Materials for HCCI Engines

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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Overview

Timeline

- Project start: March 2005
- Project end: September 2010
- Percent complete: 70%

Budget

- Total project funding Received
  - DOE 100%
- Funding Received in
  FY08: $225k
  FY09: $105k

Barriers

- Barriers Addressed
  - A. Cost of CIDI engines
  - B. Efficiency of heavy truck engines
- Targets
  - CIDI Engine efficiency of 45% by 2010
  - Cost of $30/KW
  - Heavy duty engine efficiency of 55% by 2013
- Strategic goals addressed
  - Improve the efficiency of advanced vehicles through innovative materials solutions

Partners

- Lead: ORNL

Collaborators/Interactions

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

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
  - Identify materials (if any) with high temperature stability and fatigue properties appropriate for operation at the higher temperatures based on fatigue data obtained earlier

Milestones

FY2008

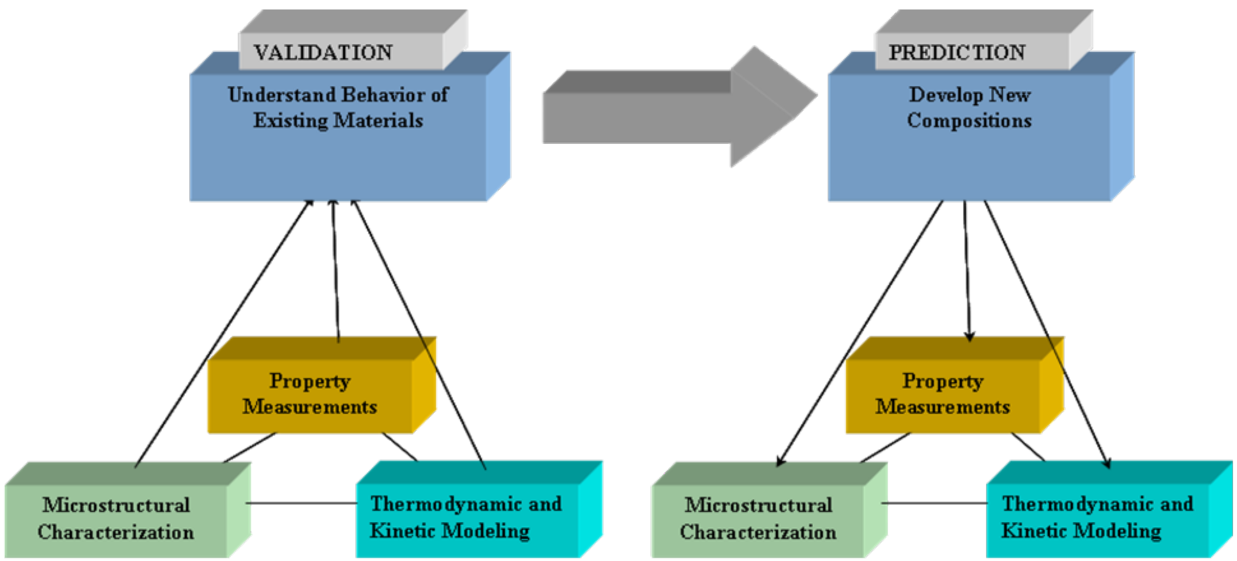
- Identify alloy composition/s that have the potential for appropriate performance in valve application at higher use temperatures **(9/08)**
  - Using fatigue tests on currently used alloys and other candidate alloys, several alloys with the potential for appropriate performance at higher temperatures have been identified (completed)

FY2009

- Develop material with appropriate performance/cost ratio for advanced engines using computational design approach (9/09)

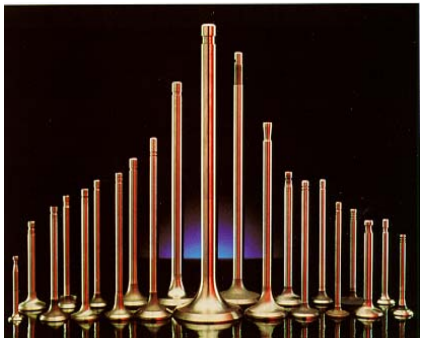
Approach

- Identify key material properties of interest for critical components
- Establish correlation between properties of interest and microstructural characteristics using existing alloys and identify desired microstructures
- Search composition space for alloys with desired microstructure and alloying element additions using validated computational models
- Reduce development time by selective testing of promising alloys with desired microstructure and cost



Technical Accomplishments: Identified Need for Valve Materials For High Temperature Applications

- Several components and corresponding materials issues were identified with help from industrial partners
  - Exhaust valves, exhaust manifolds, fuel injectors, air coolers



- Design/identification of advanced materials for exhaust valves was suggested as an area of high priority

