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Advanced Materials Technology

Lightweight Valve Train Materials

Presenter: Jeremy Trethewey
Sept 15, 2005

Lightweight Valve Train Materials Project #9128	PI: Jeremy Trethewey
Life Prediction for Diesel Engine Components Project #9110	PI: Dr. Hua-Tay Lin
Non-Destructive Evaluation of Diesel Components Project #9089	PI: Dr. Jiangang Sun

This presentation does not contain any proprietary or confidential information

Lightweight Valve Train Materials (Titanium)

21CTP

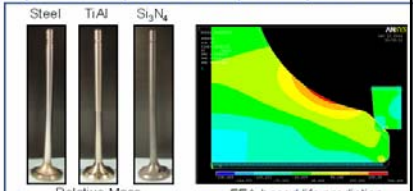
21CTP Technical Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

Project Objectives
(1) Design, procure and validate heavy duty TiAl and Si_3N_4 valves. (2) Develop life prediction tool to assist in component design with brittle materials.

FY 2005 Focus
Validation of valve performance on a Caterpillar G3406 engine platform at the National Transportation Research Center

Planned Duration
October 2001 to April 2007

DOE Funding/Industry Cost Share
FY04: $189K/$189K; FY05: $150K/$150K



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Accomplishments
(1) Designed and procured 12 TiAl and 45 Si_3N_4 heavy duty valves for G3406 engine platform – June 2005.
(2) Completed preliminary life prediction model using FEA-based NASA CARES/Life code – Jan 2005.

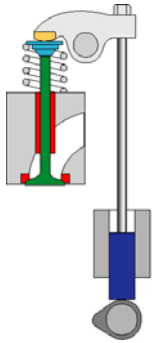
Significant Future Milestones
(1) Complete G3406 engine test and evaluate performance of advanced valves – Dec 2005.

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_9128	Materials Technology	HV Propulsion Materials	Applied Research	8-12-05

Technical Objectives

Program Motivation: Develop a lightweight valvetrain material that will improve engine efficiency and enhance engine performance.

- Improved Engine Efficiency
  - Lower density decreases reciprocating inertia enabling more efficient valvetrain operation with less frictional loss.
  - Enables operation in extreme combustion regimes (i.e. higher temperature, increased corrosive elements) leading to greater fuel efficiency.
  - Permits higher overspeed operation which allows more efficient engines to operate in more demanding regimes.
- Enhanced Durability
  - Drives towards longer service intervals, fewer replacement parts and lower maintenance costs.
  - Exploits high temperature mechanical properties and inert nature of ceramic & intermetallic materials.



Program Goal: Evaluate prospective lightweight valve materials and determine feasibility of implementation into a heavy duty diesel application.

Alignment with 21st CTP

From Heavy Vehicle Propulsion Materials Multi-Year Program Plan

"Materials for **durable valve train components** in advanced engines will be necessary in all classes of heavy-duty diesel engines."

"R&D is needed to **develop lightweight, wear-and corrosion-resistant** valve train materials . . ."

"Camless engine designs, if adopted, will need **high-speed valve actuators**."

"Cost-effective **manufacturing processes** are necessary for the widespread commercialization of stronger, higher-temperature corrosion-resistant materials . . ."

"There will be an increasing need to **simulate component performance** and life to avoid expensive engine testing."

Emphasis of "Lightweight Valve Train Materials" Program

1) Demonstrate on-engine performance advantages
2) Develop ceramic/intermetallic life prediction component design tool
3) Investigate machining process of ceramic/intermetallic materials

Development Partners

- Collaborative 21CTP programs
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
- Additional Collaborators
  - National Transportation Research Center
  - University of Wisconsin – Platteville
  - OEM Suppliers

Background

Over the past decade, the automotive engine industry has demonstrated moderate success with TiAl as a valve material . . .

