Advanced Fuel Concepts for Nuclear Reactors

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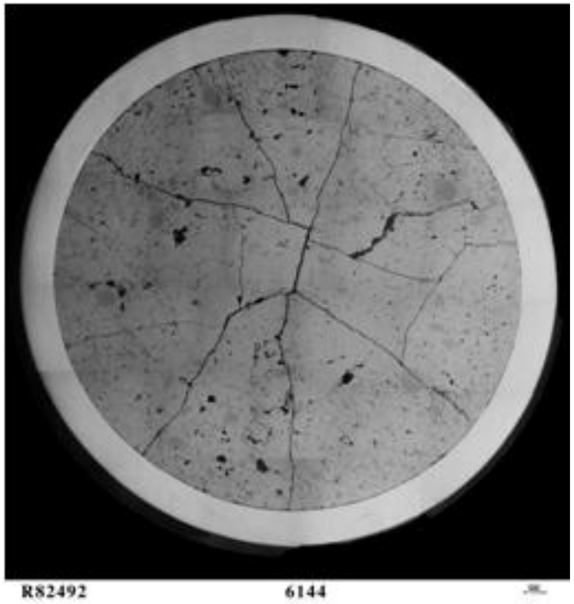
Current Reactors and Fuels

- Pressurized Water Reactors (PWR)
- Boiling Water Reactors (BWR)
- Heavy Water/Natural Uranium Reactors (CANDU)
- All Reactor Types use UO_2 Fuel
- Uranium enriched up to 5 wt% ^{235}U
- Fuel is in the form of pellets: ~1 cm in diameter
- Pellets compressed to ~95% theoretical density

Problems with Current Fuels

- Burnup is limited by the degradation of the Fuel and cladding
- Fuel damage caused by thermal stresses high temperature gradients and fission product accumulation
- Cladding damage caused by Fretting, Corrosion, Chemical Interaction (PCI), Irradiation and Thermal Stresses
- Current Burnup Limits are ~50 GWd/MtU
- Low Thermal Conductivity (~3 W/m°K) limits Power Density



Advanced Fuels Campaign (AFC)

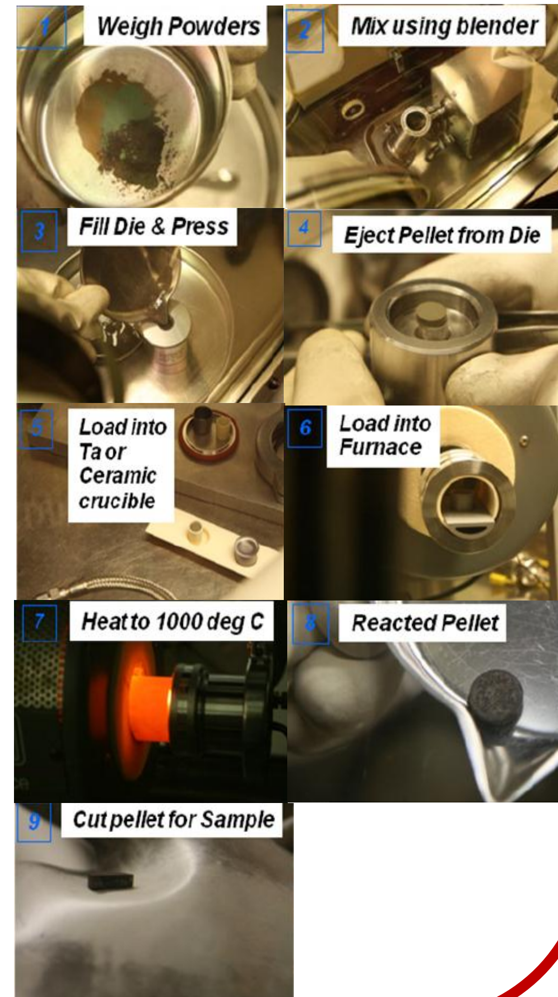
- DOE – Fuel Cycle Research and Development (FCRD) Program
- Use a Science Based approach focused on developing a microstructural understanding of nuclear fuels and material.
- Manage, Integrate and Coordinate the major R&D activities across National Laboratories and Universities
- Collaborates with the FCRD, Industry, Other DOE Programs, Laboratories, Federal Agencies and International Organizations.