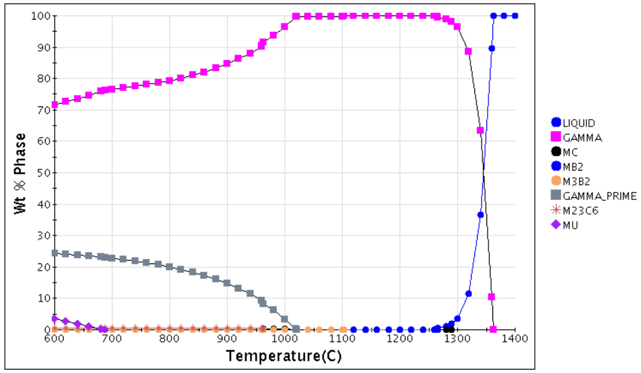
- Property of interest is improved fatigue life at 870^{o}C (from current 760^{o}C)
  - Desired: 10^8 cycles to failure in rotating beam fatigue tests at 35 Ksi

Summary Accomplishments/Progress/Results: Alloys with Potential to Perform at Higher Temperatures Have Been Identified

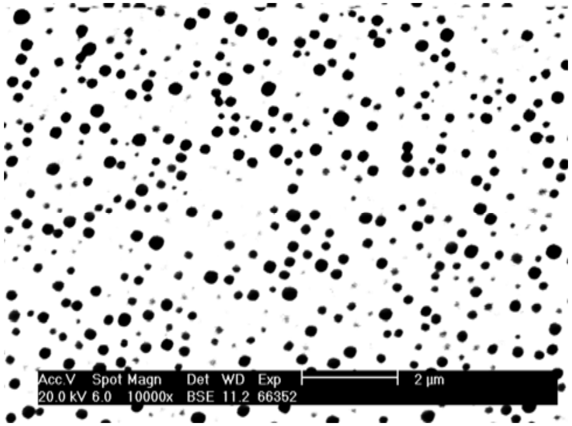
- Thermodynamic and kinetic modeling have been performed to correlate compositions with microstructure in selected alloys
- Microstructural characterization have been carried out to verify specific computational predictions
- High temperature fatigue properties using fully reversed fatigue tests have been obtained from alloys with well-defined compositions, heat-treatments, and microstructure
- Approximate relationship between rotating beam fatigue data (required by the industry) and fully reversed fatigue data has been developed
- Desired fatigue life in fully reversed fatigue tests has been quantified based on industrial requirements on rotating beam fatigue data
- Several commercial alloys with potential to perform under new service conditions have been identified

Selected Ni-based Alloys are Primarily Strengthened by γ' Precipitates

- Eight commercially available Ni-based alloys were down-selected (including IN 751 most popular current alloy)
- Selected Ni-base alloys are
  - austenitic
  - primarily strengthened by the precipitation of coherent intermetallic precipitates: γ'
  - Coarsening results in decrease in strength of alloys
  - Carbides (MC, $M_{23}C_6$) can also be present in alloys
  - Undesirable topological close packed phases (sigma, mu etc) may precipitate at certain temperatures



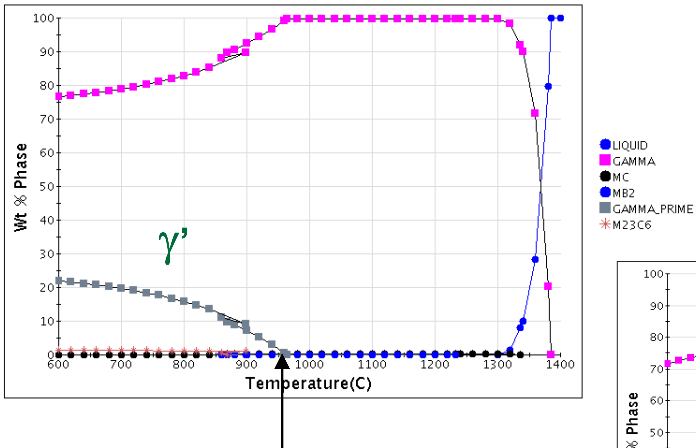
Waspaloy ®



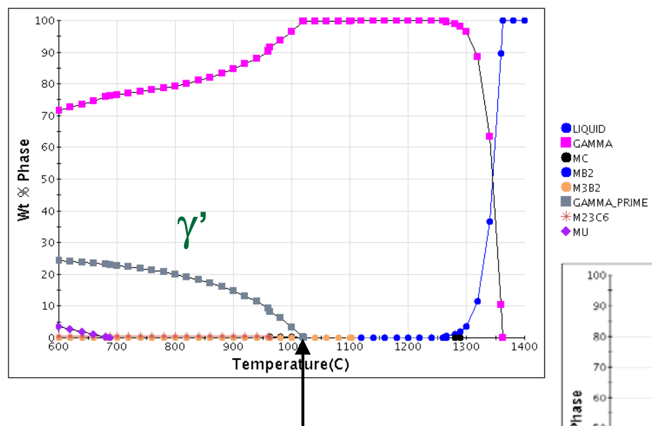
Back-scattered SEM Image showing γ' Precipitates

Computational Thermodynamic Modeling Predicts Correlation Between Composition and γ’ Contents

