Alloy Development for High-Performance Cast Crankshafts

PI: John Hryn

Presenter: Dileep Singh

Argonne National Laboratory

June 19, 2014

Argonne Research Team:

C. Chuang, D. Singh, J. Hryn, P. Kenesei, and J. Almer

Vehicle Technologies – Annual Merit Review

Project ID: PM058

Sponsored by US Department of Energy

Overview

Timeline

- Project start March 2014
- Project end March 2017
- 5% complete

Budget

- FY14-17 = $300 K (DOE)

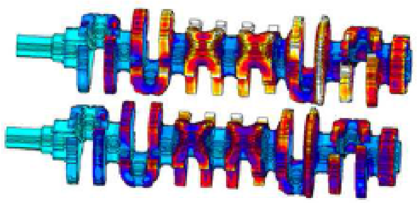
Barriers

- Performance: Meet or exceed the performance of current forged crankshafts. (as-cast UTS > 800MPa, YS > 615MPa)
- Life: Material and process must achieve local ultra-high cycle fatigue requirements of current baseline
- Cost: no more than 110% of production cast units

Project Partners

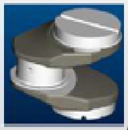
- Caterpillar, Inc. – Lead
- Argonne National Laboratory
- General Motors
- Northwestern University
- University of Iowa

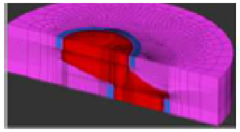
Project Team (Partners)

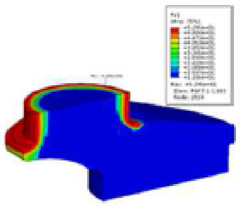


GM
- Material and Process Development
- Material Characterization
- ICME
- Design Optimization
- Concept Design Cost Model

CATERPILLAR®
- Material and Process Development
- Material Characterization
- ICME
- Design Optimization
- Concept Design Cost Model



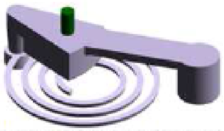




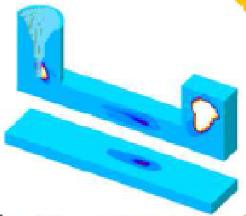
Hardness

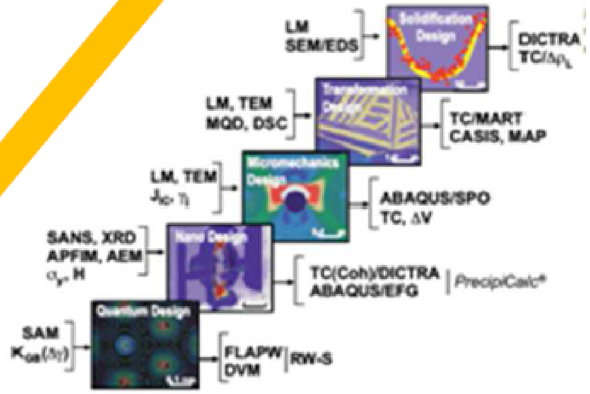
THE UNIVERSITY OF IOWA
- Casting Process Development
- Experimental Casting Samples
- Castability Evaluation (Fluidity, Hot Tear, Porosity)

NORTHWESTERN UNIVERSITY
- Computational Material Design
- Solidification Design
- Transformation Design
- Nano Design
- Material Characterization



Fluidity Spiral Test Casting





Argonne NATIONAL LABORATORY
- Material Evaluation using Advanced Photon Source (APS) X-Ray and MTS Testing Machine
- In-Situ Microstructure and Damage Measurements

Relevance

- Use of high strength steels can contribute to about 10% weight reduction as compared to mild steel. This can translate to about 6-7% improvement in fuel economy for a midsize sedan.
- Combining the casting process and the stiffness advantage of steel will allow the weight reduction potential to be maximized without sacrificing performance.
- Current forged crankshafts require machining post forging that adds to the cost. Cast steel crankshafts would not require additional machining costs.
- Implementing the technology developed in this project will provide US with energy security, while lowering costs and reducing impacts on the environment.

Objectives

- Overall project goal is to develop cast steel alloy(s) and processing techniques that are tailored for high performance crankshafts to achieve target as-cast properties of 800 MPa ultimate tensile strength and 615 MPa yield strength. This alloy will be a replacement for expensive forgings, without exceeding the cost target of 110% of the current production cast units.

- Effort at ANL will focus on several activities to support the project goals:
  - Utilize high-energy x-ray imaging and diffraction techniques to correlate microstructure/phases/defects in the alloy(s) with processing parameters. The results will be used to optimize design and processing of alloy compositions to achieve target properties.
  - Conduct in situ fatigue test to establish the durability requirements for high-performance gasoline and diesel engine applications which currently use forged crankshafts.