- Demonstrated **2% fuel savings** on 25,000 km service on Chevrolet Corvette.
  - **GM/Howmet:** Maki, K., et al., "Development of a High-Performance TiAl Exhaust Valve," SAE Paper 960303, Warrendale, PA, 1996.
- Demonstrated **1000 rpm increase** in overspeed performance on Nissan VRT35 engine.
  - **Nissan/Daido:** Eylon D., et al., "Development of permanent-mold cast TiAl automotive valves," Intermetallics, 6, 1998.
- Successfully performed three types of rigorous automotive engine tests on five varieties of TiAl alloys.
  - **Edison Materials Technology Center:** Kim, Y.-W. et al., "Titanium Alumide Automotive Engine Valves," Gamma titanium aluminides, Warrendale, PA, 1995.

Background

Property	Units	Si_3N_4	TiAl	Ni-based
Density	g/cm^3	3.2	3.8	8.3
Young's Modulus	GPa	310	172	214
Yield Strength	MPa	520	629	696
Elongation	%	~0.1	0.7	5.0
Fracture Toughness	$MPa*mm^{1/2}$	186	412	2340
CTE	$x10^{-6}/°C$	2.8	10.3	11.6

Note: All data was collected at room temp

Sources:
- Internal test results
- Supplier information database
- ASM Materials Information Handbook Online
- High Temperature Aluminides and Intermetallics; Ed. Whang, Liu, Pope & Stiegler; Minerals, Metals and Materials Society, 1989

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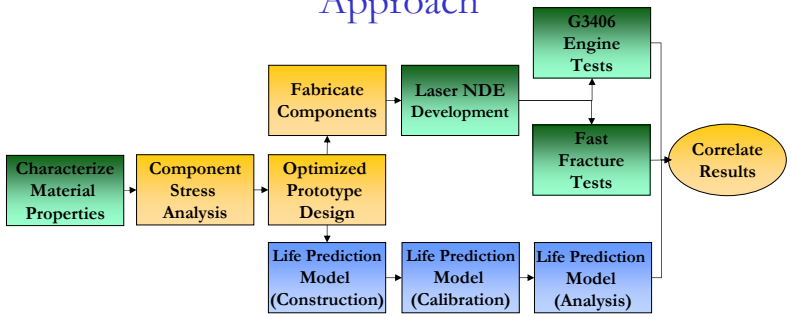
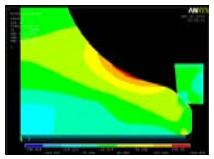
Approach




FEA stress analysis

Fabricate valves

Engine test validation

Life Prediction for Diesel Engine Components

21CTP Technical Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

Project Objectives

Characterization and design methodology development (life prediction) for advanced Si_3N_4 ceramics and TiAl alloys in order to manufacture consistent and reliable complex-shaped components for diesel engine applications.

FY 2005 Focus

1) Evaluation of mechanical properties and microstructure characterization of NT551 Si_3N_4 valves and valve stems after 500h bench rig test. 2) Mechanical database for co-processed SN235P Si_3N_4 valve material. 3) Valve field test preparations.

Planned Duration

October 2001 to September 2006

DOE Funding/Industry Cost Share

FY04: $100K; FY05: $95K

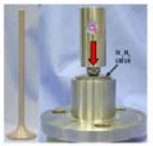


Figure 1. Photo of NT551 valve after 500h test and valve mechanical testing fixture.

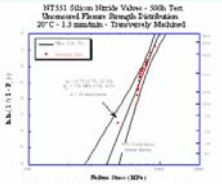


Figure 2. Strength distribution of 500h-tested Norton NT551 Si_3N_4 valve transversely machined and tested at 20°C.