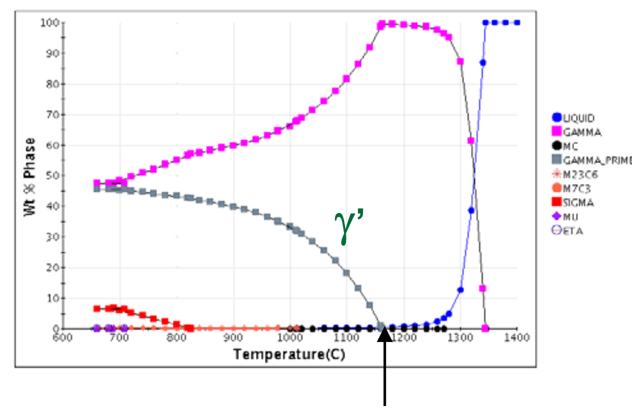
Nimonic ® 90



Waspaloy ®

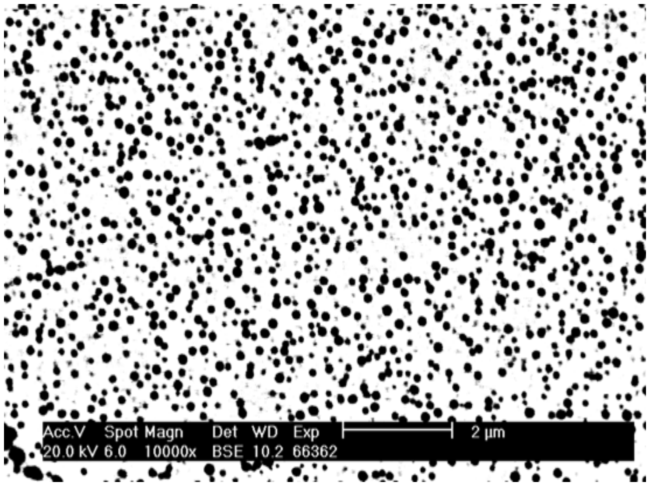


Udimet ® 720

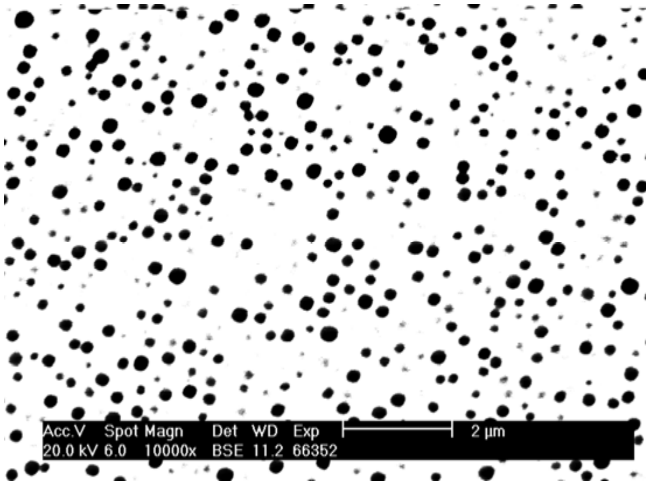


Amount of γ’ and highest temperature of stability of γ’ are affected by alloying element additions

Scanning Electron Microscopy is Used to Estimate the Volume Fraction of Precipitates (Example: Waspaloy®)



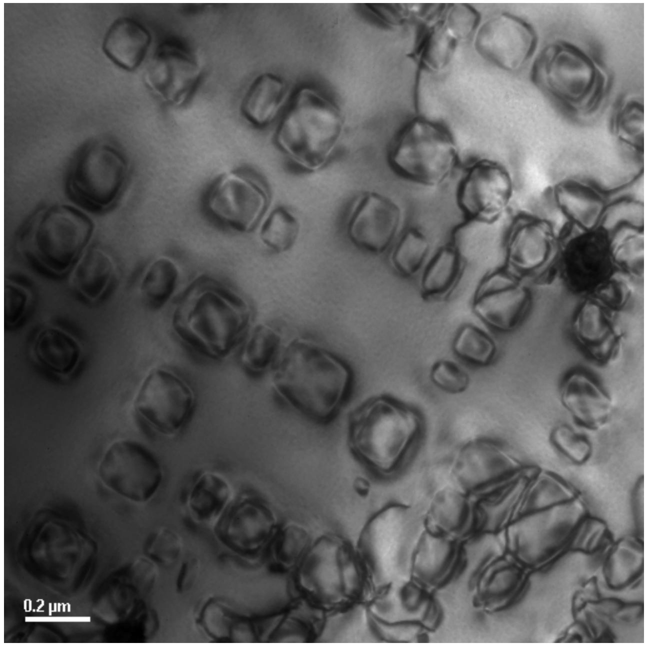
2.4 million cycles
Time: 22 hours
Average V_f=17.1%