Milestones

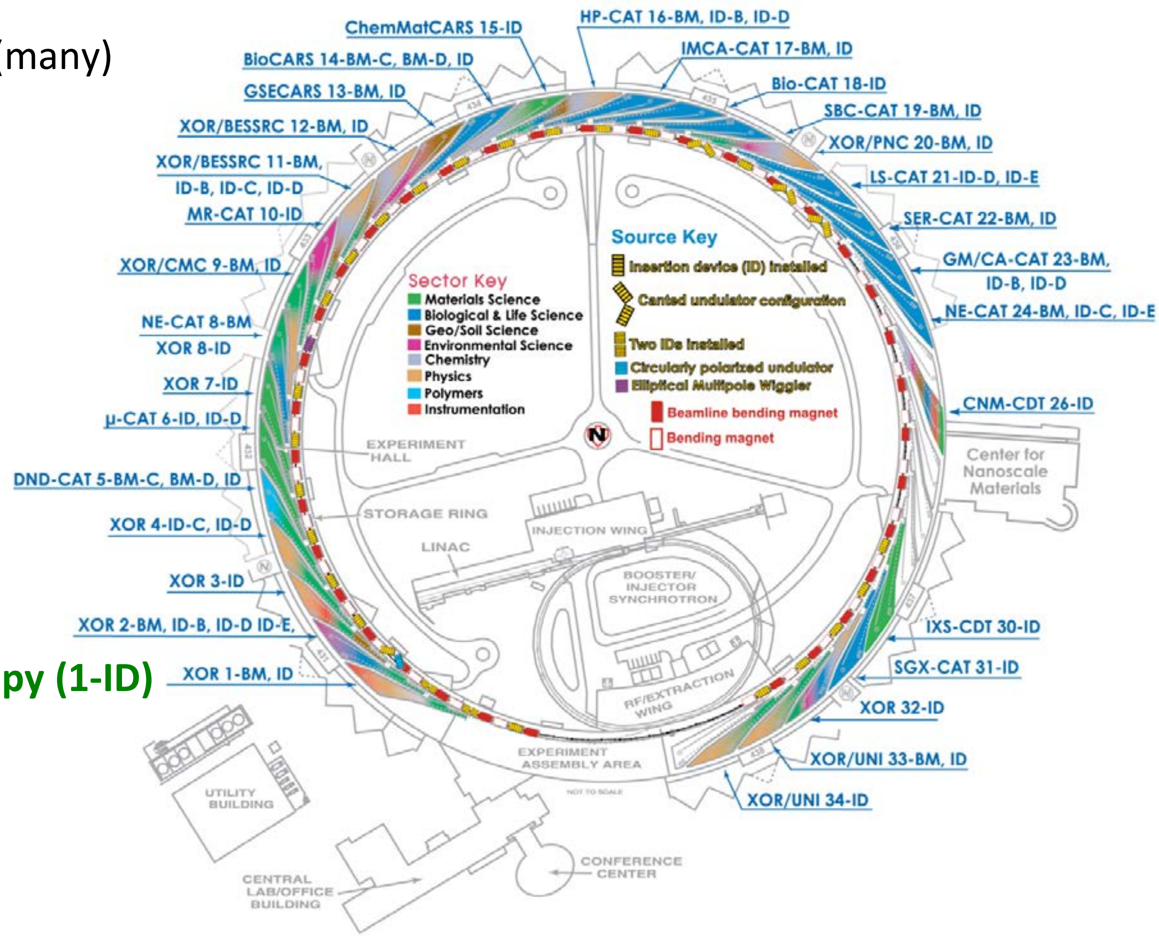
- FY2014 (On-going)
  - Tomographic study of casting quality and structure
  - Design and develop high temperature apparatus for in-situ phase evolution study
  - Evaluation of laboratory sample castings (microstructure, property, and quality)
- FY2015
  - Optimize and characterize the high potential alloy & process concepts
  - Tomographic study of selected candidate cast alloys
  - In-situ phase evolution studies, including formation of precipitates and voids as a function of cool down temperature
- FY2016/17
  - In-situ tensile and fatigue behavior study on down-selected compositions/heat treatment at room and elevated temperatures
  - Investigate formation of micro-cracks during tensile loading and growth of cracks during cyclic fatigue

Correlate microstructure to processing and mechanical properties to optimize cast alloy for crankshafts

Approach

Advanced Photon Source – “Industrial” techniques

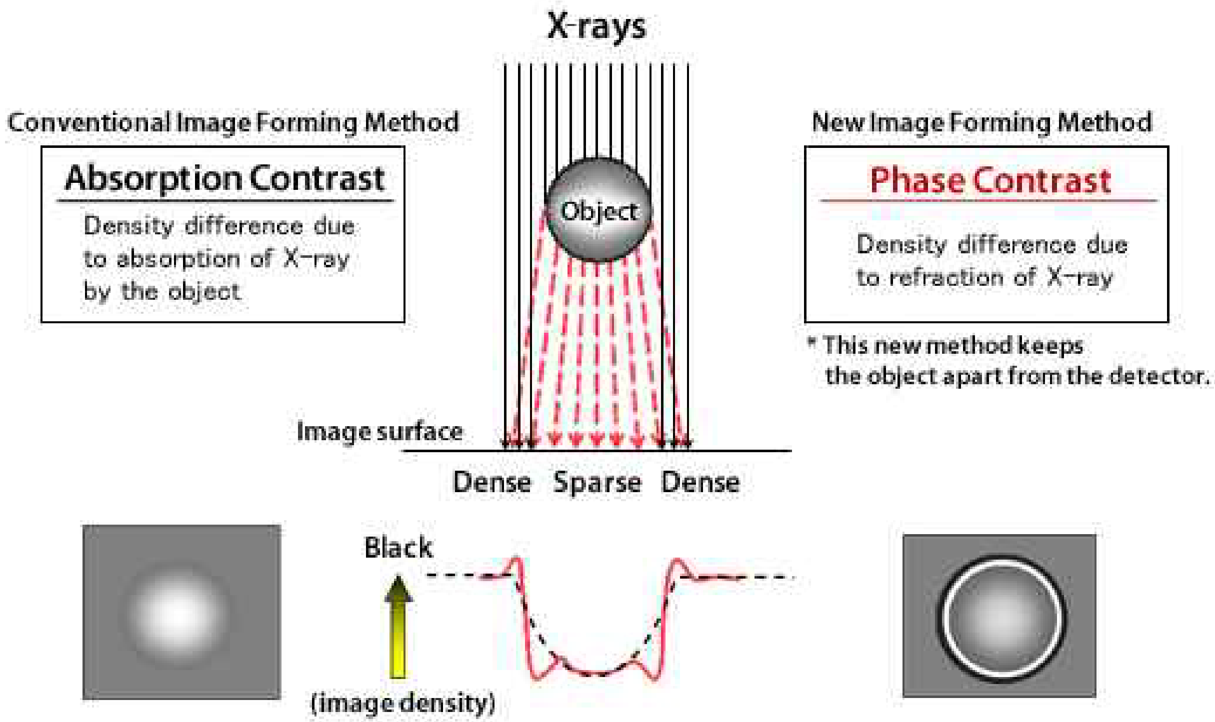
- Core
  - Macromolecular crystallography (many)
  - Powder diffraction (1-BM,11-BM)
  - XAFS (S20)
  - **Tomography (2-BM)**
  - SAXS (various)
  - **Strain scanning (1-ID)**
- Specialized/in development
  - Nano-diffraction (24-ID,34-ID)
  - **Fluorescence microscopy (2-ID)**
  - **High-energy diffraction microscopy (1-ID)**
  - **Time resolved imaging (32-ID)**
  - **Combined techniques**
    - **EXAFS/SAXS/PDF**
    - **SAXS/WAXS (1-ID)**
    - **WAXS/Imaging (1-ID)**



