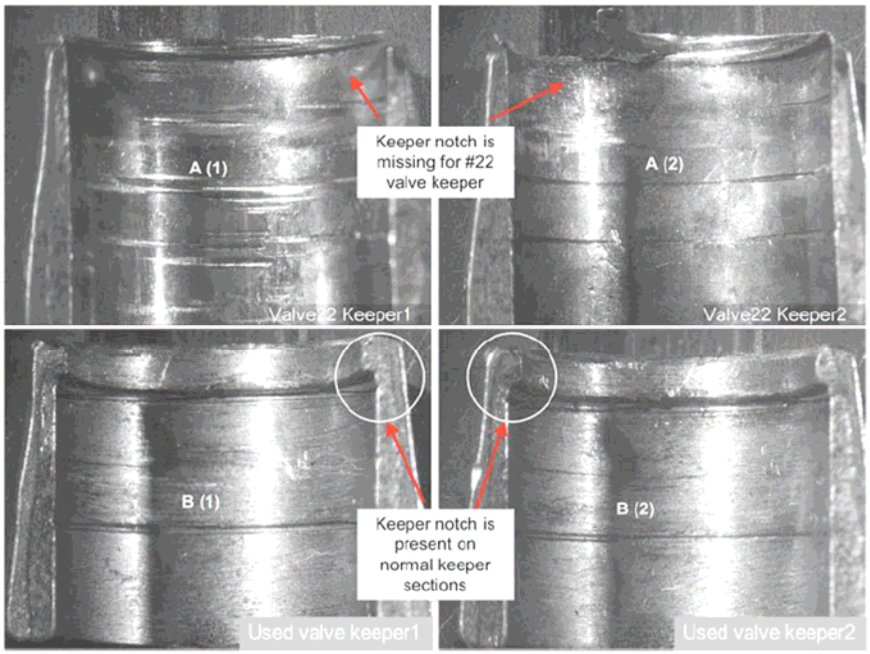


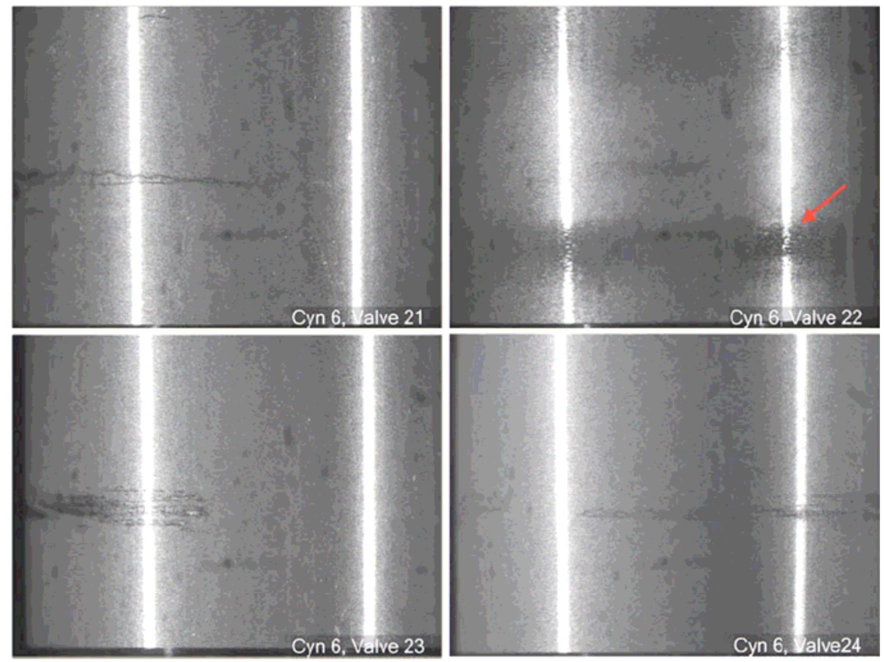
1. The keeper notch for intake valve #22 wore off or sheared, allowing the valve (composed of silicon nitride) to drop into the cylinder.
2. Once in the cylinder, the valve head was hit by the piston and shattered. Loose fragments from this valve destroyed the remaining three silicon nitride valve heads and well as damaging the piston and cylinder liner.
3. During the compression stroke a portion of the valve fragments entered the intake manifold. Since the intake valve heads for cylinder #6 were missing, an opening existed for the transport of these fragments into the intake manifold.
4. The silicon nitride fragments, which had entered the intake manifold, were subsequently sucked into the other five cylinders during the intake stroke.
5. Once inside the combustion chamber, the fragments destroyed the other valves, piston crowns, and liners via high velocity impact.
6. During the exhaust stroke, a portion of the silicon nitride fragments entered the exhaust and subsequently damaged the turbocharger.