Principal Investigator(s)

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Accomplishments

- Completed evaluation of mechanical properties and microstructure characterization of NT551 Si_3N_4 valves and valve stems after 500h bench rig test
- Completed mechanical properties validation for SN235P Si_3N_4 co-processed with exhaust valves in as-machined and after 1000h oil immersion test

Significant Future Milestones

- Complete mechanical properties and microstructure characterization of SN235P valves after engine field test. Sept. 2006
- Complete stress rupture database for TiAl alloy at elevated temperatures. Sept. 2006

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_9110	Materials Technology	HV Propulsion Materials	Applied Research	8-12-05

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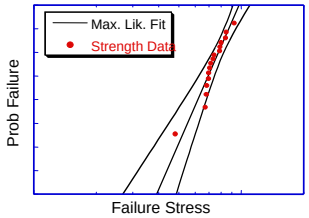
Si_3N_4 machining study

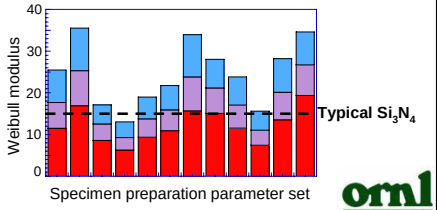
Task Objective: Optimize strength / Weibull modulus of Si_3N_4 bend bars by tuning machining parameters.

4 Pt. Bend test at ORNL



Machining parameter optimization

- Rough machining process
- Finishing machining process
- Machining parameters
  - Feed Rate
  - Rotational Rate



ornl

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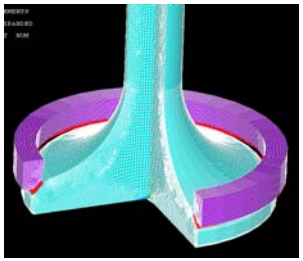
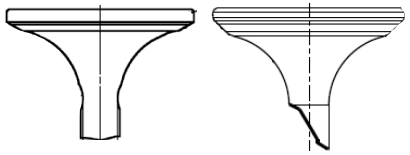
Design Iterations

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



Component Stress Analysis



Valve Design Optimization

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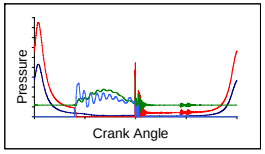
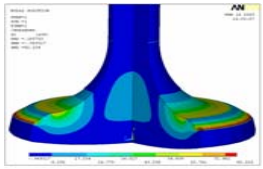
Life Prediction Modeling

Introduction

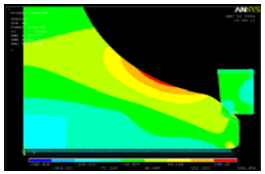
Task Objective: Develop FEA-based life prediction model (CARES/Life) that will generate life prediction curves for advanced valve materials.



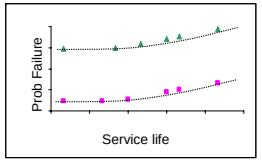
Thermo-mechanical Bound. Cond.



Thermal Stress Evaluation



Contact Stress Evaluation



Life Prediction Curve

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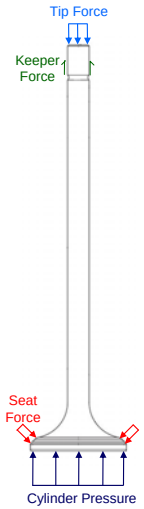
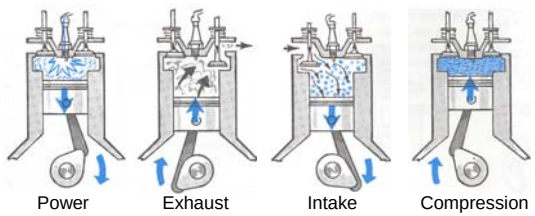
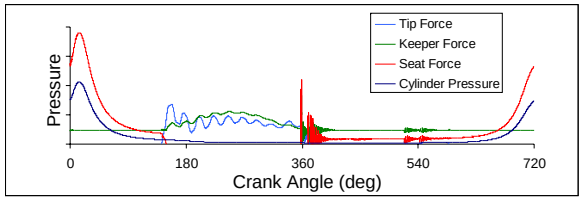
Life Prediction Modeling