Approach

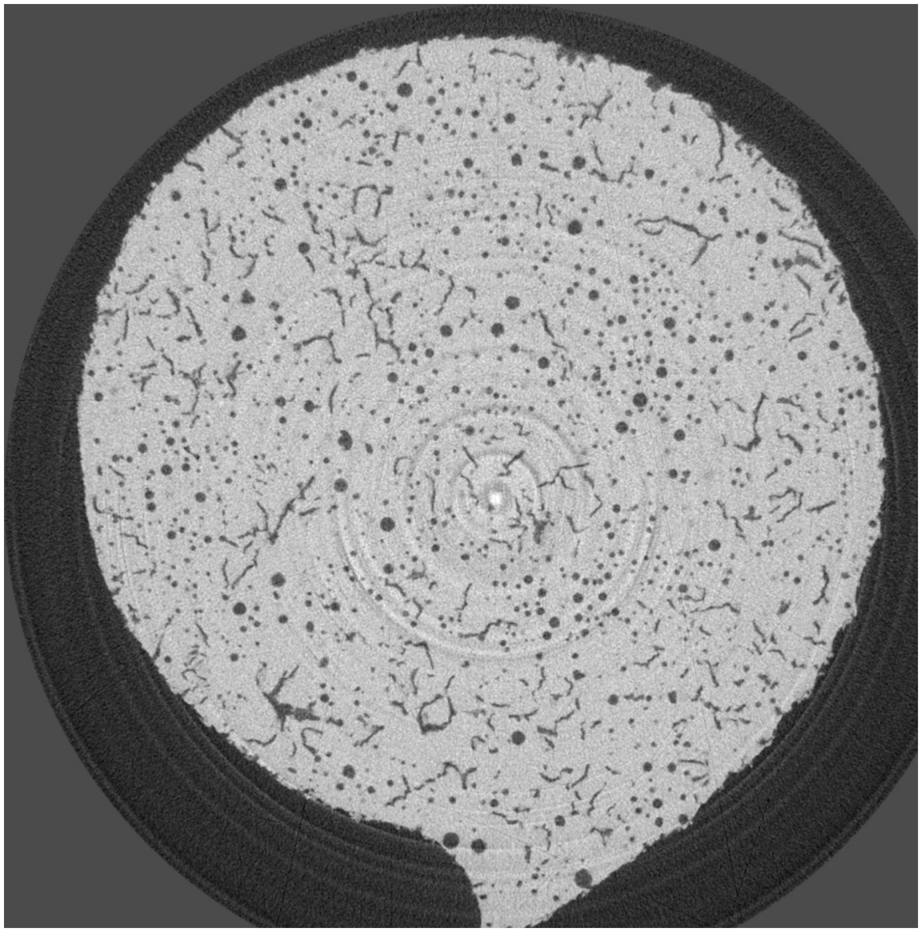
Imaging techniques for internal structure

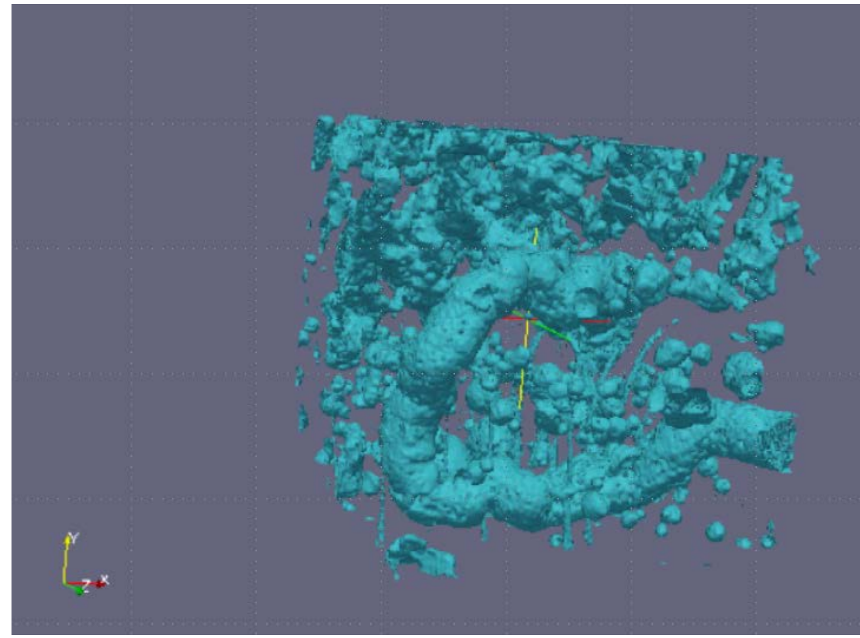
- Absorption or phase tomography
  - Full field 2D image (mm^2) of direct beam
  - Absorption contrast (near) to phase contrast (far) by changing sample-detector
  - Take image and rotate M times (M images)
  - Reconstruct ->3D volume with resolution ~ 1 µm