G3406 Engine Test

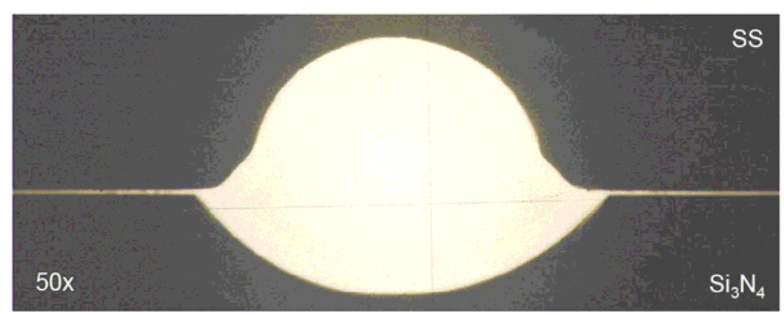
Phase III: Engine Failure





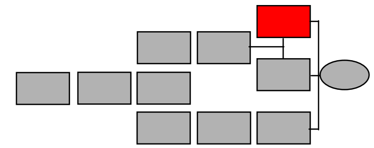


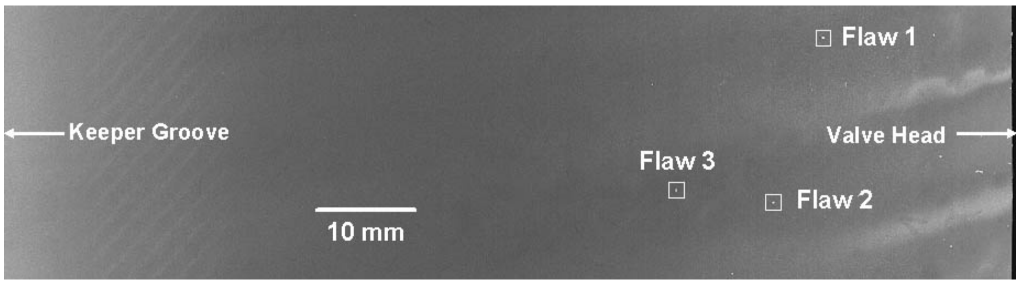
- Keeper notch on the steel keeper was completely worn away
- Surface roughness of keeper groove on Valve #22 was ~40% finer than the other Si_3N_4 valves
- Keeper groove radius on Si_3N_4 valves were significantly larger than the steel valves (same keepers)