Boundary Conditions







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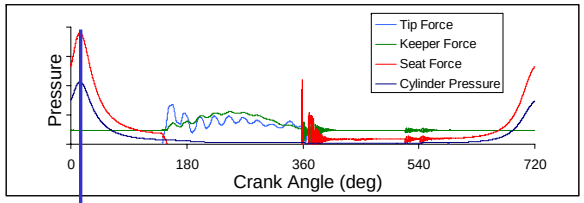
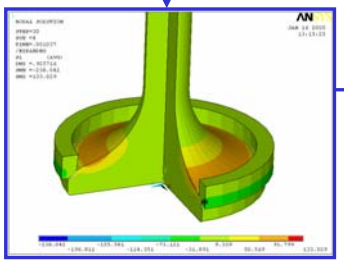
Life Prediction Modeling

Stress Analysis





Transient Reliability Analysis Procedure

1) Calculate probability of failure at a single time step (i.e. crank angle)
2) Step through discretize load profile
3) Valve will accumulate damage through load cycles
4) Failure mode: Slow crack growth

Life Prediction Curve

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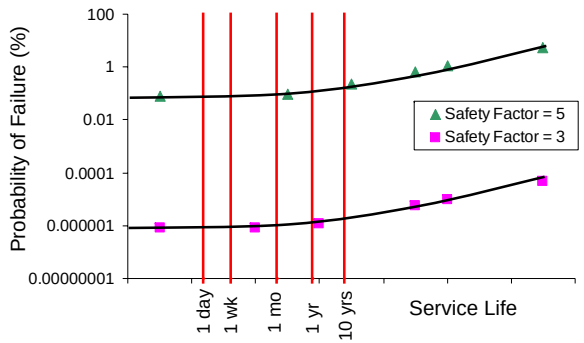
Life Prediction Modeling

Life Prediction Curve

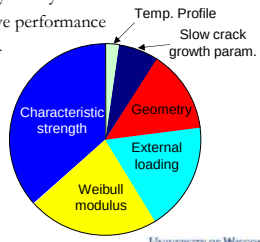


- This life prediction curve demonstrates the model's capabilities
- However, using more realistic boundary conditions will yield more realistic service life predictions

Life Prediction Modeling

Next Steps

- Refine loading conditions (3D vs. axisymmetric)
  - More realistic modeling of engine environment
  - Adding more deformation modes should increase probability of failure
- Extend model to include TiAl
  - TiAl may follow 3-parameter Weibull distribution*
  - Will require gathering TiAl mechanical properties
- Perform Probabilistic Design System (PDS) reliability analysis
  - Determines which parameters have the largest impact on valve performance
    - material properties, boundary conditions, machining quality, etc.
  - Will focus design effort to address these parameters



* Biery et al., "Use of Weibull Statistics to Quantify Property Variability in TiAl Alloys," **Metallurgical and Materials Transactions A**, Vol 33A, p. 3127-3136, Oct 2002.

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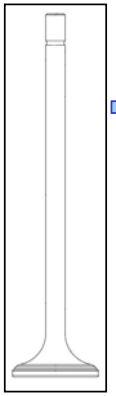
Valve Fabrication

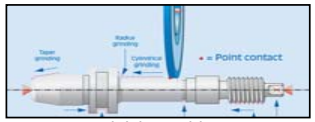
Task Objective: Fabricate valves using optimized geometry and machining parameters.



Design Drawing

Cast blanks

Join head to stem



Finish machine

Completed valve

NDE of Diesel Components

21CTP

21CTP Technical Goal: Develop and demonstrate an emissions compliant engine system for Class 7-8 highway trucks that improves the engine system efficiency from ~42% today to 50% by 2010.

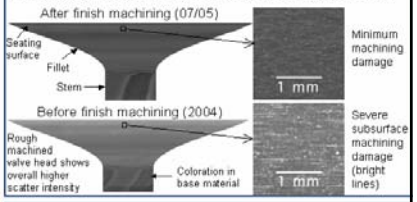
Project Objectives
Develop NDE methods to detect defect/damage in diesel components made from advanced materials

FY 2005 Focus
Develop fast and reliable laser-scatter NDE systems for characterization of ceramic and intermetallic valves being validated in engine duration tests