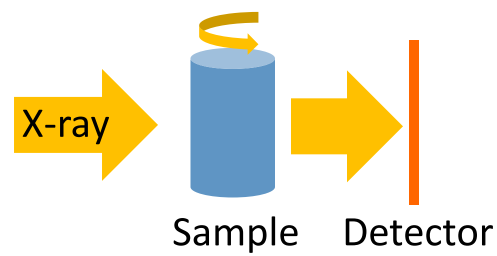


Example of Typical Result

Tomography study of high strength cast iron



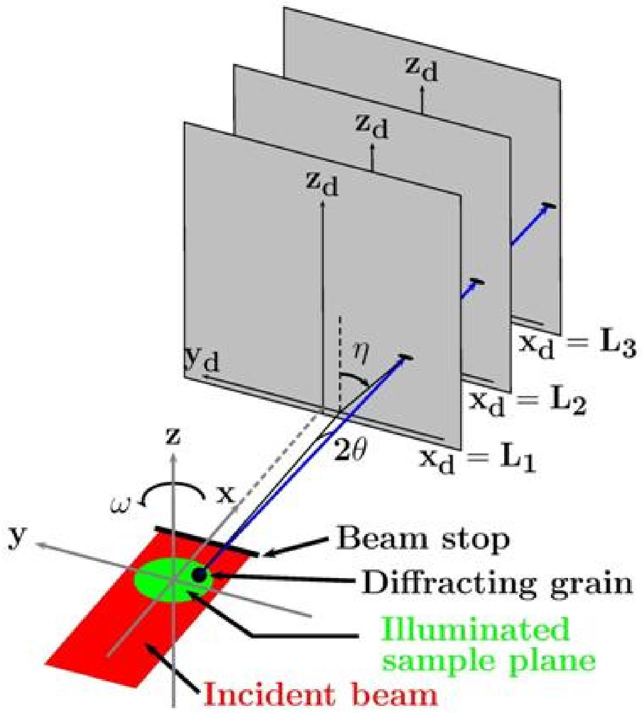


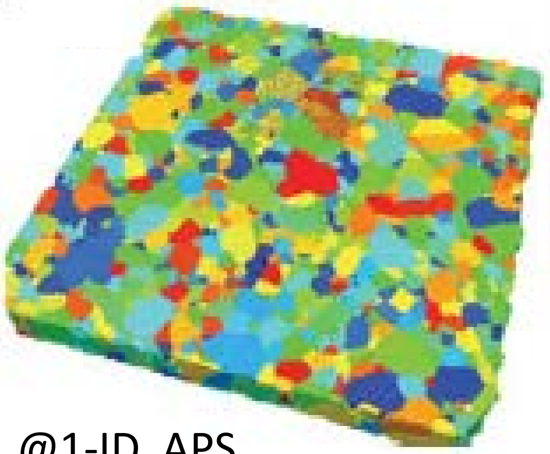


- Internal structure of graphite phases, their network connectivity, voids and casting defects can be reconstructed in 3D

Approach

High Energy Diffraction Microscopy (HEDM)
- Non-destructive microstructural mapping