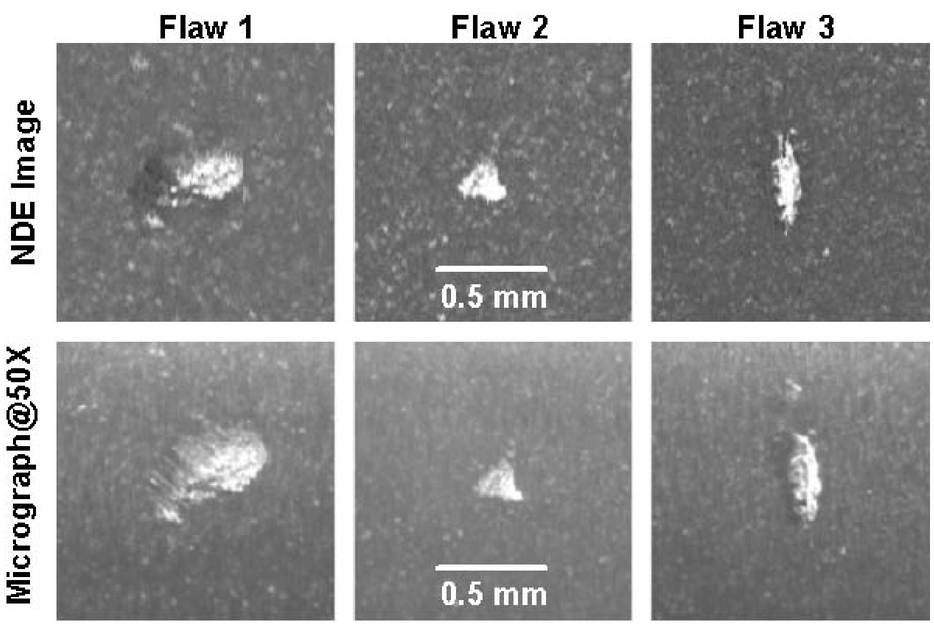
G3406 Engine Test

Phase III: Post Engine Failure NDE



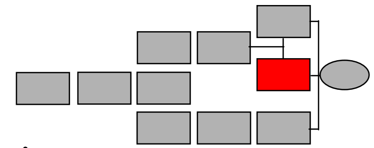


Laser Scattered Image, Valve #22



- Post-test NDE of all valves revealed:
  - ➢ No large scale damage
  - ➢ Several surface and subsurface flaws along the stem
- Several flaws close to the head of Valve #22 could have degraded the component strength
  - ➢ Flaws #1 and #3 were minor scratches
  - ➢ Flaw #2 was an impact chipping defect

Fast Fracture Tests



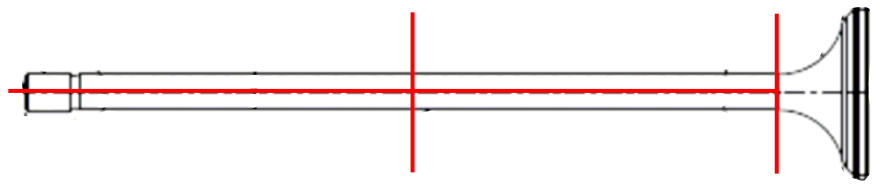
Task Objective: Perform fast fracture tests to determine retained strength in valves with varying accumulated engine hours.

Collaborators: HT Lin (ORNL–HTML)

Valves accumulate set number of engine hours (0 and 500 hours)

↓

Section valves into 5 pieces



Perform ASTM standard 4pt flexure test to determine retained strength

Perform valve failure test at ORNL to determine retained strength

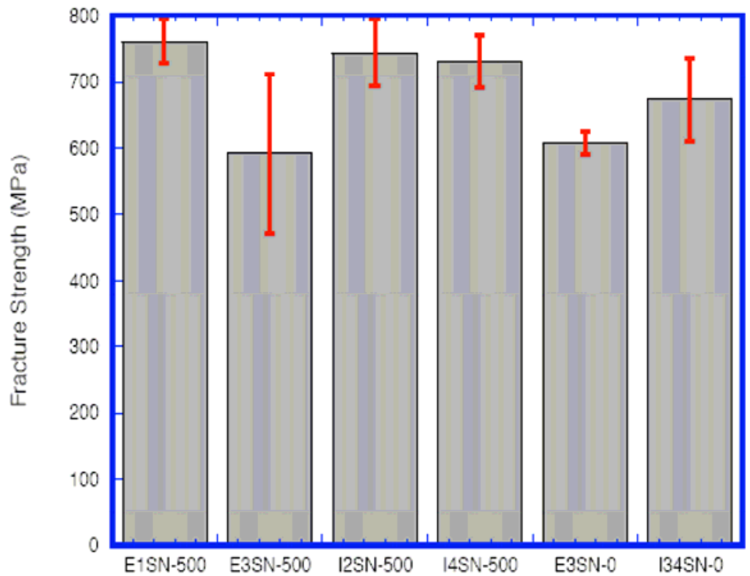
↓

Perform fractographic analysis to back-correlate to JG Sun's NDE images

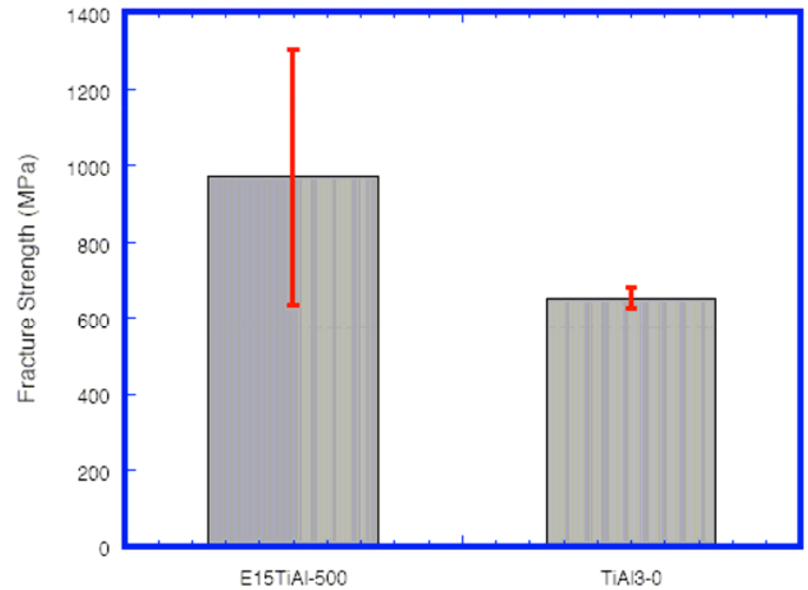
Correlate retained strength to probability of failure