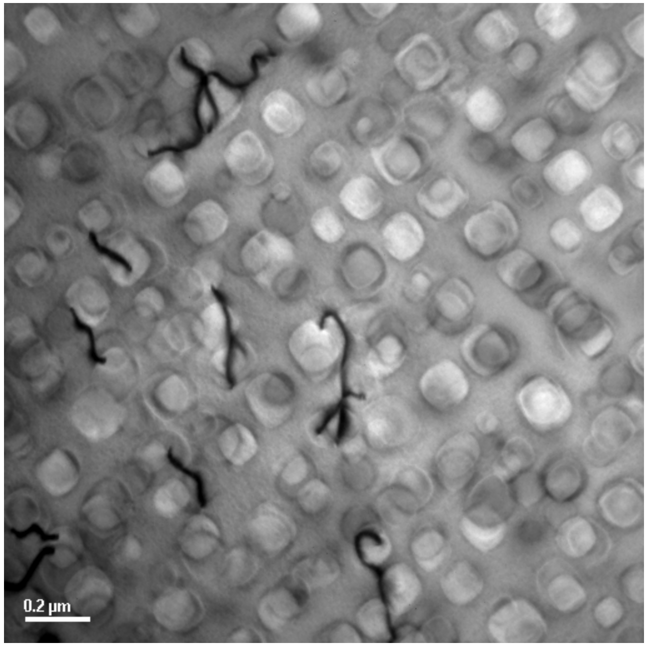
55 million cycles
Time: 509 Hours
Average V_f=17.1%

Reasonable agreement with predicted value of γ'= 16.7 wt.%

Transmission Electron Microscopy Allows Study of Size, Shape, and Distribution of Strengthening Precipitates



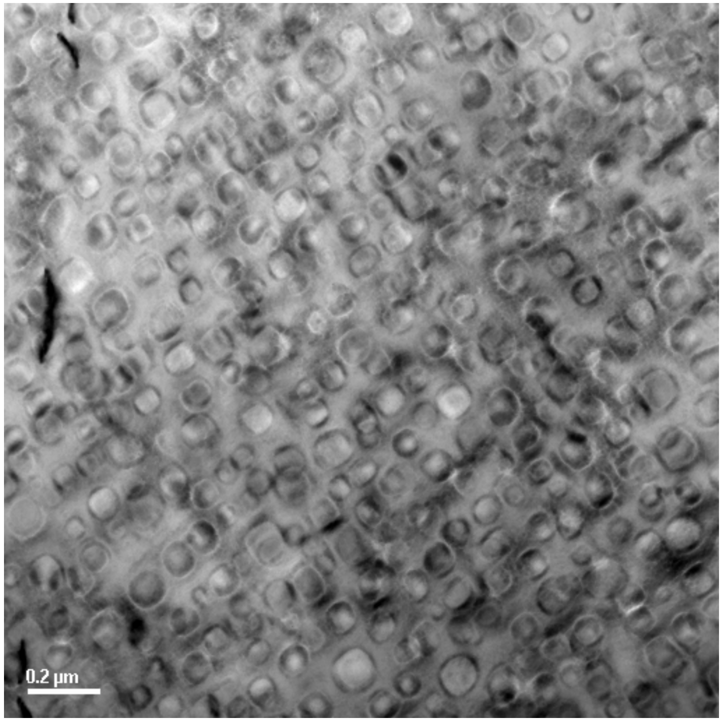
Nimonic® 90 (226 Hours)



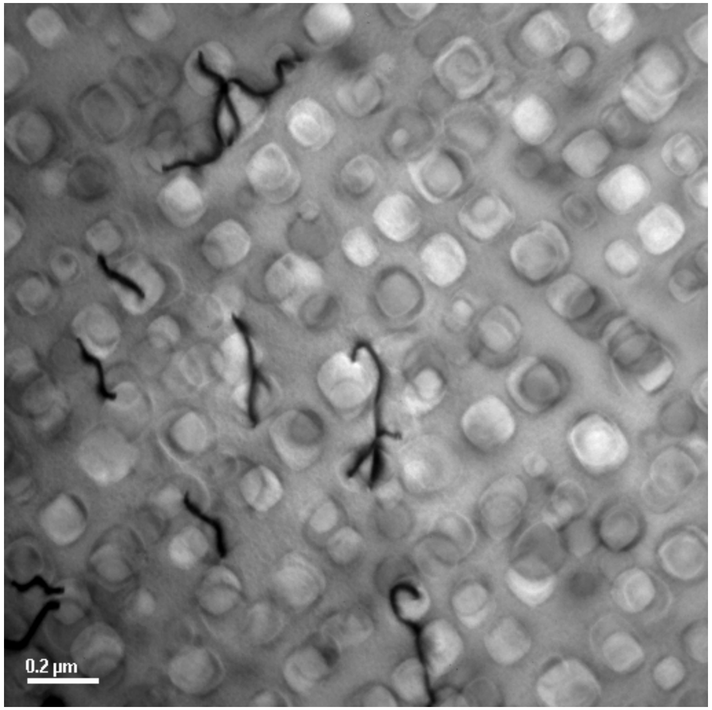
Udimet® 41 (181 Hours)

Calculations shows that Udimet® 41 should have a larger volume fraction of strengthening precipitates