@1-ID, APS

NF-HEDM
- 3D grain map

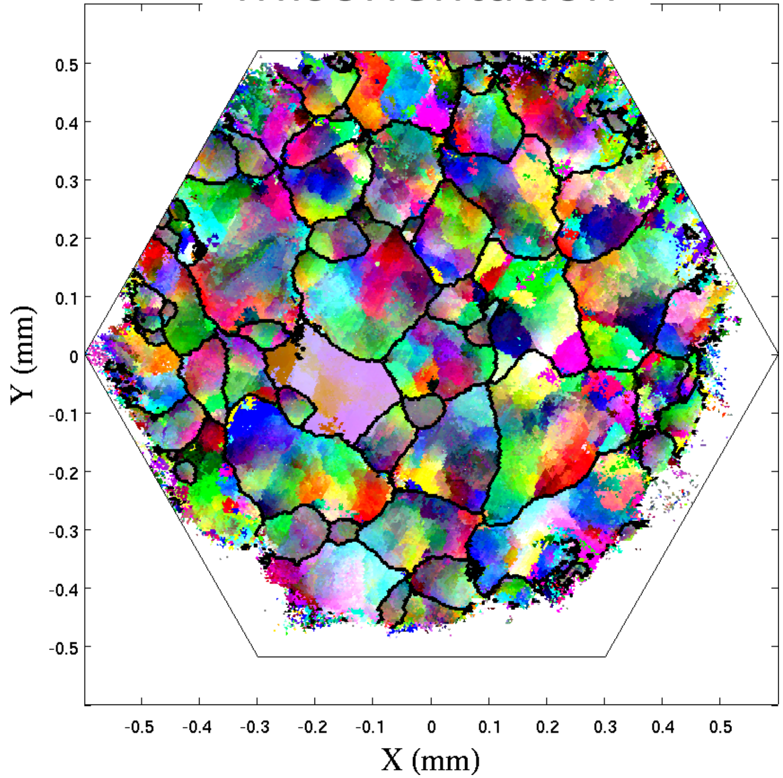
FF-HEDM
- Grain-level strains vs load

Tomography
- Inclusion content

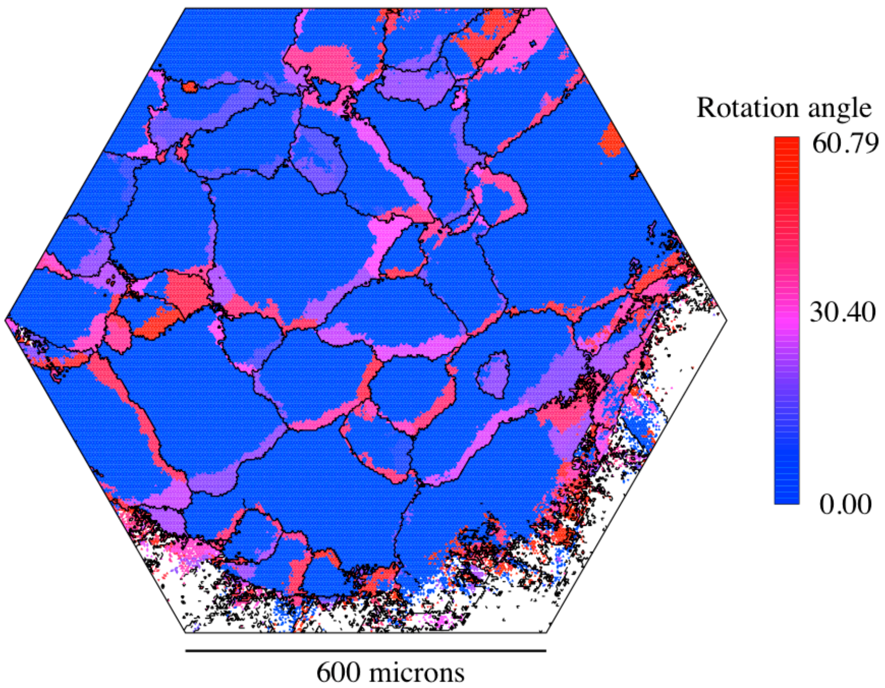
Example of Typical Result

In-situ HEDM study of grain rotation during annealing

Misorientation



Annealing response



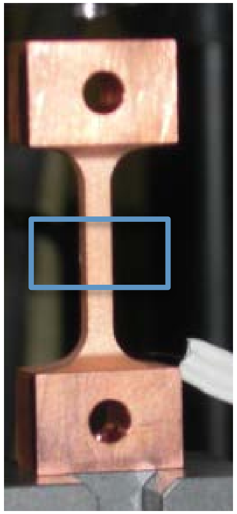
- 4 deg color scale
- 2 deg boundaries

- orientation changes located at boundaries

* Information is being used to drive and test computational materials science predictions

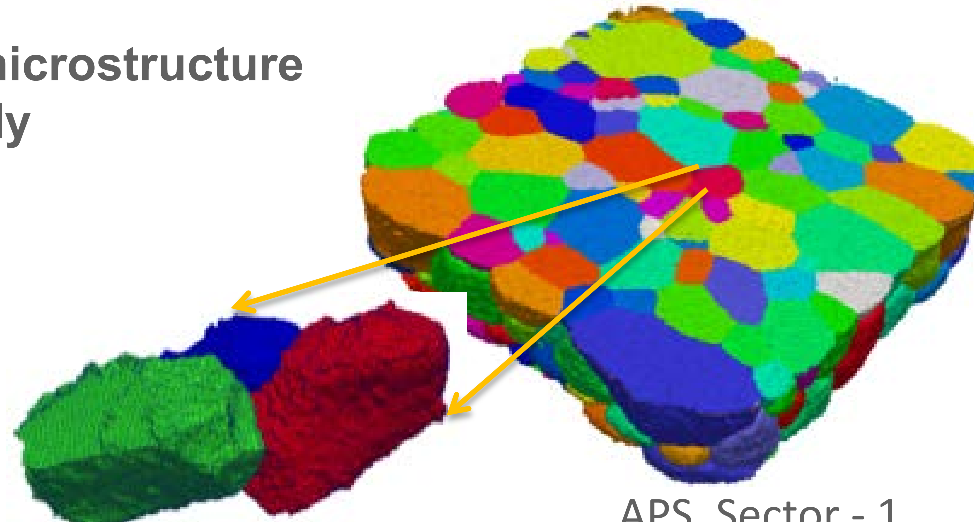
Exampe of Typical Result

In-situ HEDM study of copper during mechanical loading

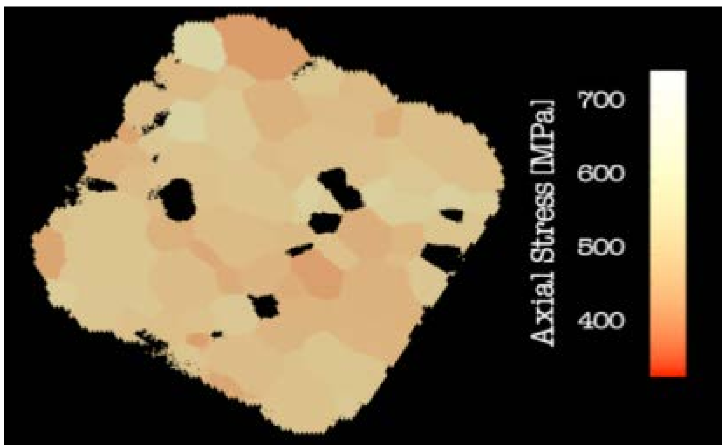


Determine the microstructure non-destructively

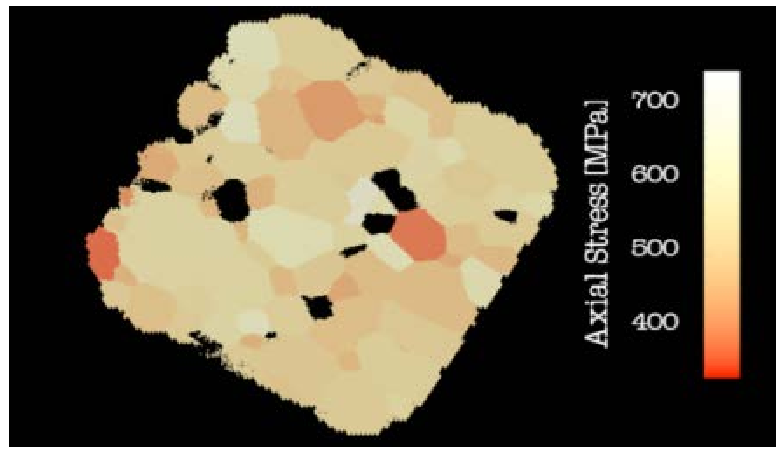
"3D EBSD"