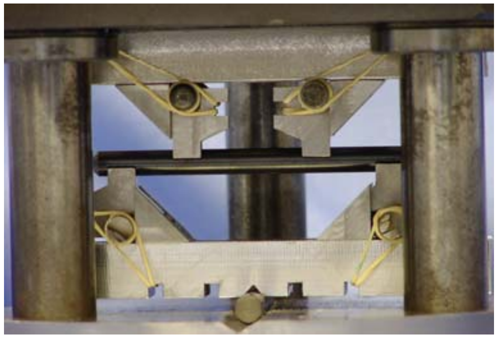
Fast Fracture Tests

Si_3N_4



TiAl



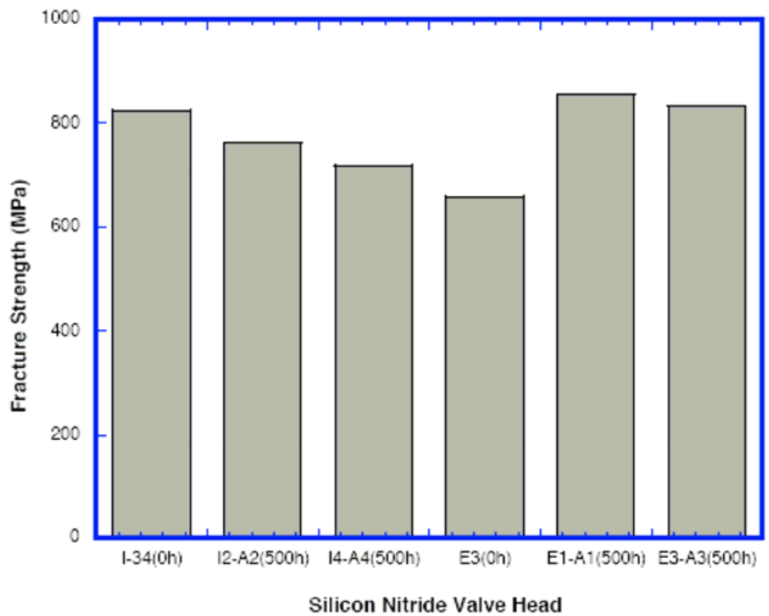


Half-cylindrical valve stem test fixture (30/60 mm spans)

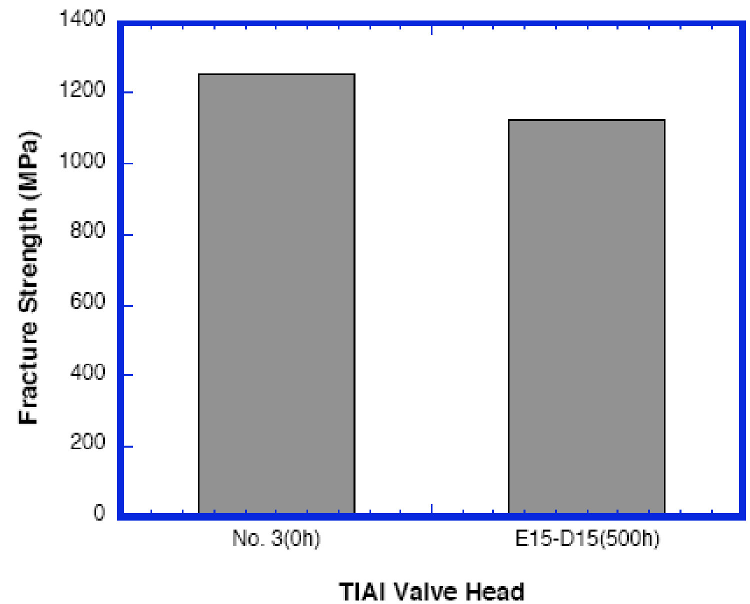
✓ **No mechanical strength degradation of valve stem material after 500h engine test**