Coarsening Kinetics of Precipitates Can be Measured Using TEM micrographs



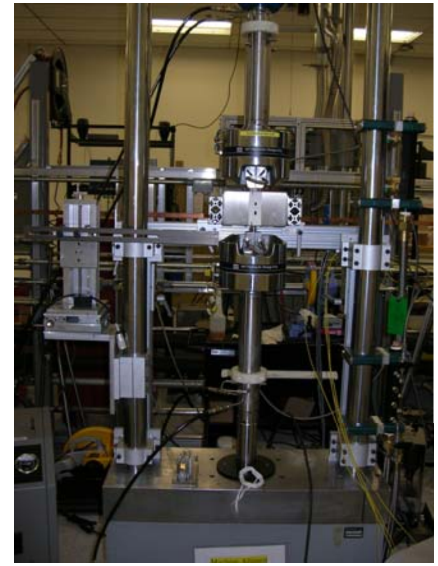
Udimet® 41 (27.2 hours)



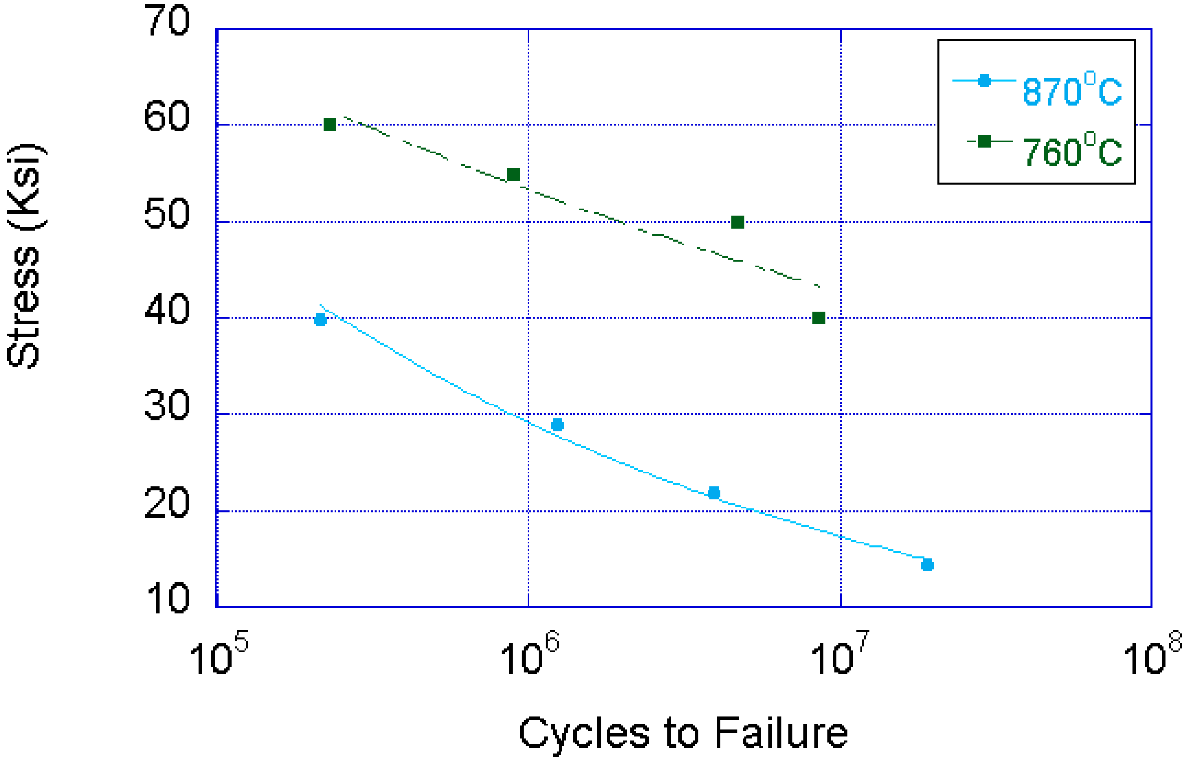
Udimet® 41 (181 hours)

Fully Reversed Fatigue Tests are Being Carried out *in-situ* at 870°C

- Two types of fatigue tests are relevant to the study of high cycle fatigue of valve materials
  - Uniaxial, fully reversed fatigue
  - Rotating beam fatigue
- Fully reversed fatigue tests are being carried out at ORNL at the temperature of interest under load control at a frequency of about 30 Hz
- Stresses used are:
  - 21.8 (150) Ksi (MPa),
  - 29 (200),
  - 39.9 (275),
  - 43.5(300),
  - 50.8(350),
  - 54.4(375)