Innovative Transmutation Fuel Concepts

1. Advanced Metallic Fuel Concept for Reliable Performance to Ultra-high Burnup (ANL, INL)
2. Better Fuel Pin Concept for Enhanced Burnup (BNL)
3. Uranium Alloy Metal Fuel for LWRs (PNNL)
4. Advanced Dispersion Fuel R&D Plan (INL)
5. Ultra-high Burnup Metallic Inert Matrix Nuclear Fuel Concept (LNLL)
6. Advanced High Integrity Gas Cooled Fast Reactor Fuel: MAX Phase Ceramic Materials (SRNL)
7. Multi-Layer Co-Extruded Fast Reactor Metallic Fuel (SRNL)
8. Enhanced Thermal Conductivity and Grain Boundary Engineering for Oxide Fuels (ORNL)
9. High Burn-up Ceramic Composite Nuclear Fuels (LANL)
10. Input to AFC on R&D Issues and Requirements for Thorium Based Fuels (BNL)

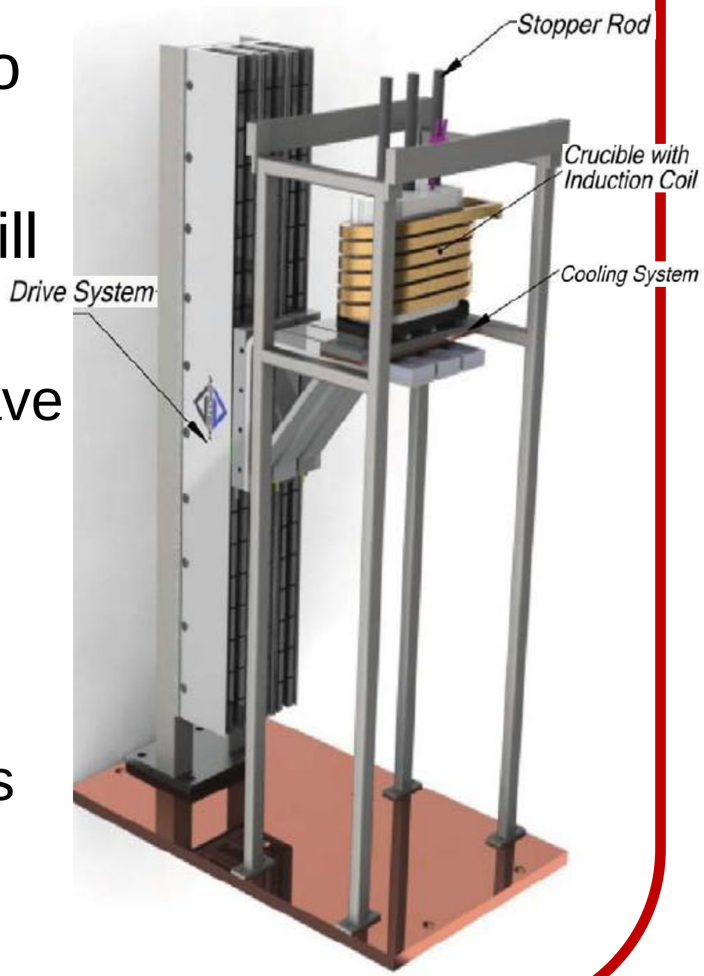
Metal Based Fuels – Feed Stock

- INL manages database on DOE TRU supply (Pu, Am, Np)
- Obtain Feedstock and convert to appropriate chemical forms for fuel fabrication
  - Americium Extraction
  - Reduction of PuO_2 and AmO_2 to Pu and Am Metal
  - X-ray diffraction analysis of reduction process show Pu, PuO but no Am or AmO_2
  - Am metal formed but evaporated



Metal Based Fuels – Fabrication & Casting

- INL fabricates required material to support studies
- Develop a casting process that will function using remote handling
  - Examined induction and microwave casting techniques
  - Feasible to case small diameter pellets (~2.4 mm) using a continuous induction process
  - Perform multi-physics simulations of the INL bench scale metal fuel casting furnace