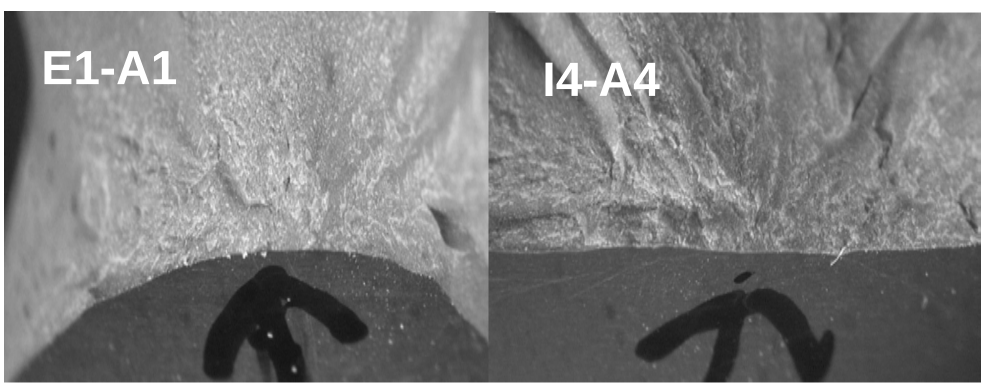
Fast Fracture Tests

Fracture strength of Si_3N_4 valve heads



Fracture strength of TiAl valve heads

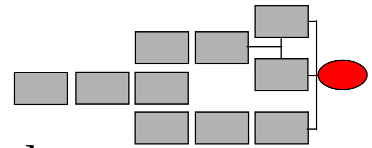




✓Fracture mostly initiated at the original machining flaw (groove) region.

✓There is little or no environmental effect on the mechanical performance of Si_3N_4 valves.

Model/Experimental Correlation



Task Objective: Compare model prediction with experimental results; evaluate effectiveness of full-scale life prediction model.

- Indirect correlation: Retained strength analysis
  - If no significant damage is incurred to valves after 500 hrs, this indirectly verifies low probability of failure as predicted by the CARES/Life model
  - Consider results from fast fracture tests as "retained strength"
  - Compare "retained strength" to probability of failure predictions from CARES/Life model

Valve Material	ID	Retained Strength (Mpa)	Predicted Probability of Failure	Characteristic Strength (Mpa)
Si_3N_4	E1	857.22	5.57E-14	761.57
Si_3N_4	E3	833.54		
Si_3N_4	I2	762		
Si_3N_4	I4	719.74		
TiAl	E15	1123.3	1.51E-07	560.1

✓ Retained strength measurements from the head of the valves after 500 hours of engine exposure indicate that the probability of failure would be equal to or less than the predicted probability; however, the engine was only exposed to half-rated conditions and the predicted probability of failure was based on fully-rated conditions.

Summary

- Life prediction of ceramic and intermetallic valves depends highly on the boundary conditions, especially the transient loading conditions. Nevertheless, the probability of failure is low considering all boundary conditions.
- Machining process directly influences life expectancy of Si_3N_4 components due to residual stress differences at the near surface (first 2 – 3 μm).
- Due to pre-ignition complications, the design of Si_3N_4 valves needs to be adjusted so that the valve does not recede from the head as far.
- Si_3N_4 and TiAl valves showed significant wear improvements over production steel valves after 500 hours of engine testing
- The failure of the G3406 engine was caused by the failure of a steel keeper, not the durability and reliability of the Si_3N_4 valves
  - ➢ Future keeper designs need to have a tight fit against the keeper groove radius of the valves
  - ➢ More wear resistant materials need to be used while in contact with hard ceramic components
- Results from the engine tests align well with predicted results from the Life Prediction Model and satisfy the program objectives set at the beginning of the project (further tests on fuel efficiency needed)

Technology Transfer

- High raw material and machining costs make it hard to justify the use ceramic and intermetallic valves in on-highway trucks, even though there is an obvious performance advantage. However, there are international companies whose raw material costs are much lower than the United States'.
- Possible future uses could include:
  - Heavy-duty diesel engines that currently use Ni-Superalloys (High Efficiency CRADA will examine this possibility)
  - Marine and EPG engines
  - Other high temperature engine platforms that experience high valve wear rates resulting from the ever increasing emissions regulations and need for higher power ratings
- The thermo-mechanical FEA analysis capabilities will be used to help predict maximum stresses and temperatures as a function of engine operating conditions and material properties

Patents and Publications/Presentations

Patents:

Sun, J.G., "Device and Nondestructive Method to Determine Subsurface Microstructure in Dense Materials," US Patent No. 7,042,556, issued May 9, 2006.