APS, Sector - 1



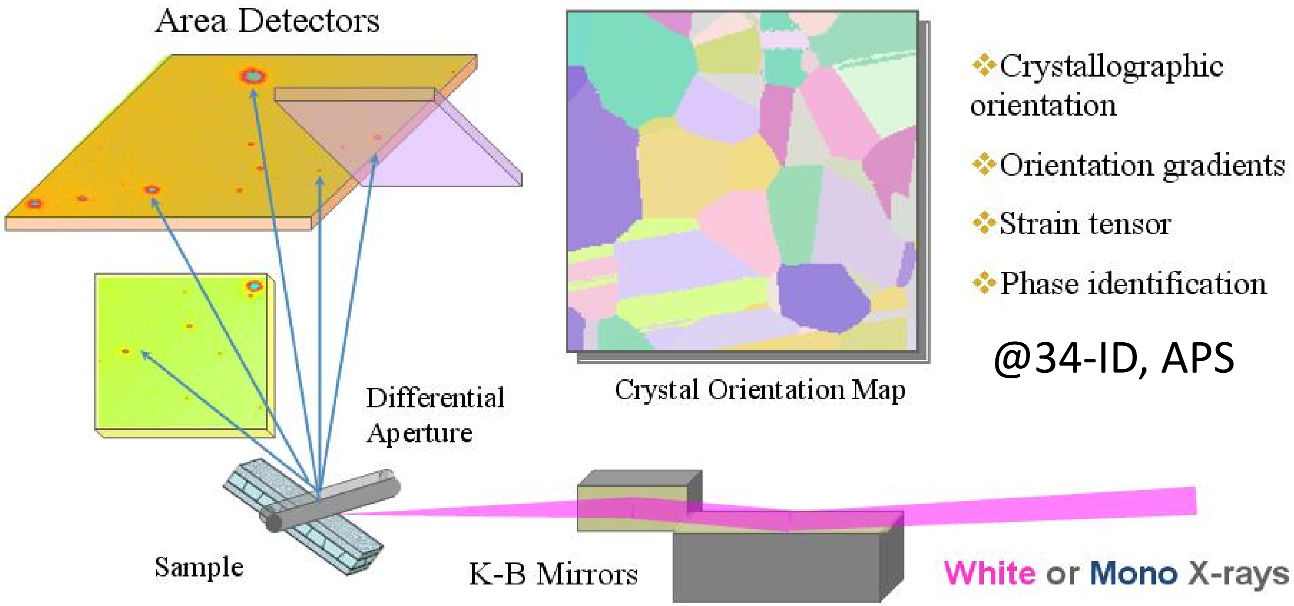
Near Elastic Limit



After 1% Creep Strain

Approach

X-ray micro-beam for phase and chemistry characterization



@34-ID, APS

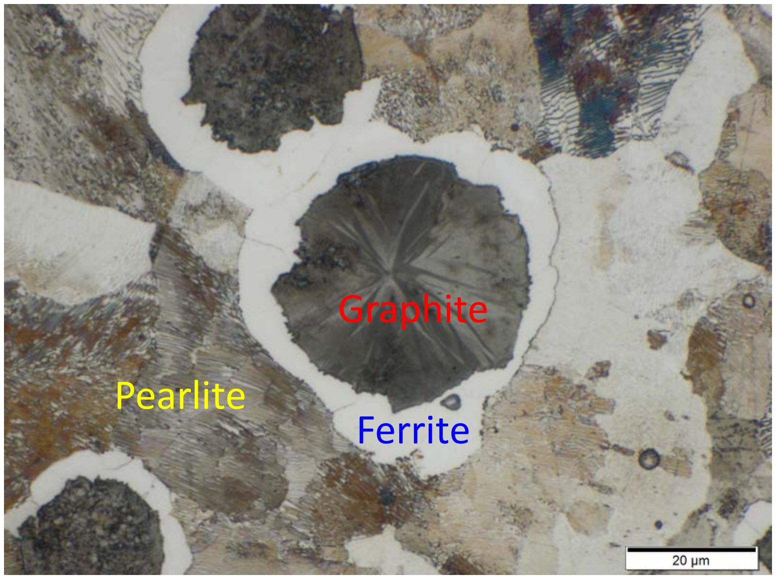
Beam size: 0.3 µm x 0.4 µm

Diffraction approach ➔ structure information

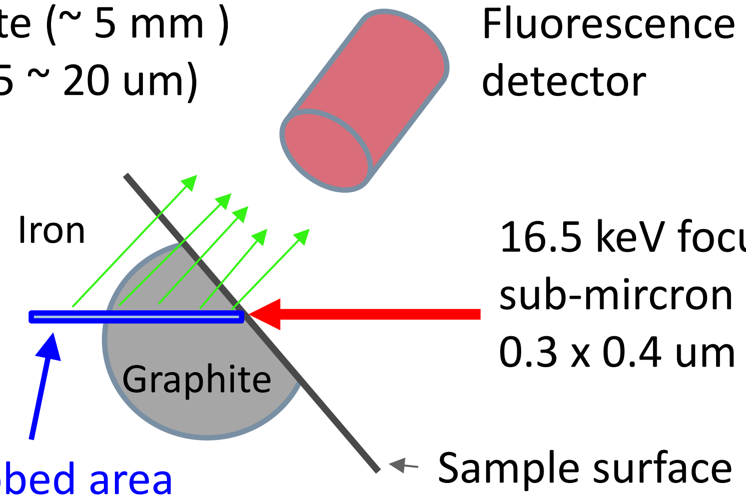
Fluorescence approach ➔ chemical information