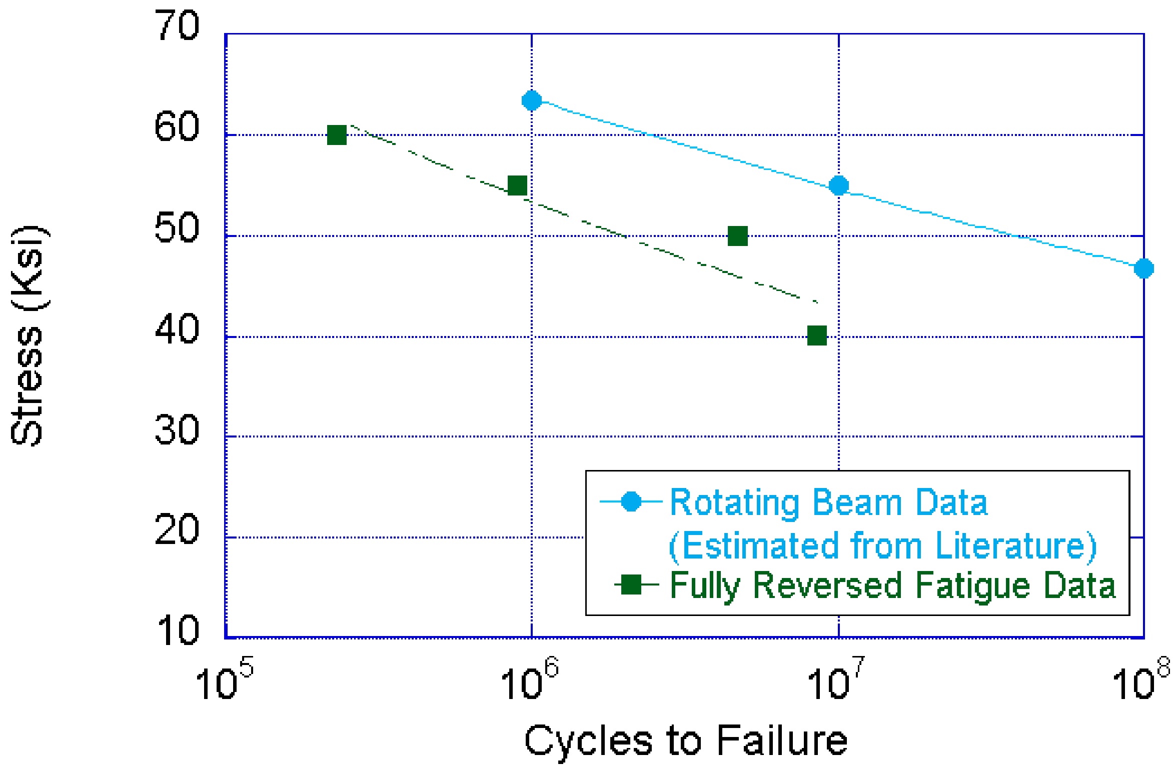


Fatigue Properties of IN 751 Have Been Measured at 760°C and 870°C using Fully Reversed Fatigue Tests



Fatigue properties of IN 751 at 760°C were measured using fully reversed fatigue tests to facilitate comparison with rotating beam data in literature and common in industrial practice

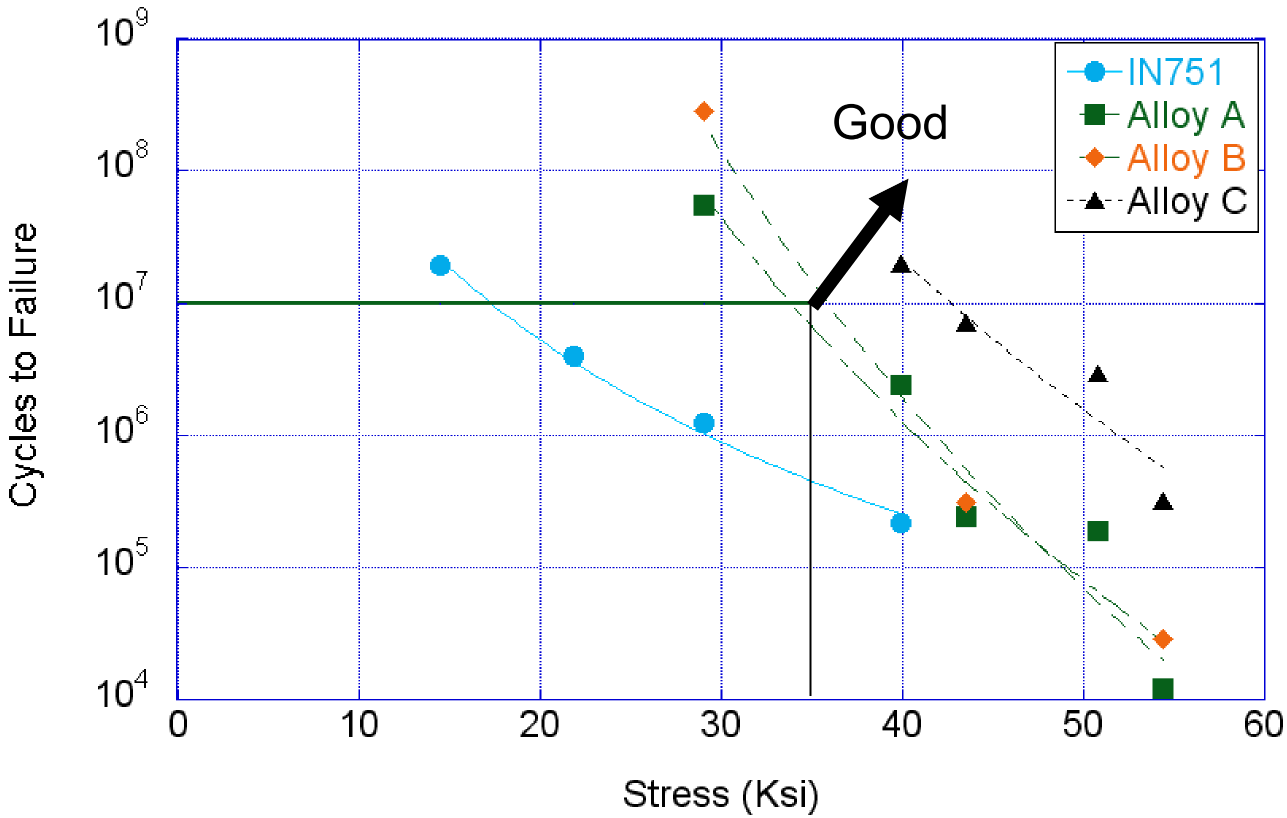
Fatigue Lives of IN751 at 760°C Measured Using Two Techniques Are Different