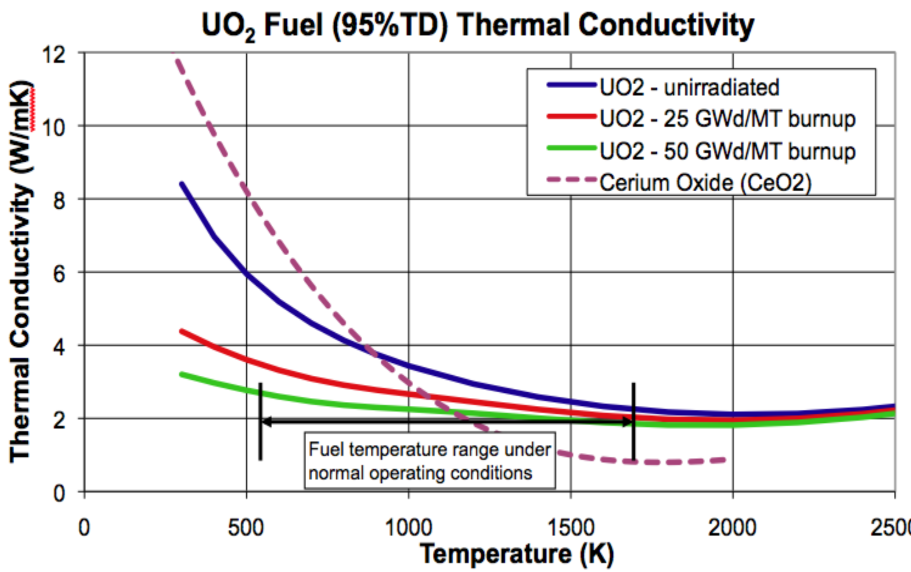


Ultra-high Burnup Sodium cooled Fast Reactor Metal Fuel (INL, ANL, PNNL)

- Has the potential to reach burnups of ~40 at.%
  - Decrease fuel smear density to accommodate swelling
  - Cladding inner surface liner to mitigate fuel-clad chemical interaction
  - Vented fuel pin design to reduce fission gas stress on cladding at high burnup
  - Mo-based fuel alloy
  - Minor alloy additions to immobilize lanthanide F.P.
  - Minimize waste generation during fuel fabrication

Ceramic Based Fuels – Oxide Fuels

- UO_2 properties
- Fuel performance
- Fuel compositions
- Material properties
- Pellet fabrication processes
- Fundamental understanding of fuel forms

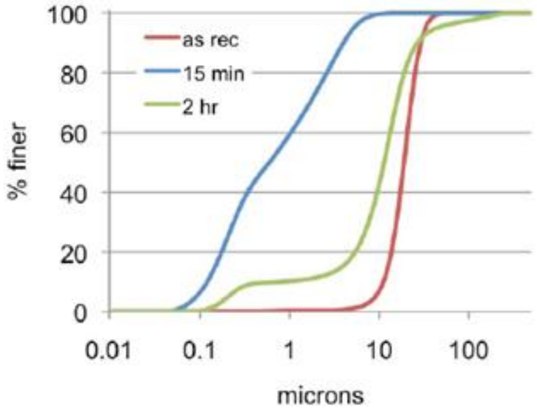


Ceramic Based Fuels – UO_2 Studies

- Improve fuel pellet properties by engineering its microstructure
  - Reduce Pellet Clad Interaction (PCI)
  - Allow Higher Power Levels and Burnup
  - Reduce the number of pellet fabrication steps
  - More uniformity among pellets
- A fundamental scientific understanding of the UO_2 powder processing science is required to understand the relationship between fuel processing methods and fuel performance