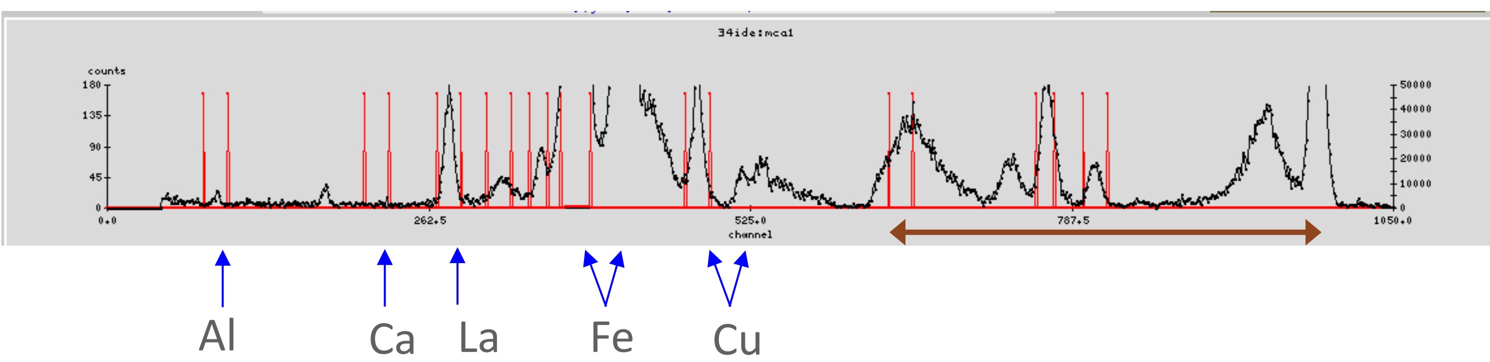
Approach

X-ray micro-beam fluorescence analysis



Attenuation length :
Graphite (~ 5 mm)
Iron (15 ~ 20 um)

