Exhaust Valve Materials for High Efficiency Engines

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5/14/2013

Project ID # PM047

This presentation does not contain any proprietary or confidential information

Overview

Timeline

- Project start: March 2005
- Project end: June 2013
- Percent complete: 99.0%

Budget

- Total project funding Received
  - DOE 100%
- Funding Received in FY12: $225k
- Funding Received for FY13: $0k

Barriers

Barriers Addressed

- Changing internal combustion engine regimes
- Long lead-times for materials commercialization
- Cost

Targets

- Improve passenger vehicle fuel economy by 25%
- Improve commercial vehicle engine efficiency at least 20%

Partners

- Lead: ORNL

Interactions/Discussions with:

- Eaton – Manufacturer of valves
- Carpenter Technologies- Materials Supplier

Relevance and Objectives

- ***Improvements in engine efficiency*** alone have the potential to increase passenger vehicle fuel economy by 25 to 40 percent and commercial vehicle fuel economy by 30 percent with a concomitant reduction in carbon dioxide emissions
- Certain **higher performance engines** need higher temperature-capable valve materials due to increased exhaust gas temperatures, higher exhaust flow rates, higher cylinder pressures, and/or modified valve timings (target temperatures are exceeding current 760^{o}C with the potential to reach 1000^{o}C)
- There is a critical need to develop materials that meet projected operational performance parameters but meet ***cost constraints***
- **Objectives: Develop cost-effective exhaust valve materials suitable for operating at higher temperatures (870^{o}C vs. current 760^{o}C) for use in advanced engine concepts**
  - Test current exhaust valve material for fatigue performance at higher temperatures and compare performance with other suitable candidate materials
  - Develop new materials with high temperature stability and fatigue properties appropriate for operation at the higher temperatures based on fatigue data on commercial alloys

Milestones

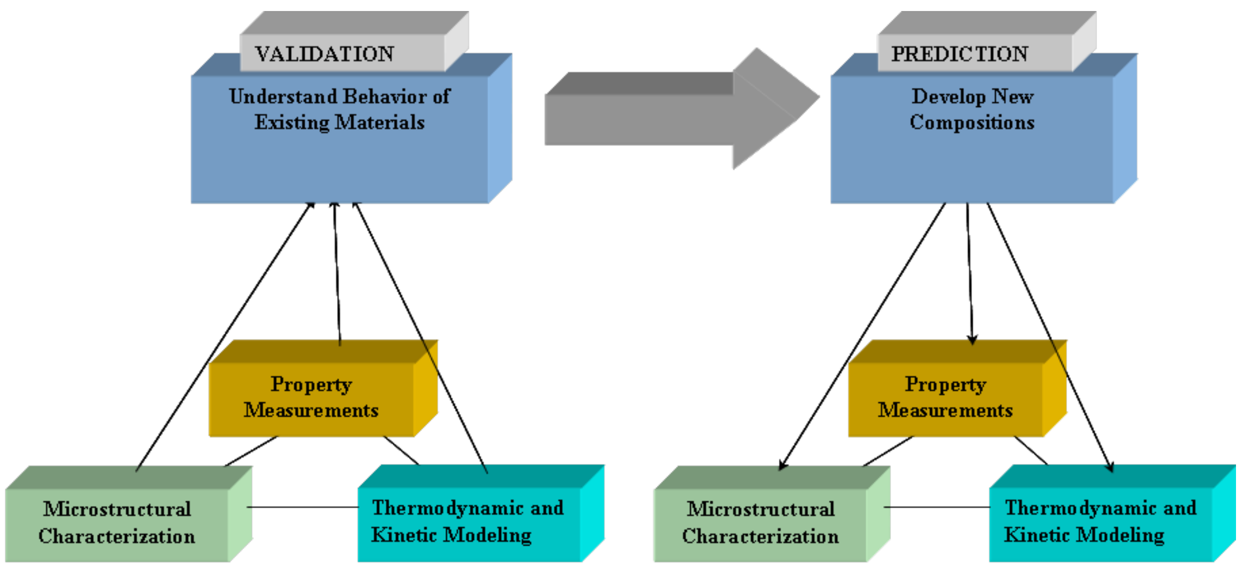
FY 2013

- **Complete rotating beam fatigue tests on at least two new alloys with the potential for improved fatigue properties at 870°C**
  - **Completed on time**
- **Complete microstructural characterization of new alloys to relate microstructure to improved high temperature strength**
  - **Completed on time**