W.A. Ellingson, J. A. Todd, and J. G. Sun, "Optical Method and Apparatus for Detection of Defects and Microstructuring Changes in Ceramics and Ceramic Coatings," US Patent, No. 6285449, 2001

W. A. Ellingson and J. G. Sun, "Automated Real-Time Detection of Defects During Machining of Ceramics," U.S. Patent, No. 5689332, 1998

Publications/presentations:

J. G. Sun, J. M. Zhang, M. J. Andrews, J. S. Trethewey, N. S. L. Phillips, and J. A. Jensen, "Evaluation of Silicon-Nitride Ceramic Valves," paper to appear in Int. J. Appl. Ceram. Technol., 2008.

J. G. Sun, Z. P. Liu, Z. J. Pei, N. S. L. Phillips, and J. A. Jensen, Optical Methods for Nondestructive Evaluation of Subsurface Flaws in Silicon Nitride Ceramics," paper presented at the 32nd Int. Conf. & Exposition on Advanced Ceramics and Composites in Daytona Beach, FL, January 27-February 1, 2008.

N. S. L. Phillips, J. A. Jensen, M. J. Andrews, J. S. Tretheway, D. M. Longanbach, H. T. Lin, and J. G Sun, "Effect of Machining Procedures on the Strength of Ceramics for Diesel Engine Valves," abstract presented at the 13th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, Michigan, August 13-16, 2007.

J.G. Sun, J. S. Trethewey, N. Phillips, N. N. Vanderspiegel, and J. A. Jensen, "Nondestructive Evaluation of Silicon-Nitride Ceramic Valves from Engine Duration Test," in *Ceramic Eng. Sci. Proc*., eds. J. Salem, D. Zhu, and E. Lara-Curzio, Vol.28, no. 2, pp. 371-377, 2007.

J. G. Sun, J. M. Zhang, and J. S. Trethewey, "Nondestructive Evaluation of Machining and Engine-Test Damage in Silicon-Nitride Ceramic Valves," in *Ceramic Eng. Sci. Proc*., eds. A. Wereszczack and E. Lara-Curzio, Vol.27, no. 2, pp. 275-280, 2006.

Patents and Publications/Presentations

Publications/presentations (cont.):

J. M. Zhang, J. G. Sun, M. J. Andrews, A. Ramesh, J. S. Trethewey, and D. M. Longanbach, “Characterization of Subsurface defects in Ceramic Rods by Laser Scattering and Fractography,” in Review of Quantitative Nondestructive Evaluation, eds. D.O. Thompson and D.E. Chimenti, Vol. 25, pp. 1209-1216, 2006.

J. G. Sun, J. M. Zhang, J. S. Trethewey, J. A. Grassi, M. P. Fletcher, and M. J. Andrews, “Nondestructive Evaluation of Machining and Bench-Test Damage in Silicon-Nitride Ceramic Valves,” in Ceramic Eng. Sci. Proc., eds. D. Zhu and W.M. Kriven, Vol.26, Issue 2, pp. 127-132, 2005.

J. G. Sun, J. M. Zhang and M. J. Andrews “Laser Scattering Characterization of Subsurface Defect/Damage in Silicon-Nitride Ceramic Valves,” in Ceramic Engineering and Science Proceedings, Vol.25, no.4: pp307-12, 2004.