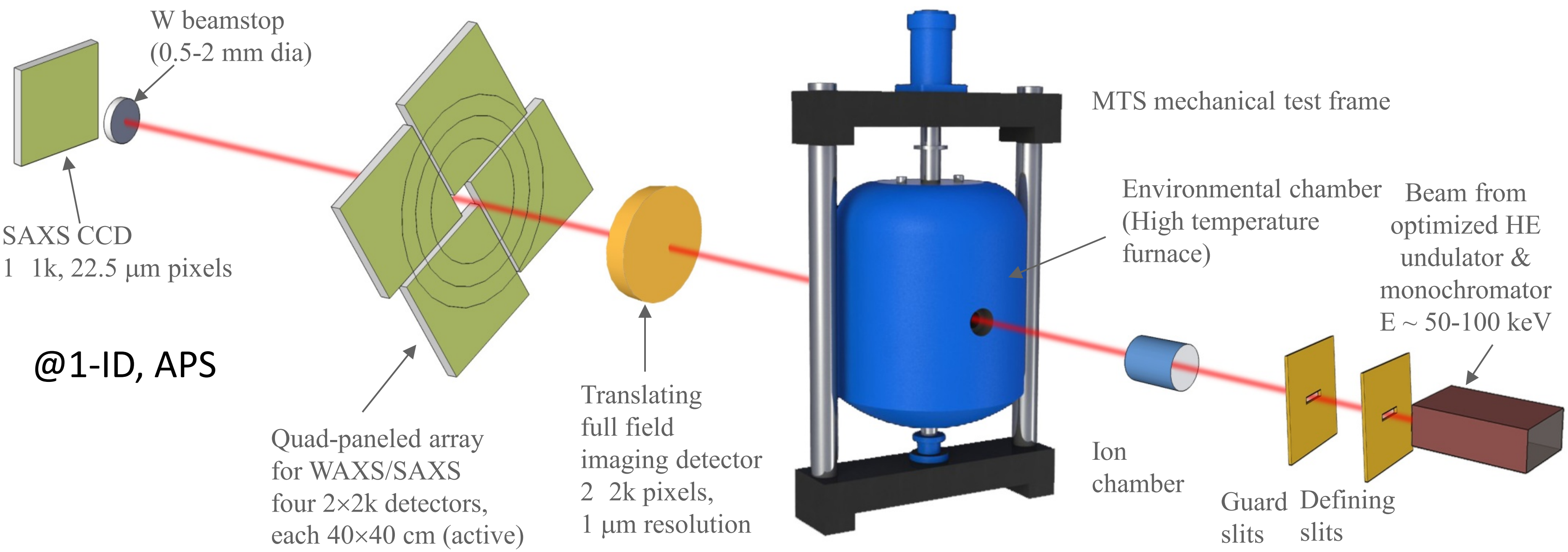




- Fluorescence analysis provide chemical information

Approach

High Energy Diffraction for phase evolution study

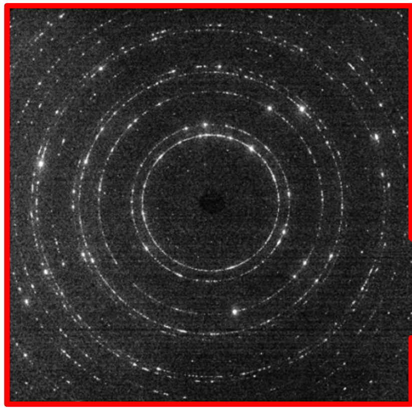


@1-ID, APS

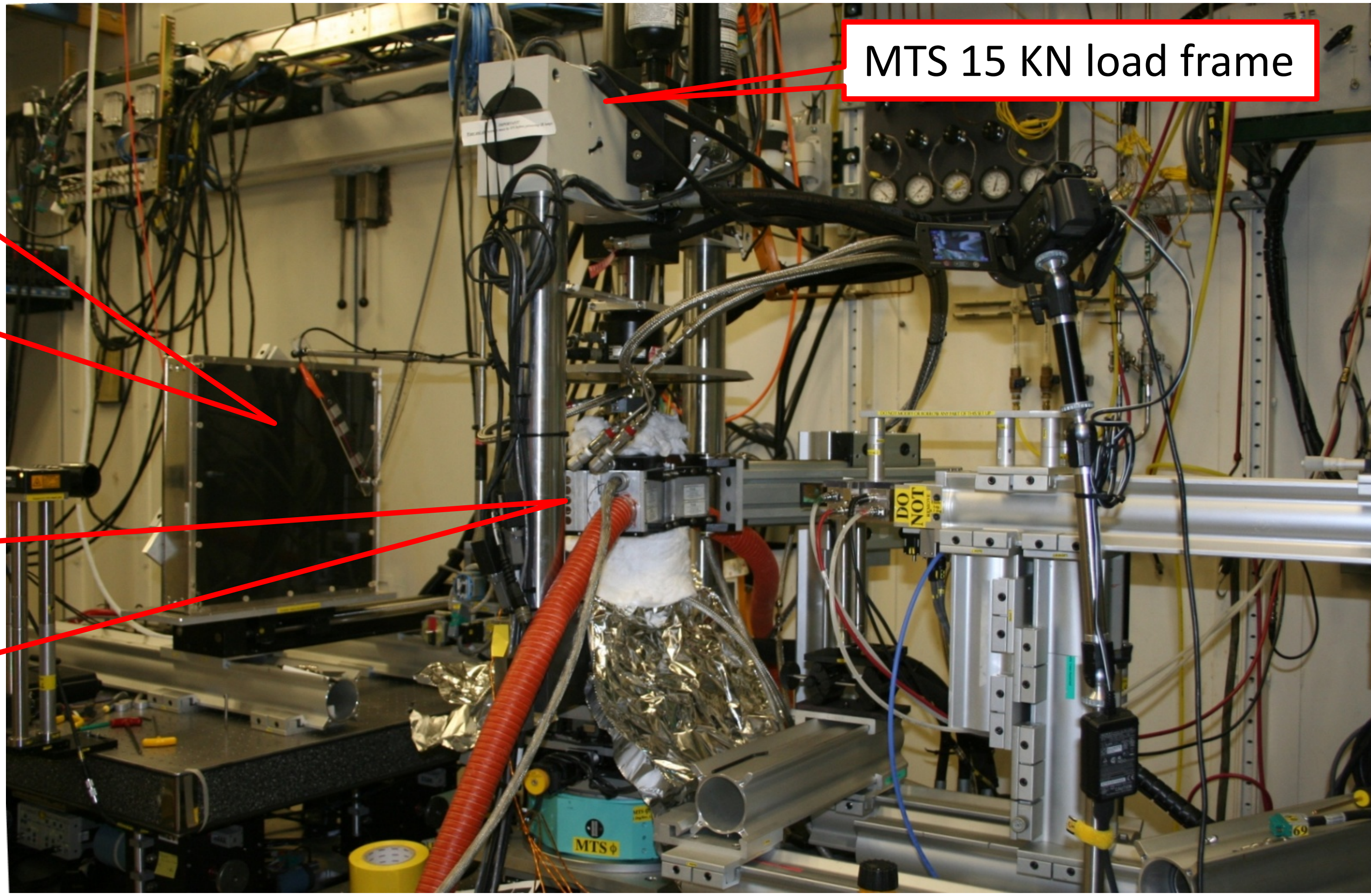
- *In situ* characterization of alloy solidification process
- Simultaneous WAXS/SAXS and full-field imaging
  - WAXS: lattice strain, texture, phases evolution
  - SAXS: nanoscale voids, bubbles, particles, crystal nucleation and growth
  - Imaging: microsize cracks, porosity
- 2D detector array for long sample-detector distance provide High-resolution data

Approach

In-situ structure characterization during thermal-mechanical loading



2D diffraction pattern



In-situ high-temperature diffraction setup at 1-ID-C

Combining mechanical testing and strain mapping

Collaborations

- **Project Lead – Caterpillar, Inc.**

- **Caterpillar & GM**
  - ANL will characterize microstructures for structure/property correlations for optimized alloy compositions and processing variables. Validate mechanical performance of the alloy(s) by in-situ fatigue testing.

- **Northwestern Univ. & Univ. of Iowa**
  - Validate Integrated Computational Materials Engineering (ICME) modeling efforts by using high energy x-ray tools. Specifically, phase and microstructures, residual stresses based on geometry-specific casting simulations, cooling rates, etc.

- **Caterpillar/Questek/University of Alabama**
  - Working on another project related to cast iron development.

- **Air Force Research Lab**

Conclusions

- ANL role in the overall project is: (a) characterization of alloy microstructures and (b) support ICME activity
- Several high-energy x-ray techniques have been identified for this project. Preliminary baseline experiments on some of the techniques have been initiated.
- Results of phase evolution study will be crucial in alloy development. Optimization of the controlled cooling rates to achieve desired phase/microstructures will be a key parameter.
- Microstructure interaction/evolution under thermal-mechanical loading will provide critical information for alloy composition optimizations/flaw initiation and crack growth for overall mechanical performance enhancements.