Conservative estimates show that cycles to failure in rotating beam data ~10 times life measured in fully reversed fatigue tests under the conditions used for testing at ORNL

*Literature data from US Patent # 6,372,181, M. G. Fahrmann, Gaylord D. Smith, INCO Alloys

Alloys with the Potential for Operation at Higher Temperatures Have Been Identified

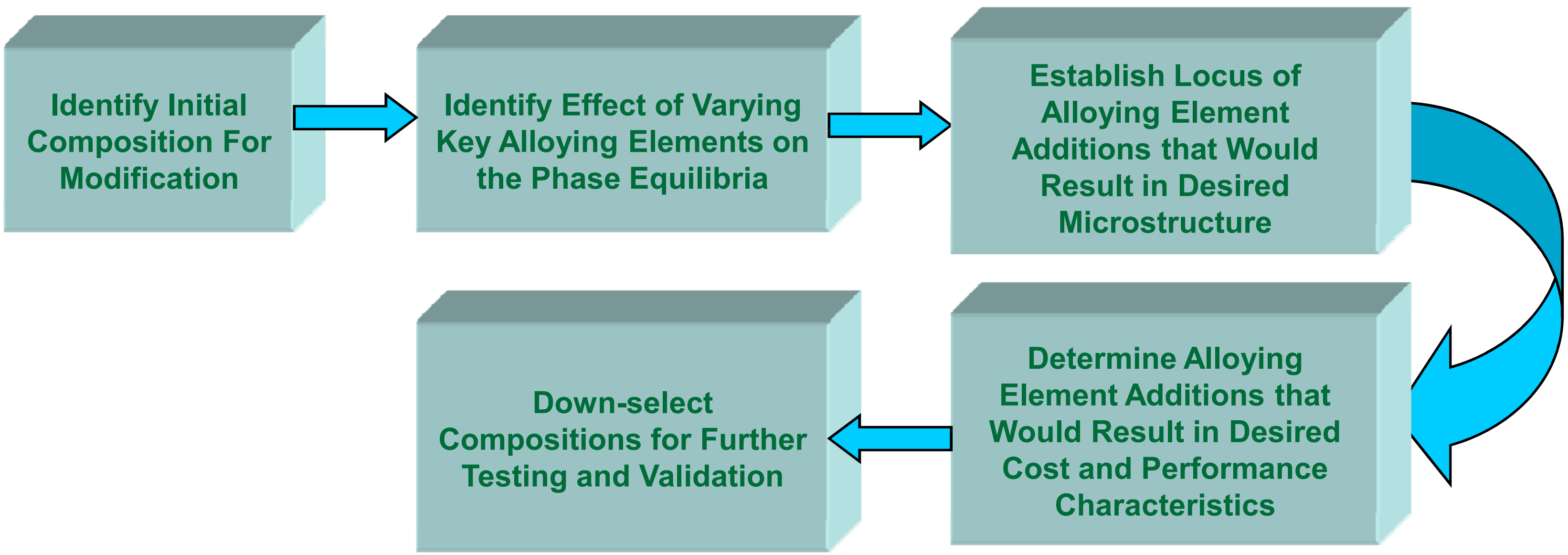


Alloys with minimum lifetime of 10^7 cycles to failure at 35 Ksi in fully reversed fatigue tests are potential candidates

Why are New Alloys Necessary?

