Irradiation testing of LWR Additively Manufactured Materials

Ron Horn
Chief Consulting Engineer:
Materials Technology
GE Hitachi Nuclear Energy

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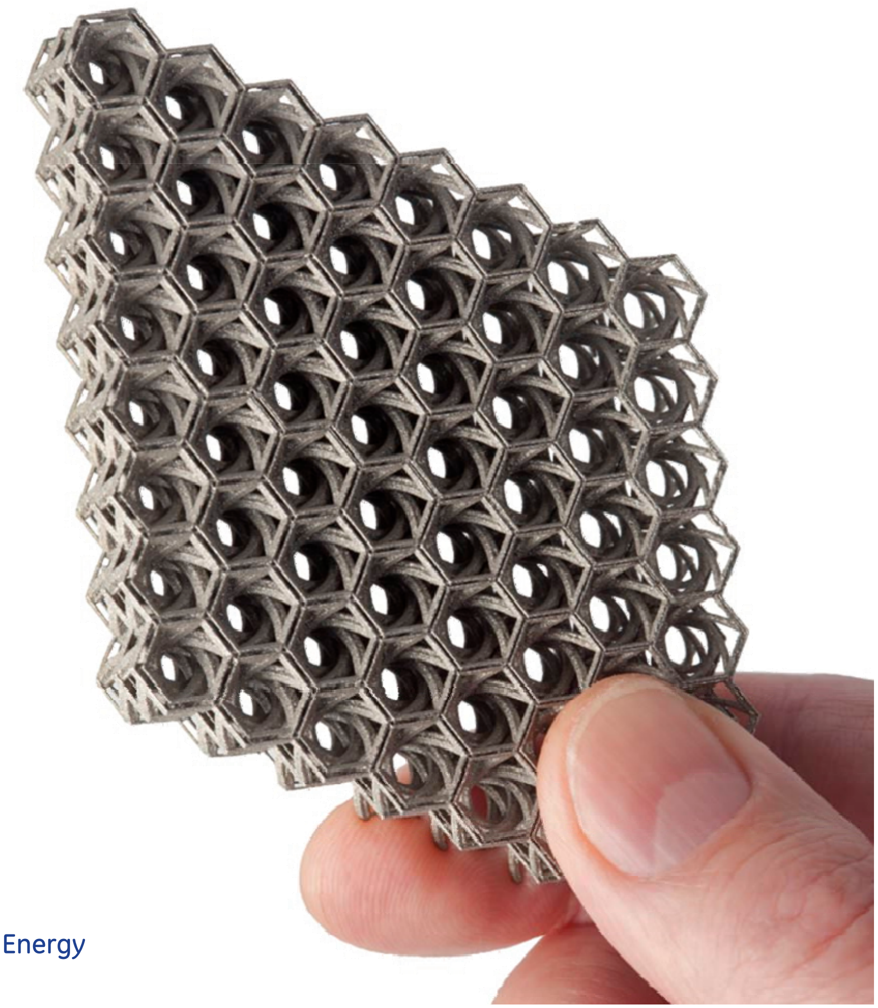
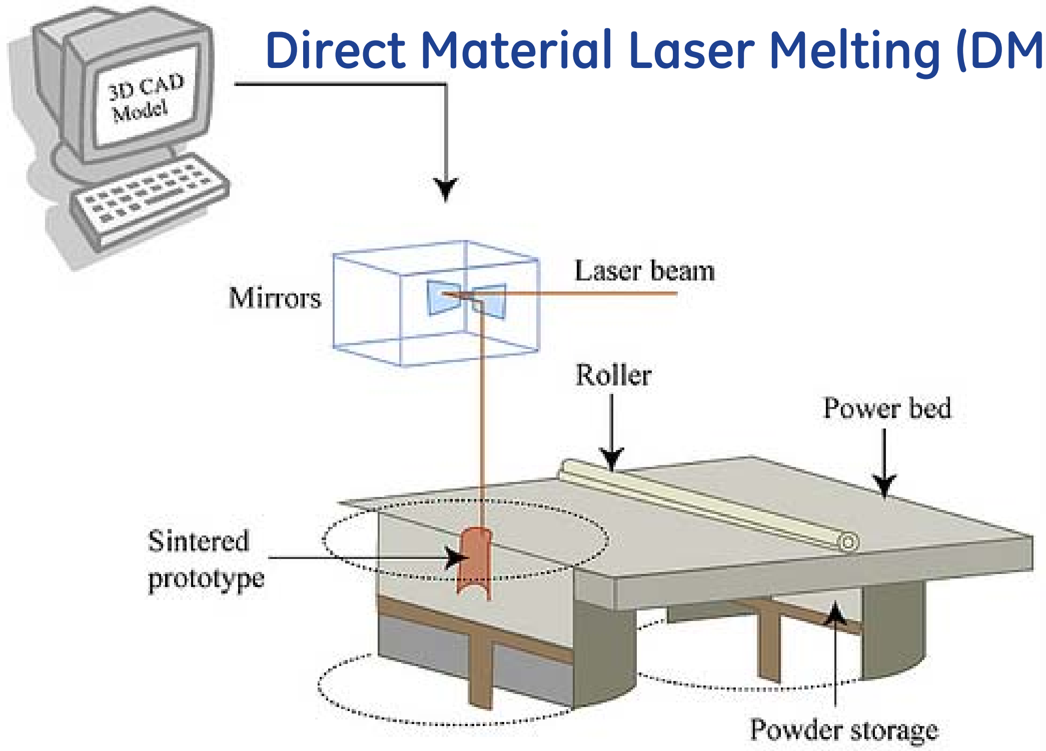