Approach: Integrated Computational Materials Engineering (ICME) -Materials-By-Design

- Identify key material properties of interest for critical components
- Establish correlation between properties of interest and microstructural characteristics using existing alloys to identify desired microstructures for ICME
- Search composition space for alloys with desired microstructure and alloying element additions using validated ICME models

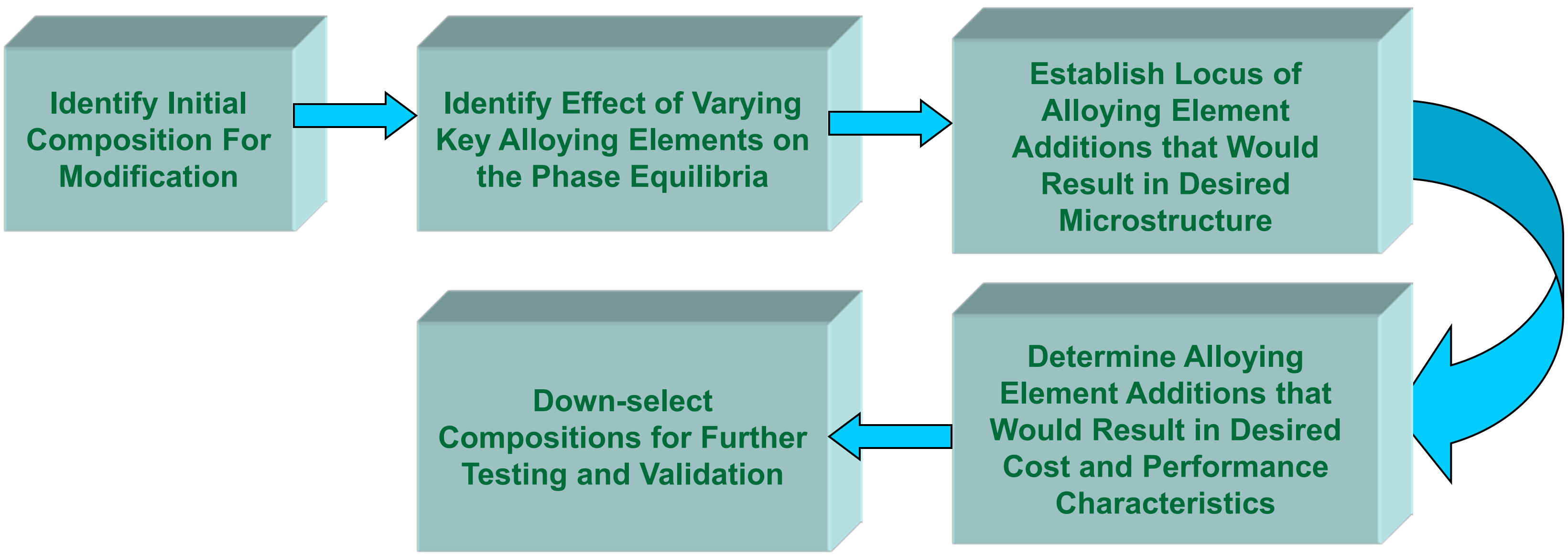
Validated ICME Models are Used to Predict New Alloy Compositions



Why are New Alloys Necessary?