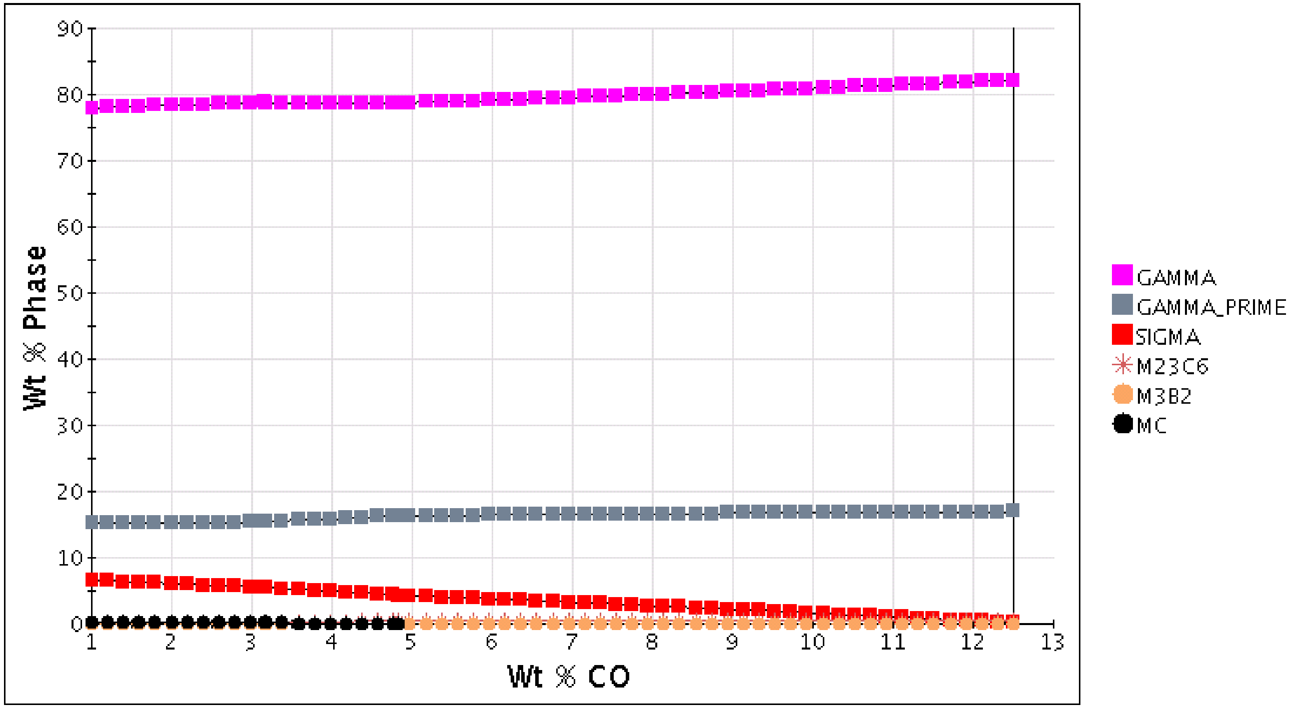
- New alloys may be required to
  - Achieve slightly improved performance when compared to existing alloys without must cost penalty or at decreased cost
  - Achieve desired performance with removal of strategic alloying element additions
  - Other factors such as processing ability are also important from manufacturing cost perspective
- Alloy development can be performed using existing alloys as a starting point

Example Methodology For New Alloy Development



Computational thermodynamic/kinetic modeling allows for rapid identification of new alloys with desired microstructure, and alloying element characteristics

Example Showing Effect of Replacing Iron with Cobalt on Phase Equilibria



T = 870.0C (Balance: FE)

Computational thermodynamic calculations using JMatPro show that replacement of iron with cobalt decreases amount of undesirable sigma phase (red square) at 870^{o}C

Status of Development of New Alloys

- Computational modeling is on-going along several schemes to identify new alloy compositions with comparable/better properties without cost penalties
- Alloy compositions identified as capable of operation at higher temperatures will be used as a basis to develop new alloys with improved performance/cost ratio
- Selected alloys will be prepared in small quantities and microstructures will be studied
- Refinement of alloy compositions will be performed based upon microstructural observations

Accomplishments: A New Rotating Beam System Has Been Installed

- Data obtained on new alloys can be readily compared with industry requirements
- Rotational Speeds up to 10000 rpm are possible

Future Work

FY09

- Verify fatigue performance of identified alloys at higher temperature using rotating beam tests
- Identify one most suitable commercial alloy for higher temperature valve applications
- Develop one new alloy using computational modeling techniques with the potential for improved performance/cost ratio
- Prepare laboratory sized quantity of alloy and evaluate high temperature properties

FY10

- Complete rotating beam fatigue and/or fully reversed fatigue tests as required on new alloy
- Prepare appropriate sized heat of THE BEST suited alloy for testing in actual/simulated application

Summary

- Improvement in high temperature capability of exhaust valve materials is an enabler for future advanced engine concepts
- Targets for improvement are the fatigue properties and performance/cost ratio of exhaust valve materials at 870^{o}C
- Correlations have been established between microstructure and fatigue properties
- Several alloys with potential for improved performance at the higher temperature have been identified and hypotheses regarding performance are being verified
- New alloy with improved performance/cost ratio will be developed using computational modeling techniques