Topics of Discussion

- Background Additive Manufacturing Overview
- Benefits of Additive Manufacturing
  - Innovative design and Rapid Prototyping
  - Rapid Hardware Build
- Background Additive Manufacturing Efforts
  - GE Global Research/GEH Efforts
- Overview of the NSUF INL-DOE-GEH Program
  - Objectives and Scope
- Benefits of NSUF Program to the Industry
- Summary

Background: Additive (3D Printing) P

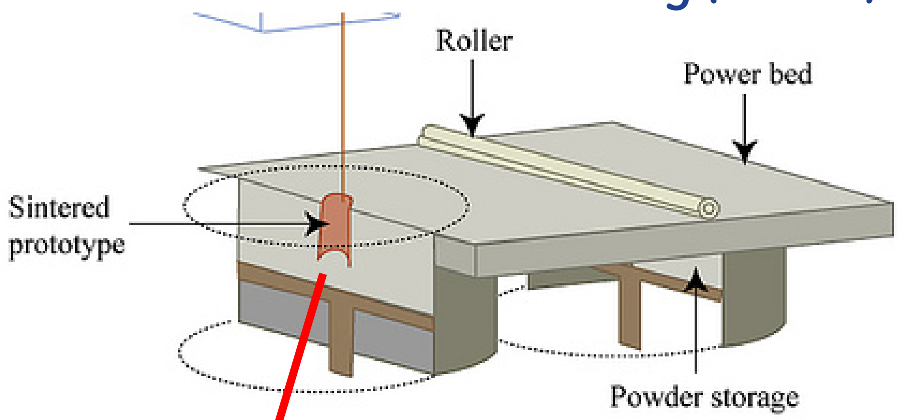
Direct Material Laser Melting (DMLM)