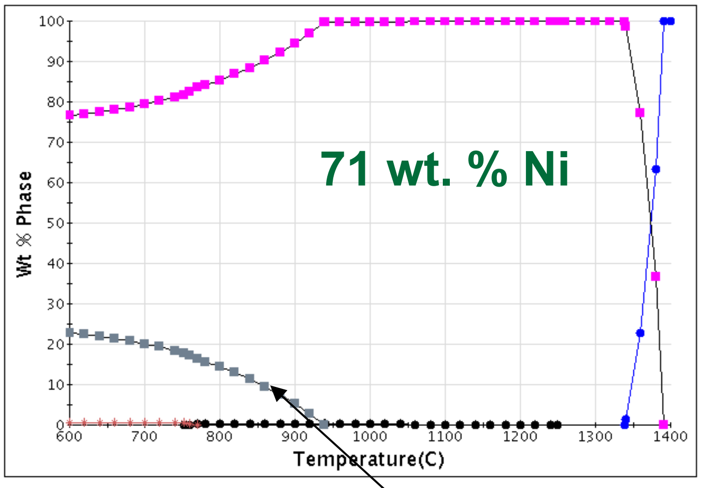
- **Current baseline commercial valve alloy 751** does not have the strength properties for operation at 870^{o}C
- Traditional Ni-based alloys used in aerospace applications are very expensive due to high Ni and other alloying element contents
- Strength requirements for Ni-based alloys for automotive valve applications are lower compared to aerospace applications
  - Target to achieve desired performance while reducing expensive alloying element additions such as Ni and Co
- **New alloys have been developed based on model microstructure of existing commercial alloys**
- **Target is to improve fatigue life at a temperature of 870^{o}C, 35Ksi stress while maintaining the lowest possible cost (lowest Ni additions)**
  - Commonly used exhaust valve alloy is Alloy 751 which has 71 wt.% Ni and a fatigue life of about 5x10^6 cycles under these conditions

Example ICME-Based Methodology For New Alloy Development

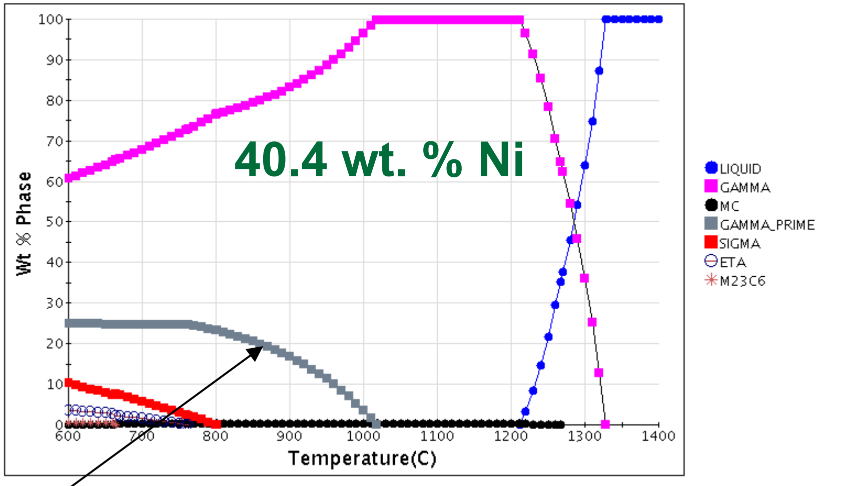


ICME models (computational thermodynamic/kinetic models) allow for rapid identification of new alloys with desired microstructure, and alloying element characteristics

Computational Thermodynamics Predictions are Used to Guide Alloy Development



Phase Equilibria Predicted in Existing Commercial Alloy: X751



Phase Equilibria Predicted in A New Generation I Alloy: HCCI-9

Primary Strengthening Phase (γ’) is Predicted to be Present in Larger Amounts in HCCI-9 at 870^{o}C