Planned Duration
October 2001 to September 2007

DOE Funding/Industry Cost Share
FY04: $200; FY05: $175K

Laser Scatter Images of SN235P Natural Gas Inlet Valve #8



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Accomplishments
Six times (6X) increase in scan speed for a laser-scatter system that allows for fast NDE inspection of large number of valves to meet tight engine test schedule (03/05)

Established detection sensitivity for fracture initiation flaws in cylindrical Si_3N_4 specimens machined at various conditions (05/05)

Significant Future Milestones
Complete NDE evaluation of accumulated damage in prototype valves from engine duration tests (06/06)

Project ID/Agreement ID	Program Structure	Sub-Program Element	R&D Phase	Date
PM_9089	Materials Technology	HV Propulsion Materials	Applied Research	8-12-05

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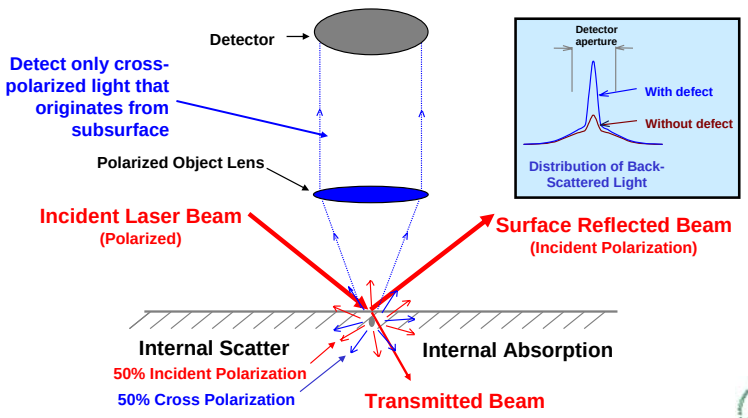
Laser Scatter NDE

Fundamental Physics

Task Objective: Develop novel NDE technique to evaluate integrity of ceramic and intermetallic components.



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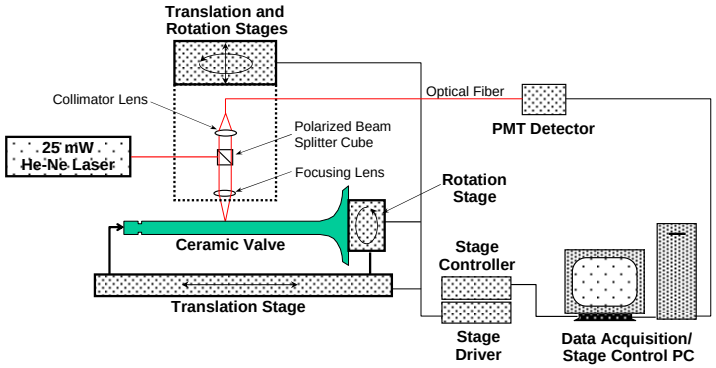
Laser Scatter NDE

Experimental Schematic



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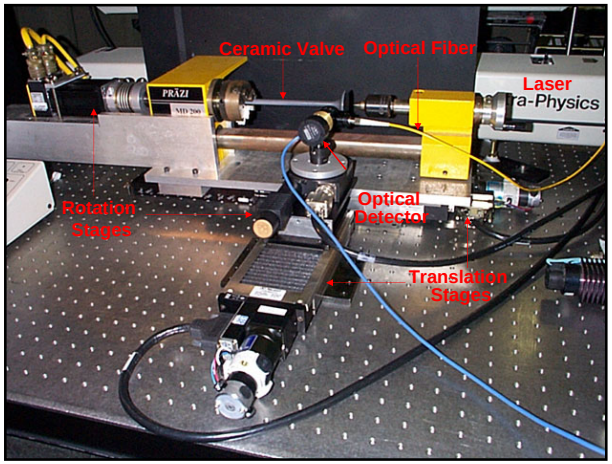
Laser Scatter NDE

Experimental Setup



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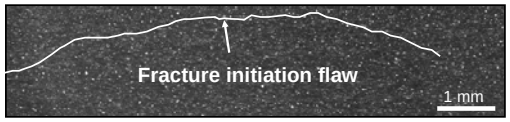
Laser Scatter NDE