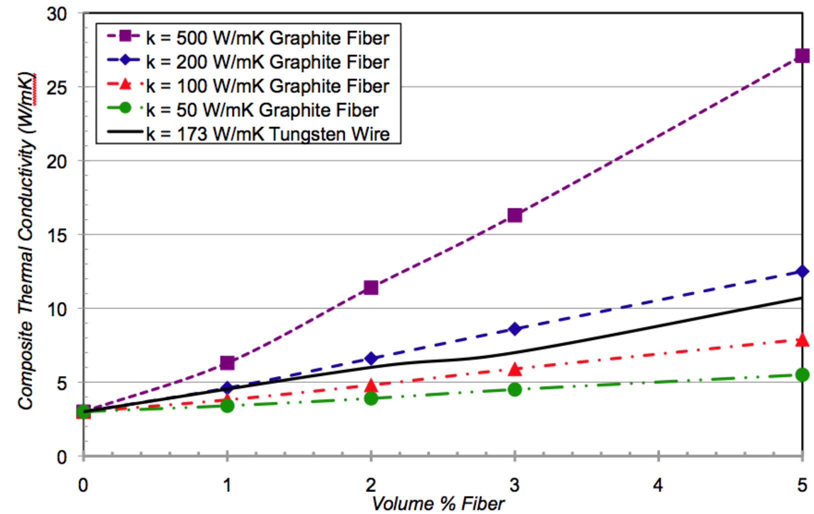
Ceramic Based Fuels – UO_2 Processing

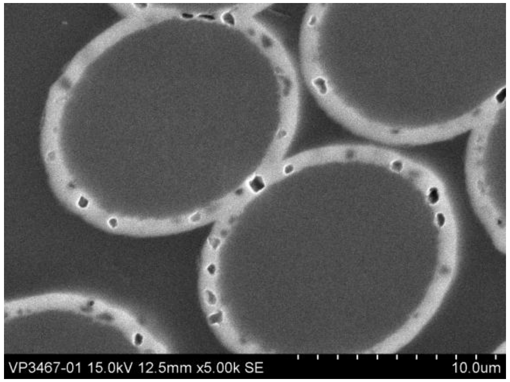
- Introduce pores to prevent fission gas buildup
- Add second phase material to increase thermal conductivity thus reducing centerline temperature
- Add trace materials to pin grain boundaries
- Control O/M Ratio
- Control milled particle size
  - Finer size does not compact as well but sinters more readily



Ceramic Based Fuels – Fiber/UO_2 Fuel

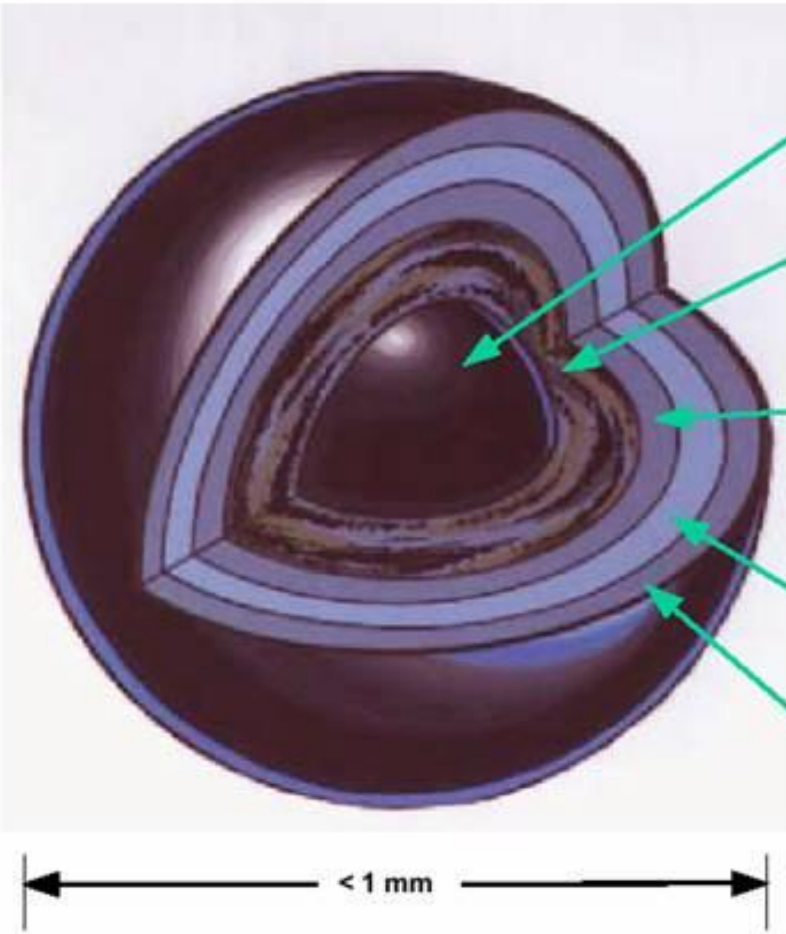
- Adding long thin fibers of a high thermal conductivity material to UO_2 increases bulk thermal conductivity
- SiC coated graphite fibers examined because
  - High thermal conductivity
  - SiC protects graphite from interaction with UO_2





- Siliconized fiber outer layer
  - Flow Ar-SiH4 gas over graphite fiber at high temperature in a reaction chamber
  - Post deposit heat treat under inert gas forming SiC