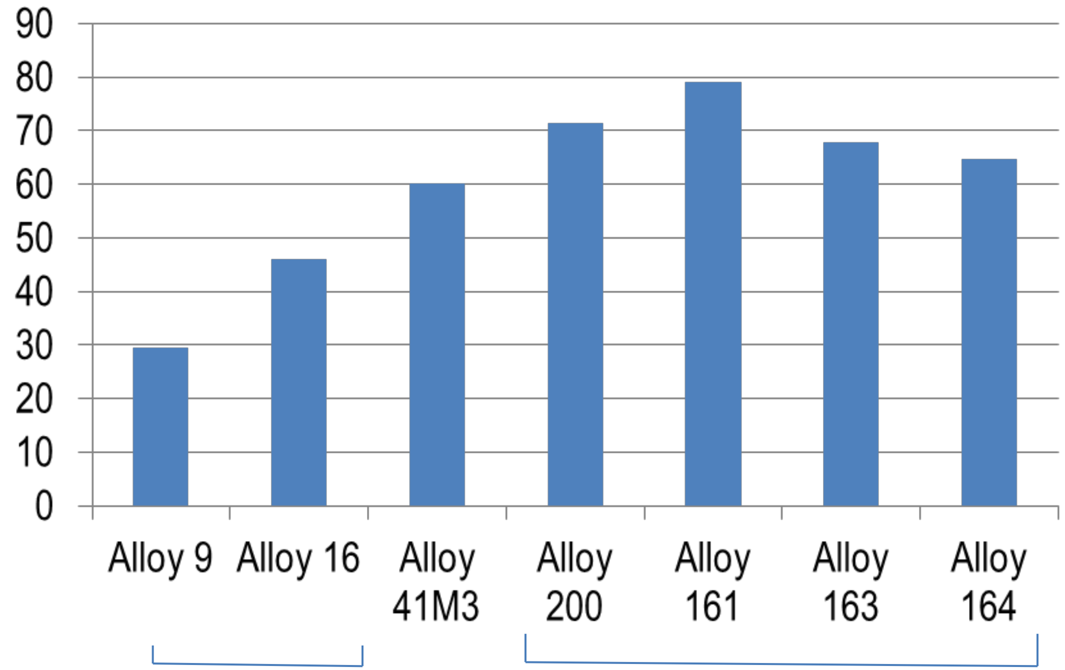
Phase equilibria predictions are used to estimate amount of strengthening phases (γ’ and carbides(MC and $M_{23}C_6$)) as a function of alloying element additions

Technical Accomplishments and Progress: Several New Generations of Alloys with Improved High Temperature Strength Have Been Developed

- Thermodynamic and kinetic modeling has been performed to correlate compositions with microstructure in selected commercial alloys
- Microstructural characterization has been carried out to verify specific computational predictions of microstructure
- High temperature fatigue properties using fully reversed fatigue tests have been obtained from alloys with well-defined compositions, heat-treatments, and microstructure
  - Desirable microstructures were identified
- Several commercial alloys with the desired microstructure have been identified and performance has been verified using rotating beam fatigue tests
- Several new alloys with lower Ni+Co contents with desirable microstructures have been designed and fabricated

New Alloys Developed Have Higher Strength at 870°C

% Improvement in Yield Strength Compared to Alloy 751



IN 751 ~71 Ni
Baseline
Cost

1st Generation ~30%-40% Lower cost

2nd Generation

3rd Generation ~25% lower cost

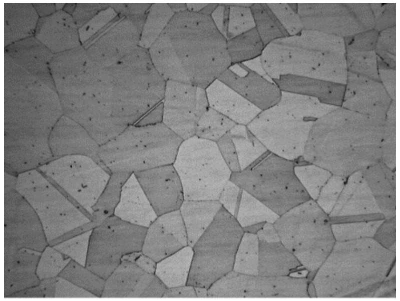
Yield Strengths of 3rd Generation of Alloys are 60-80% better than that of Alloy 751

Technical Accomplishments: Our New Alloys are Stronger and More Ductile Than Our Previous Generation Alloys