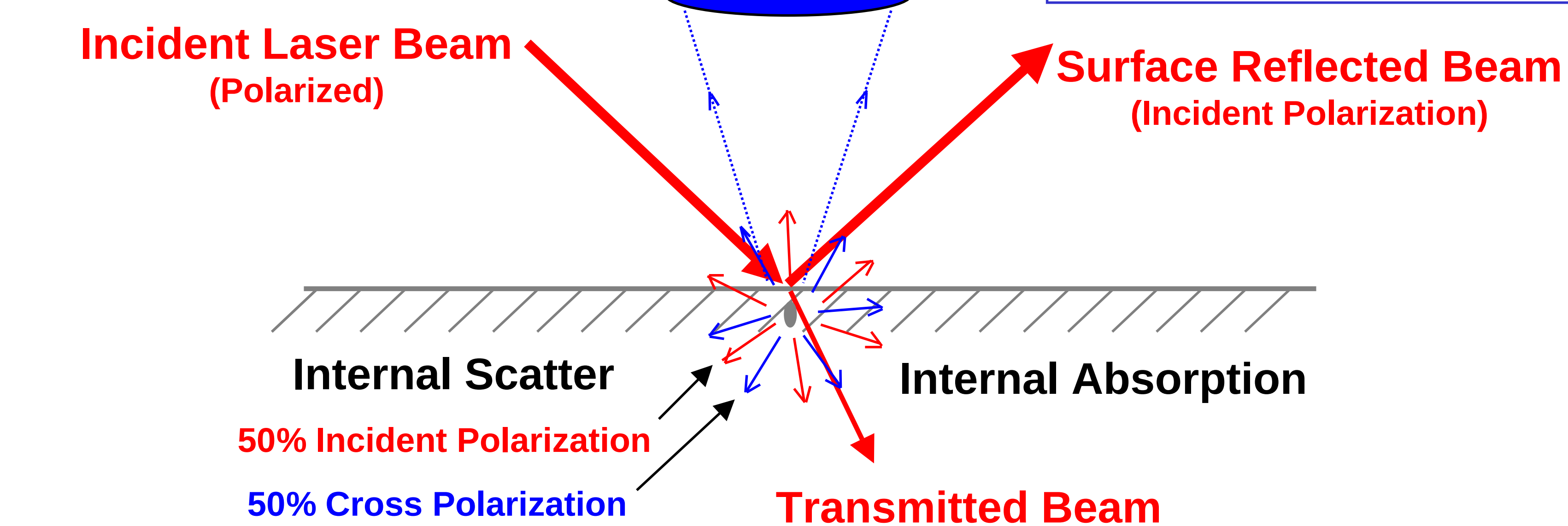
J. M. Zhang, J. G. Sun, and Z. J. Pei, “Designed Experimental Study on Set-Up Parameters of Laser Scattering System,” in Trans. North American Manufacturing Research Institution of SME, Vol. XXXI, pp. 563-570, 2003.

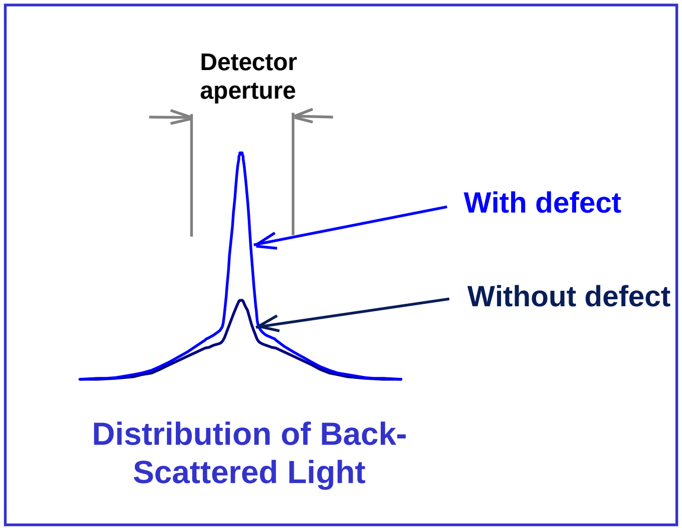
H.-T. Lin, T. Kirkland, A. A. Wereszczak, M. D. Kass, N. Domingo, and T. J. Theiss, “Design and Implementation of Silicon Nitride Valves for Heavy Duty Diesel Engines,” abstract presented at the 13th Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, Michigan, August 12-16, 2007.

H. T. Lin, T. P. Kirkland, A. A. Wereszczak, and M. J. Andrews, “Strength Retention of Silicon Nitride After Long-term Oil Immersion Exposure,” J. Mater. Sci. 41, 8313-8319 (2006).

Backup Slides

Physics of Cross-Polarization Detection of Optical Scattering from Subsurface Defects