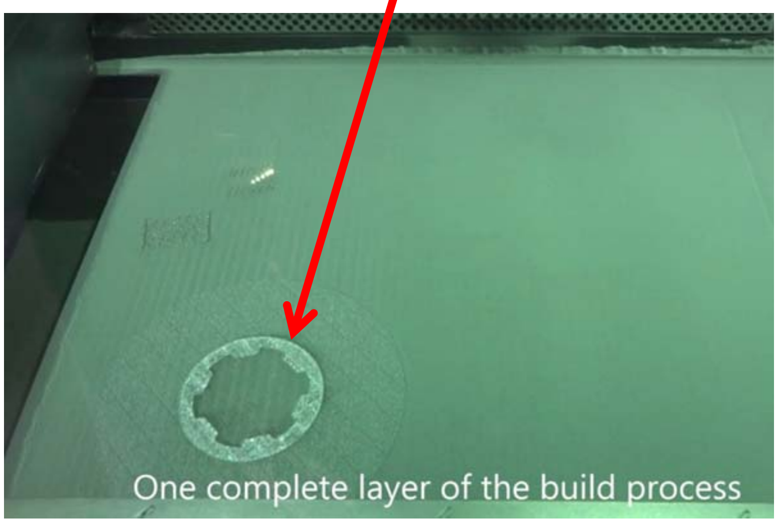


Post Processing (HIP, Heat Treat, Machining, etc.)

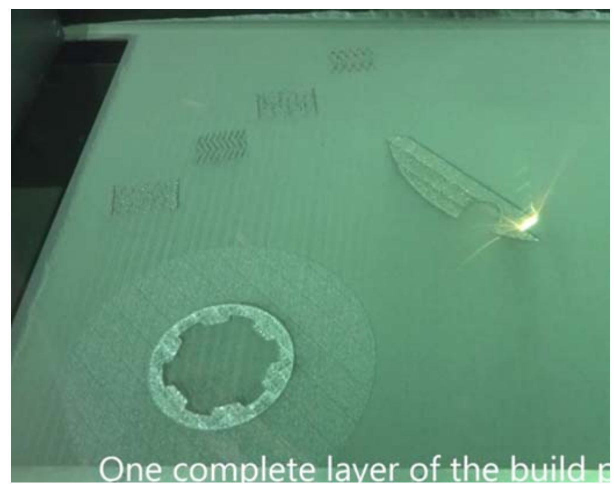
Additive (3D Printing) Process (cont.)

Direct Material Laser Melting (DMLM)





1^{st} layer, t_0



1^{st} layer, $t_0 + t$

Steps in the Additive Buildup

Post Processing (HIP, Heat Treat, Machining, etc.)

Benefits of Additive Manufacturing

- Rapid Assessment of Prototypes
  - Quick evaluation: “I’ve got this great idea”
- Unique Designs for Performance Enhancement
  - Get away from conventional constraints
    - “Can’t make it using standard methods
    - “Never did it before”
    - “I only need one”
    - “It will take too long”

Example: 3D support for Rapid Prototyping

- Using current design programs, component designs can be immediately manufactured
  - Rapid Visualization
  - Ability to build and assemble piece parts
  - Show design to others within the company
  - Discuss key features with the customer
  - Prepare rapid iterations
  - Develop concepts for installation tooling