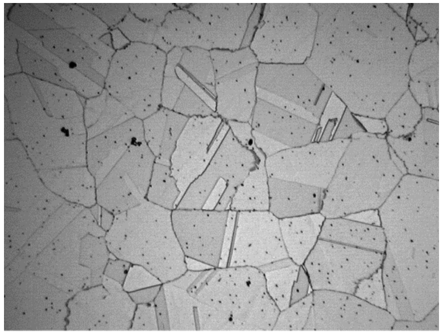
Commercial Alloy

Alloy 751
0.2% YS at 870°C= 49.1 Ksi
Plastic Strain at Break= 37.0%

Generation 1 ORNL Alloys

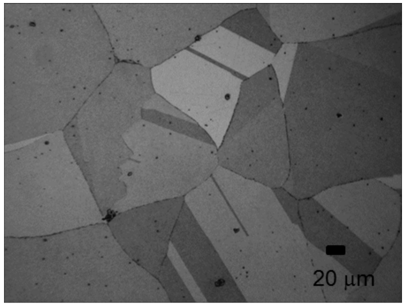


Alloy 9
0.2% YS at 870°C= 63.4 Ksi
Plastic Strain at Break= 0.35%



Alloy 16
0.2% YS at 870°C= 71.5 Ksi
Plastic Strain at Break= 2.26%

Generation 3 ORNL Alloy



Alloy 200
0.2% YS at 870°C= 74.2
Plastic Strain at Break= 5.1%

Etchant: Glyceregia

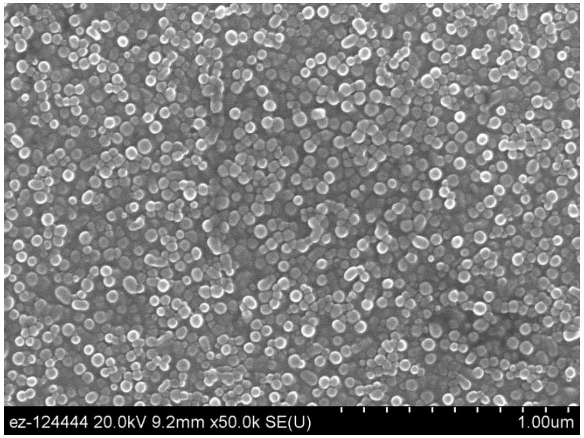
Yield strengths are comparable to commercial Ni-based alloys YS at 870°C= 40-80Ksi*

*L. M. Pike, Superalloys 2008, pp.191-200

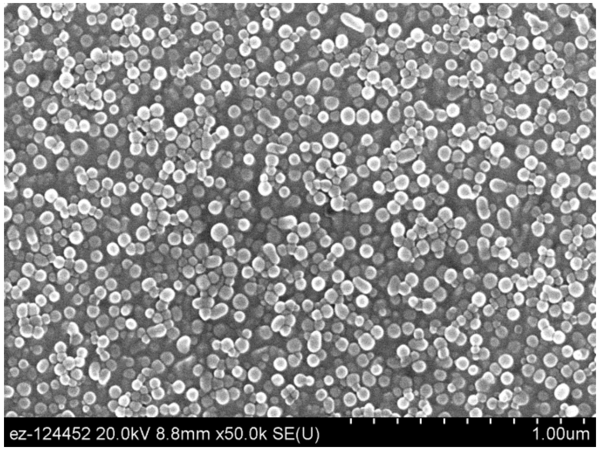
Technical Accomplishments: Several Larger Heats of Alloys Were Cast and Successfully Rolled into Plates For Specimen Machining

New alloys were successfully rolled to a length of over 8" required for fatigue tests (from an initial length of about 3.5").

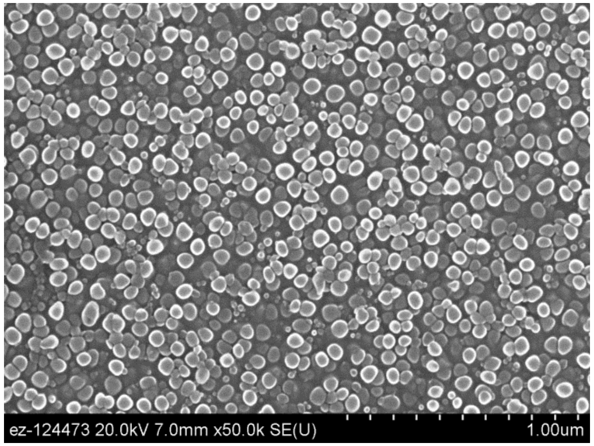
Technical Accomplishments: Scanning Electron Microscopy Shows Presence of Fine Strengthening Precipitates In Aged Condition