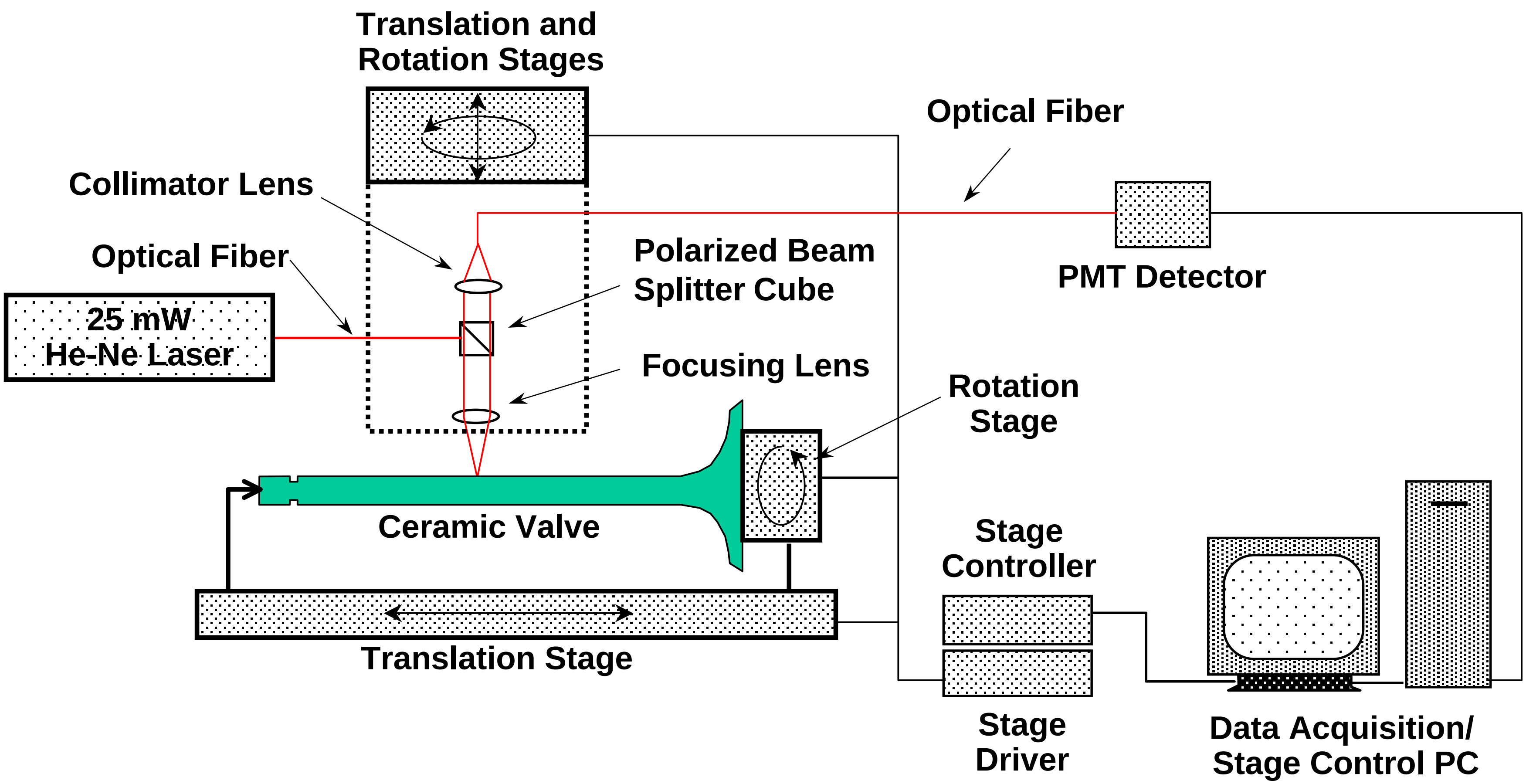




Physics of Cross-Polarization Detection of Optical Scattering from Subsurface Defects

- Incident laser light is linearly polarized (any light is composed of two linearly perpendicular-polarized components)
- Surface reflection/scatter has same polarization as incident; because the polarized detection optics ("object lens") is aligned in the cross-polarized direction relative to the incident, this light will not pass through the optics to the detector (in real setup, incident light is normal to the surface and the polarized optics consists of an object lens and a polarized beam splitter)
- Light transmitted into the material will interact with material microstructure so become depolarized, i.e., 50% in cross-polarized direction. When this light is backscattered out of surface, the cross-polarized component will pass through the polarized detection optics and be detected.
- Surface and subsurface defects increase local backscatter intensity
- Most defects that cause increased backscatter intensity in Si_3N_4 are porosity, void, crack, chip, etc
- Surface is raster scanned and measured backscatter intensity at all pixels are composed into a 2D "scatter intensity image"; defects and damages are shown as bright spots or lines
- Note: for TiAl material, no subsurface penetration is possible. But when surface breaking cracks exist or surface is too rough, light will be reflected/scattered several times within the surface topography before backscattered, so its polarization will change and is detected. In comparison, smooth surface causes only one reflection without polarization change.

Schematic of Automated Laser-Scattering System for Valve Scan



Laser beam maintains normally focused on the valve surface during entire scan