Ceramic Bend Specimens

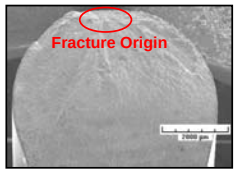
Before Fracture

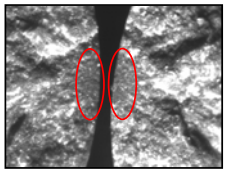
Laser-scatter image shows defect pattern



Fracture Event

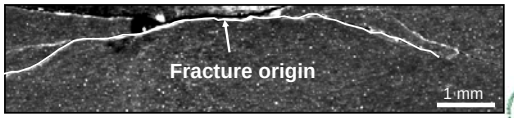
SEM images clearly show fracture origin





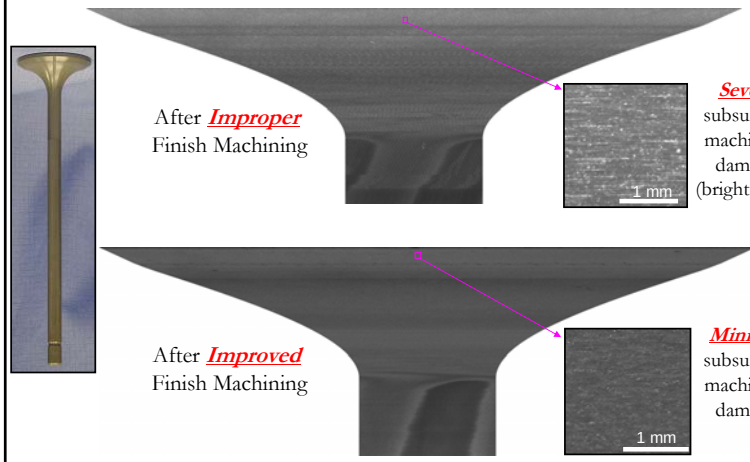
After Fracture

Photomicrograph reveals location of fracture origin



Laser Scatter NDE

Si_3N_4 Intake Valve



After ***Improper*** Finish Machining

Severe subsurface machining damage (bright lines)

After ***Improved*** Finish Machining

Minimal subsurface machining damage

Engine Test

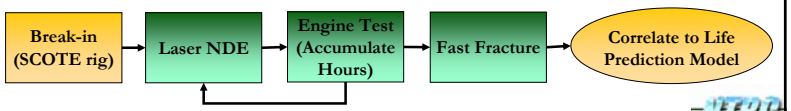
Task Objective: Subject valves to engine environment; evaluate valve wear and effect on engine performance.

Valves will accumulate 0 hrs. – 1000 hrs. on a Caterpillar G3406 Generator Set at the National Transportation Research Center:

- 1800 rpm
- 12.77 bar bmep
- λ = 0.99-1.09

Caterpillar G3406 GenSet

	Fractured at 0h	Fractured at 500h	Fractured at 1000h
Si_3N_4	7	8	8
TiAl	4	4	3



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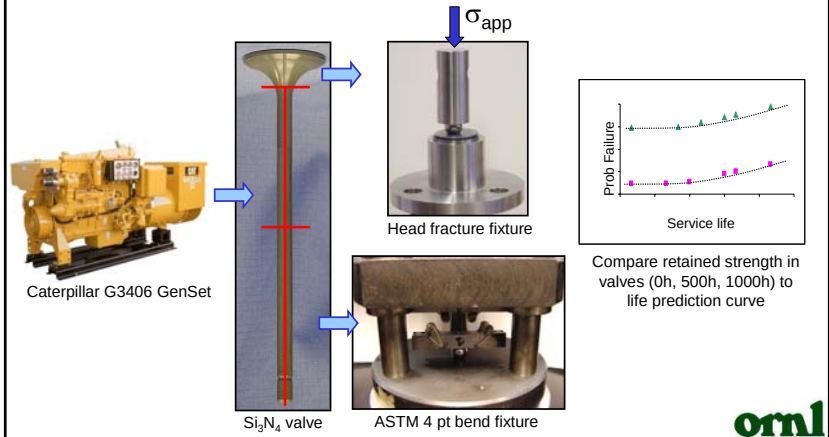
Fast Fracture Tests