HCCI-41M3
Vickers Microhardness = 391.3



HCCI-200
Vickers Microhardness= 385.5



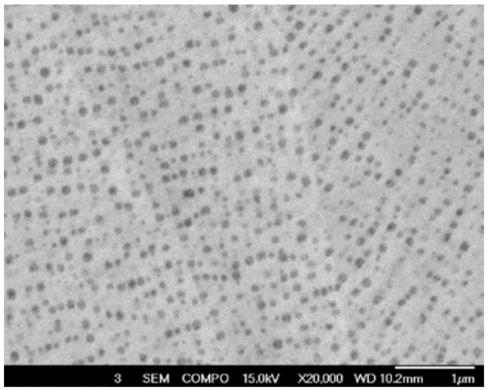
HCCI-162
Vickers Microhardness= 394.4

Etchant: Glyceregia

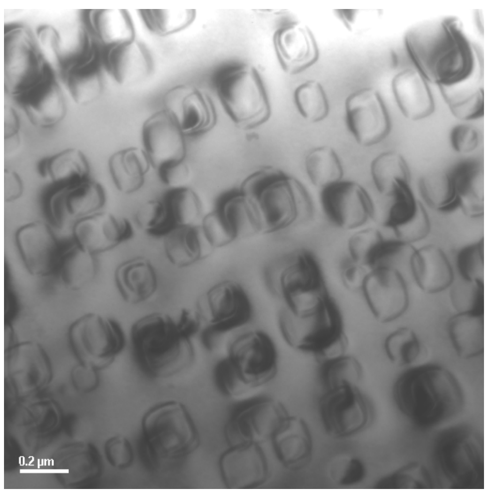
- Primary strengthening phase: γ' ($Ni_3(Al,X)$)

Technical Accomplishments: Aging at 870°C for 214 Hours Shows a Slightly Faster Reduction in Microhardness Values Compared to 751

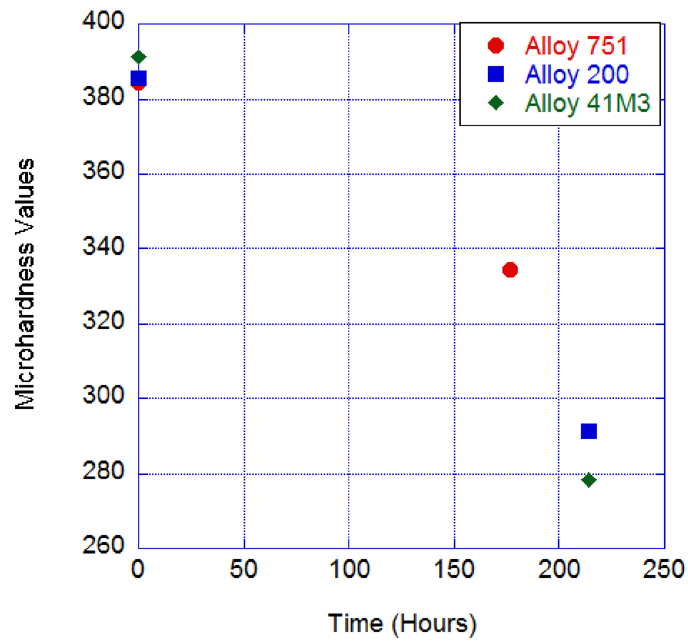
Alloy 751



37 Hours

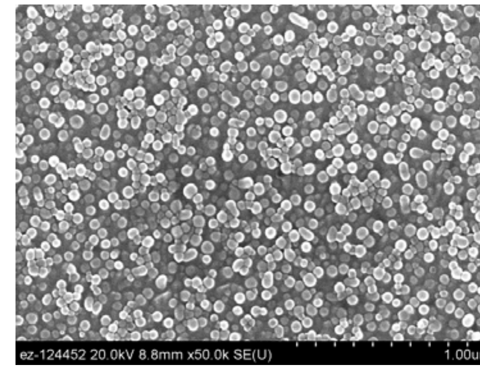


177 Hours

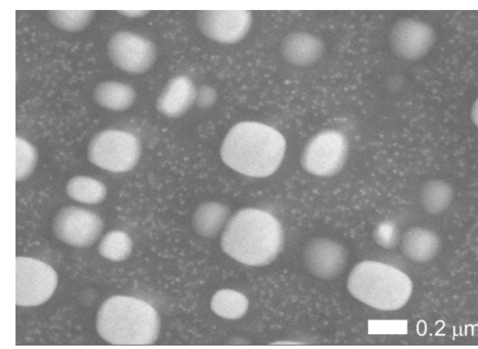


Faster coarsening kinetics of strengthening precipitate is likely responsible for faster reduction in microhardness values