3D support for Rapid Prototyping

- Examples:
  - Tooling models
  - Repair Hardware Model

The engineers can put together different parts, try out tools to install

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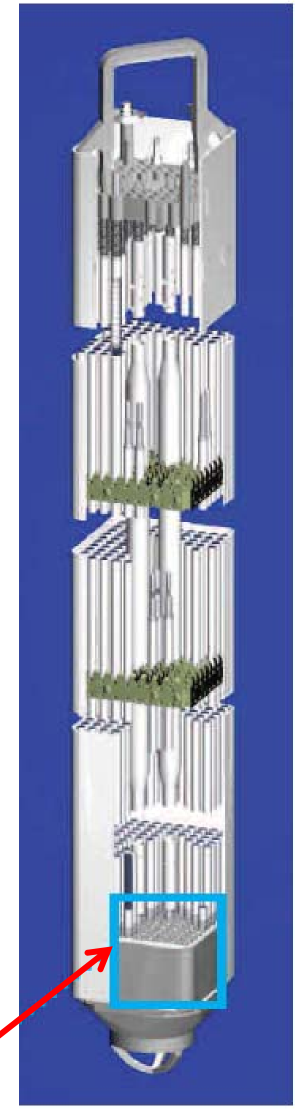
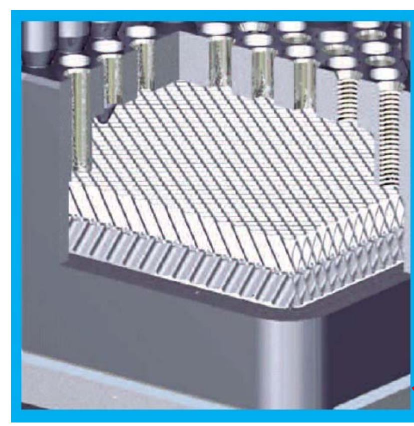
Unique Design Development Process

- Example: Enhanced Fuel debris filter: prevent fretting of fuel rods
  - 3D allows making a new design
  - Only way to make it
  - Can quickly make prototype for evaluation
  - Iterate on the design
  - Quickly build for actual in-plant trial



Key concern remains:
Can I use the materials to put a prototype into a plant?
Role of NSUF Program



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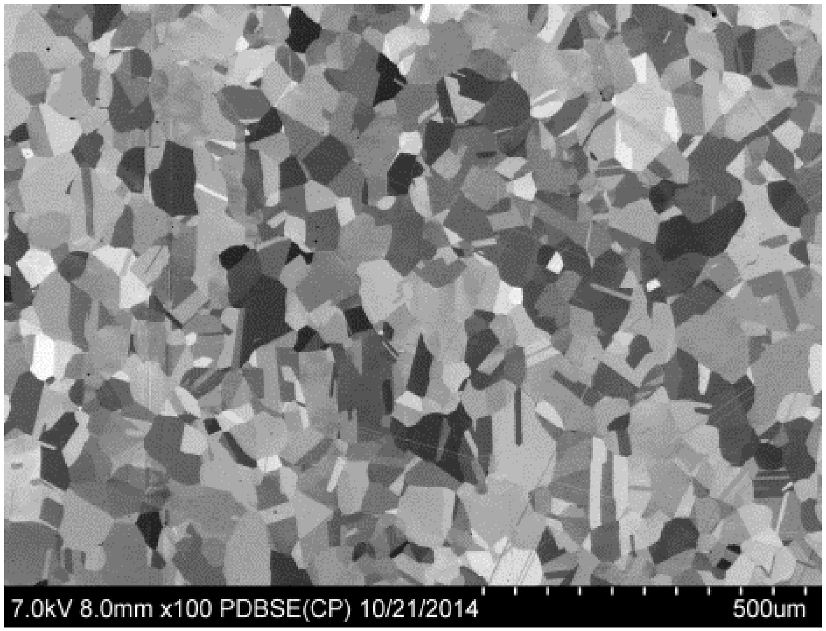
Background: Additive Manufacturing Efforts