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



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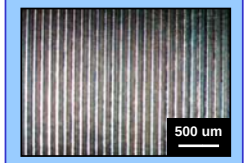
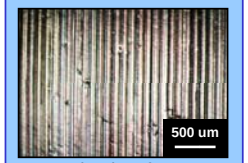
Related Investigations

TiAl machining & fast fracture study

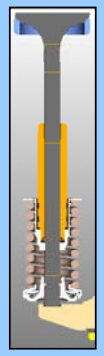


"Good" turned surface



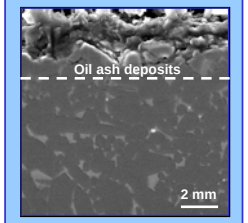
Pitted surface

Friction & wear study



Examine friction & wear at contact interfaces

Corrosion study



Observe penetration of corrosive elements

Technology Transfer

Two potential commercialization pathways . . .

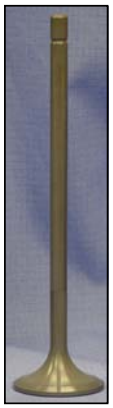
- Interest in immediate application to improve life in current field engines
- Line of sight for 2010 implementation in advanced combustion engine (HD truck) pending successful validation and cost effectiveness

Future Work

- Remainder of 2005
  - Complete Round #1 engine test on Si_3N_4 and TiAl valves
    - Perform engine test on G3406 at NTRC
    - Perform NDE evaluation at ANL
    - Perform fast fracture tests at ORNL-HTML
    - Correlate engine performance results to life prediction analysis
- Planned work in 2006
  - Perform Round #2 engine test on TiAl valves
    - Utilize life prediction model as design tool to further optimize valve geometry
  - Perform machining/fatigue test on TiAl specimens
  - Extend friction, wear and corrosion studies on TiAl
  - Work with suppliers to drive down cost of TiAl material
  - Design, material and process considerations

Conclusions

Addressing all 3 "principal barriers" presented in Heavy Vehicle Propulsion Materials Multi-Year Program Plan . . .



A. Performance

- Execute engine test on heavy duty Si_3N_4 and TiAl valves
- Verify durability/reliability of advanced materials by developing life prediction model
- Expand material property database to enable design optimization

B. Manufacturability

- Optimizing machining parameters with respect to (1) Part Quality (2) Cost and (3) Throughput
- Investigating novel NDE techniques as quality inspection metric

C. Cost

- Working with suppliers to drive down cost of TiAl

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(Any Questions?)

Patents & Publications

- Argonne National Laboratory Patents:
  - Sun, J.G., "Device and Nondestructive Method to Determine Subsurface Microstructure in Dense Materials," Invention Report ANL-IN-02-086, DOE Case No. S-101,670, US patent filed in Dec. 2003
  - 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. 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," presented at the 32nd Annual Review of Progress in Quantitative Nondestructive Evaluation, Bowdoin College, Brunswick, Maine, July 31- August 5, 2005 and paper to be published in conference proceedings.
  - 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," paper presented at the American Ceramic Society's 29th Ann. Intl. Cocoa Beach Conf. & Exposition on Advanced Ceramics & Composites, Cocoa Beach, FL, Jan. 23-28, 2005, and to be published in conference proceedings.
  - J. G. Sun, J. M. Zhang and M. J. Andrews "Laser Scattering Characterization of Subsurface Defect/Damage in Silicon-Nitride Ceramic Valves," paper presented at the 28th Ann. Cocoa Beach Conf. & Exposition on Advanced Ceramics & Composites, Cocoa Beach, FL, Jan. 25-30, 2004, and published 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," paper presented at the North American Manufacturing Research Conf., NAMRC Thirty-One, Hamilton, Ontario, Canada, May 20-23, 2003, and published in Trans. North American Manufacturing Research Institution of SME, Vol. XXXI, pp. 563-570, 2003.