ORNL Alloy 200

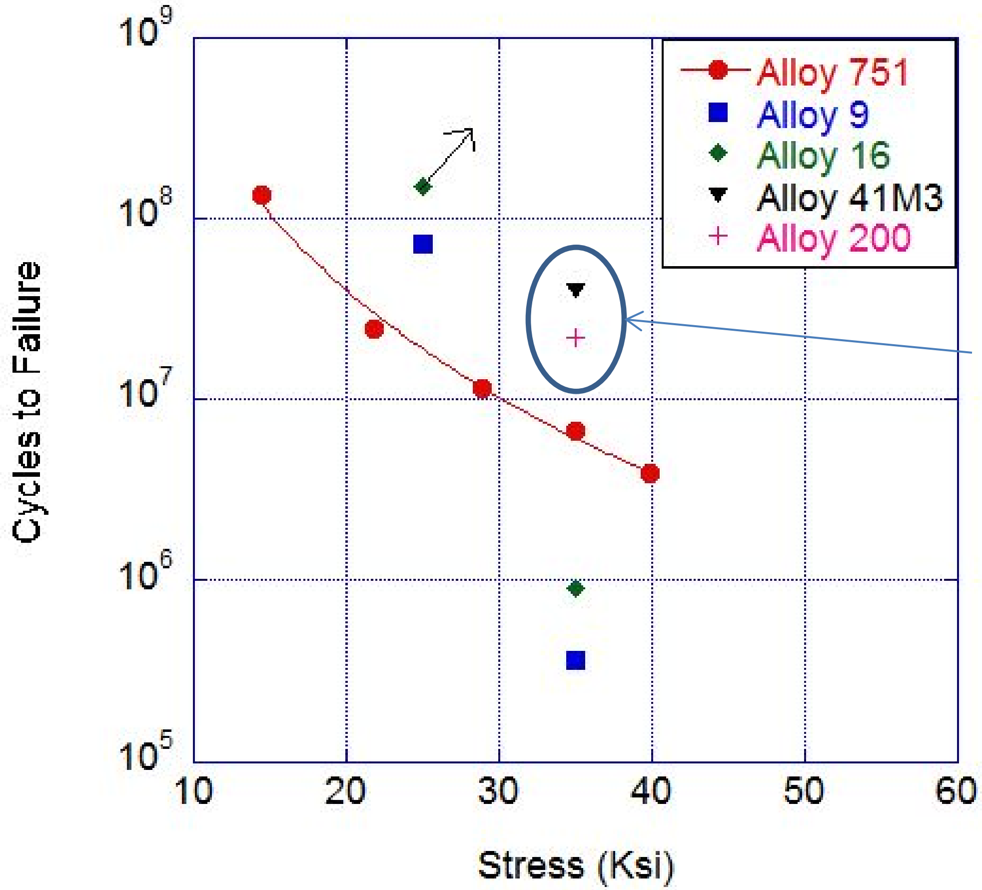


Initial, Aged



214 Hours

Rotating Beam Fatigue Tests Show Improved Properties of New Generation of Alloys



ORNL Alloys with Improved Properties at 35 Ksi (Gen. 2 & 3 Alloys)

↗ Indicates runout

Collaborations and Coordination with Other Institutions

- Exploratory conversations with Eaton Technologies (valve manufacturer) and Carpenter (materials supplier) have been held on potential paths for alloy commercialization
- Presentation about the new valves alloys was made to an automotive OEM who has expressed interest in exploring lower cost, higher-temperature capable valve alloys for the upcoming higher efficiency engines

Future Work

FY13

- Complete rotating beam fatigue fatigue tests on two additional ORNL alloys
- Complete the filing of patent applications and commercialize alloys

Summary

- Improvement in high temperature capability of exhaust valve materials is a key enabling technology for future advanced engine concepts with higher efficiencies
- Targets for improvement are the fatigue properties of exhaust valve materials at 870^{o}C with a future target of up to 1000^{o}C, and with improved performance/cost ratio
- New alloys with up to 80% increase in yield strength and with a potential 25% decrease in cost have been identified through ICME approaches, fabrication, and tensile testing
- Rotating beam fatigue tests confirm significantly improved properties of new alloys at 870^{o}C
- Two invention disclosures have been filed on the newly developed alloys