Coated particle Fuels – TRISO Fuel

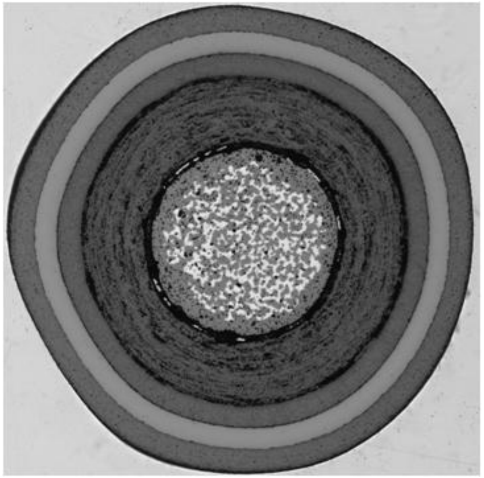


COMPONENT/PURPOSE

- Fuel Kernel
  - Provide fission energy/neutrons to destroy Pu
  - Retain short-lived fission products (FP)
- Buffer layer (porous carbon layer)
  - Attenuate fission recoils
  - Void volume for fission gases
  - accommodates kernel swelling
- Inner Pyrocarbon (IPyC)
  - Provide support for SiC during irradiation
  - Prevent Cl attach of kernel during manufacture
  - provides protection for SiC from FPs and CO
  - retains gaseous FPs
- Silicon Carbide (SiC)
  - Primary load bearing member
  - Retain gas and metal fission products
- Outer Pyrocarbon (OPyC)
  - provides structural support for SiC
  - Provide bonding surface for compacting
  - Provide fission product barrier in particles with defective SiC

Coated particle Fuels – TRISO Particles

- Fundamental modeling with experimental validation
- TRU fuel fabrication facility
- New types of fully ceramic micro-encapulated fuels
- Engineered “deep burn” kernel used SiC getters to extend fuel life
- New Simultaneous Thermal Analyzer (STA) and Mass Spectrometer (MS)
- Develop Deep Burn database
- ZrC examined as replacement for SiC as primary F.P. barrier
  - High melting point
  - Good F.P. retention
  - Corrosion resistance

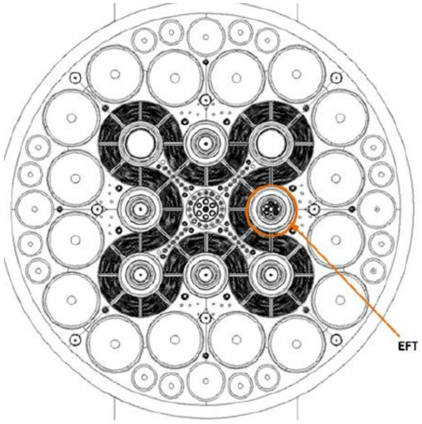


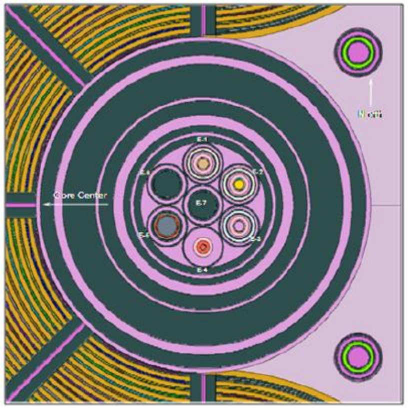
Irradiation Testing

- Feasibility testing of emergent, innovative fuel concepts
  - Small scale, integral experiments at ATR
- Development of a capability to perform separate effects testing
  - Designing and deploying irradiation test capabilities
  - Hydraulic rabbit tests at HFIR
  - Fuel performance parameter testing at ATR
- Understanding the differences & limitations with testing fast reactor fuels in thermal test reactors

Irradiation Testing - ATR

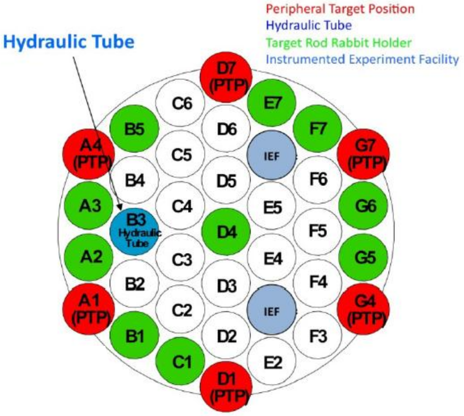
- Types of material inserted into ATR flux traps
  - Experimental assemblies
  - GFR non-fuel material
  - Linear Heat Generation Rate (LHGR)
  - Burnup distribution
- After discharge, shipped to the INL Material Fuels Complex for PIE to characterize performance of advanced fuel forms