Earlier GE Global Research/GE Hitachi Efforts

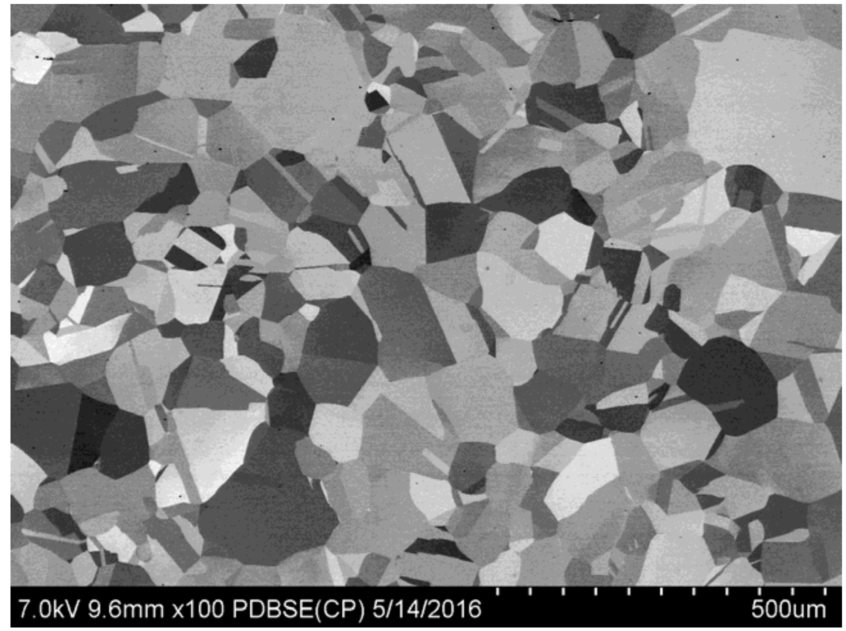
- Significant work was done by the GE GRC under GEH sponsorship to evaluate, understand and optimize the properties of Type 316L un-irradiated materials manufactured using DMLM.
- The previous study evaluated different vendors and conditions; then compared DMLM material with other standard austenitic alloys.
  - Two main process conditions evaluated: as-built and HIP-SA
  - Compared the DMLM with wrought Type 316L, Nitronic 50
  - Results:
    - DMLM Type 316L exhibited similar ductility and mechanical properties to Type 316L wrought material
    - DMLM in HIP-SA condition exhibited very dense microstructures compared to wrought product form.

Processing parameters established for DMLM Type 316L

Earlier GEH/GRC Efforts (cont.)



HIP'ed and annealed
DMLM 316L SS Grain structure



Wrought Type 316L SS Grain structure
(Annealed for at 1950°F for 25 hrs)