Irradiation Testing - HFIR

- Design and fabricate rabbit capsules
  - Perform required safety analyses
  - Secure approval for irradiation experiments supporting fuel, targets and material development
- Types of experiments
  - Microstructural evolution of metallic fuels
  - Radiation enhanced diffusion
  - FCCI
  - Historic EBR-II fuel irradiation
- Develop HFIR core reactivity model



Research Underway to Improve Processing and Fabrication in Advanced, Radiation-Tolerant ODS Steels

- Scale up processing of 14YWT into larger heats. (ORNL, UCB, UCSB, Crucible (ATI)) – Produce alloyed powders using gas atomization.
- Explore friction stir welding as a viable means of joining these advanced materials. (SDSMT, ORNL)
- The fabrication of rod, plate, and tube forms will be demonstrated. (LANL, ORNL)
- Compare irradiation resistance to that measured on smaller scale heats using ion irradiation. (LANL)
- Characterization of Alloys via SANS, TEM and atom probe tomography. (UCB, ORNL, UCSB, LANL)

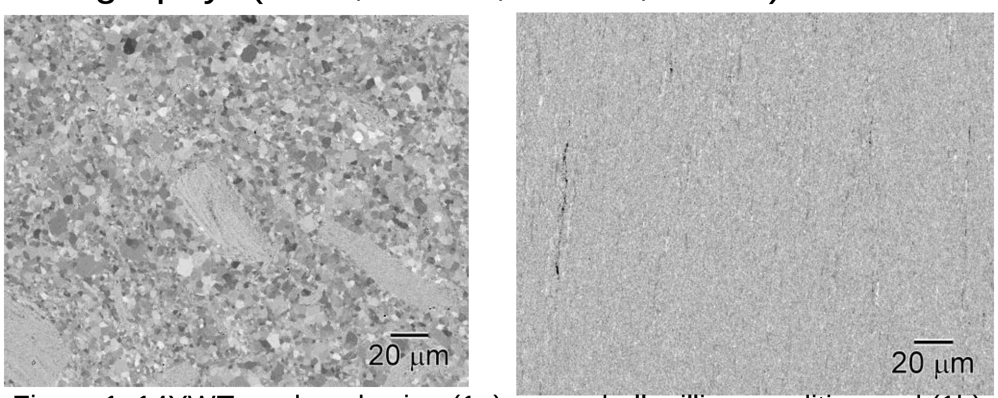


Figure 1. 14YWT produced using (1a) a poor ball milling condition and (1b) an optimized ball milling condition. Powder canning and hot extrusion conditions were identical.

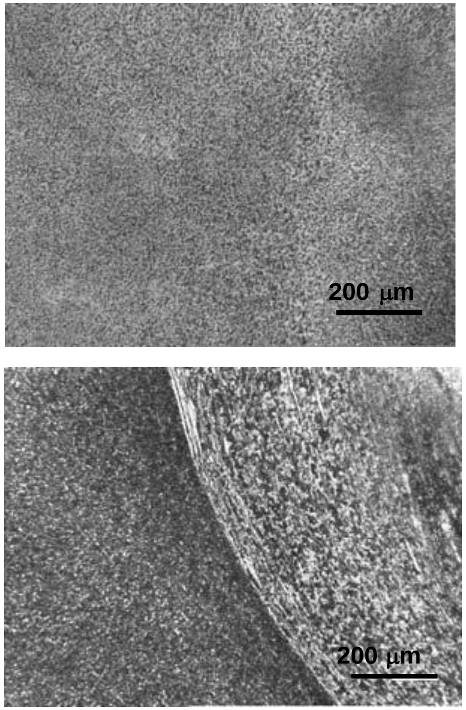


Figure 2. Micrographs of successfully friction stir welded MA 957 conducted at SDSMT (a) parent and (b) nugget-TMZ interface.

References

- Advanced Fuels Campaign FY 2010 Accomplishments Report
- INL/EXT-10-20566
- FCRD-FUEL-2011-000015