Both the AM and wrought Type 316L have very uniform microstructures

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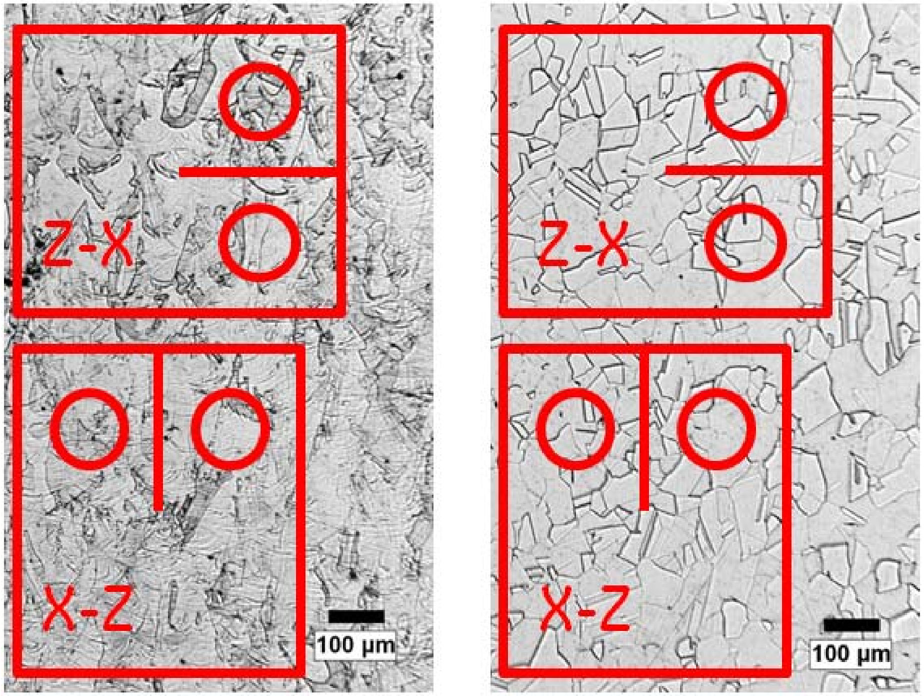
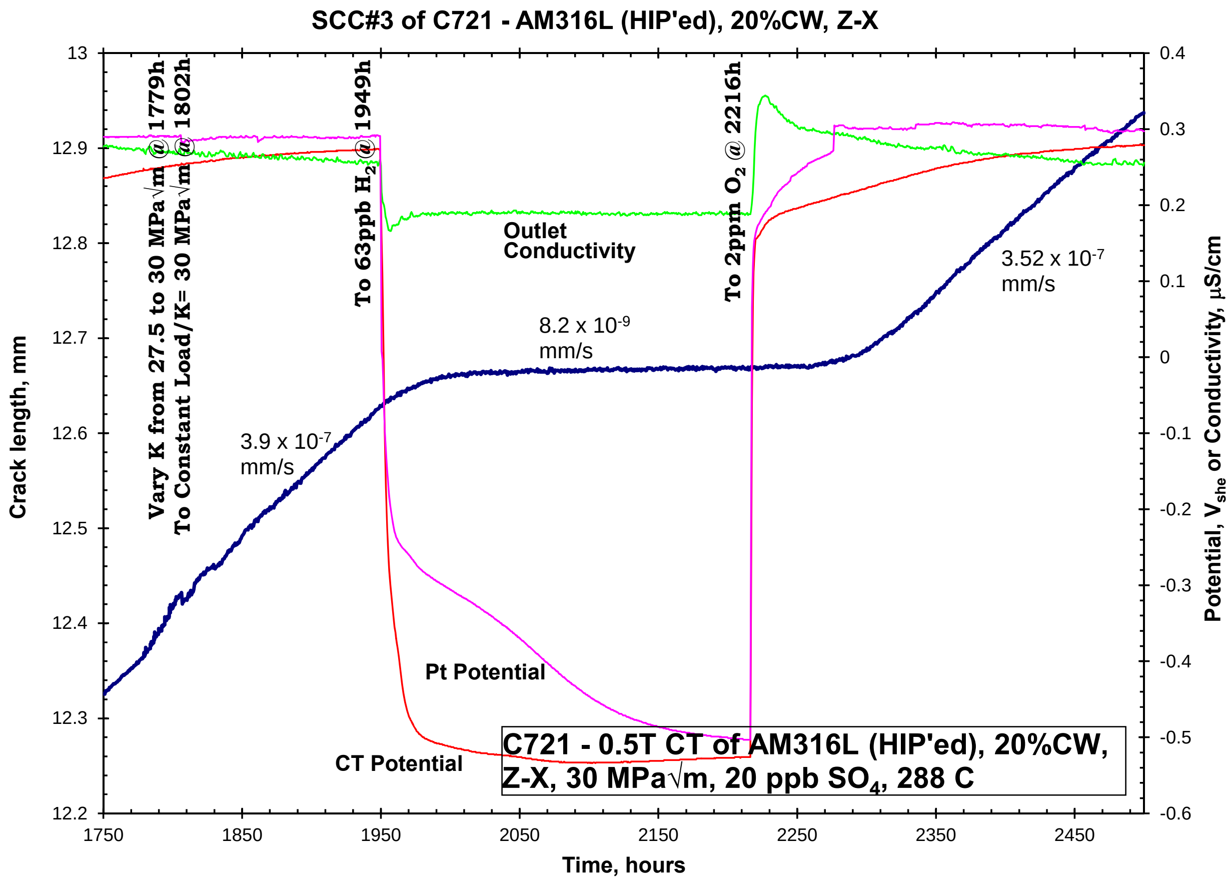
Earlier GEH/GRC Efforts (cont.)



(a) Stress-relieved (b) HIP'ed+annealed

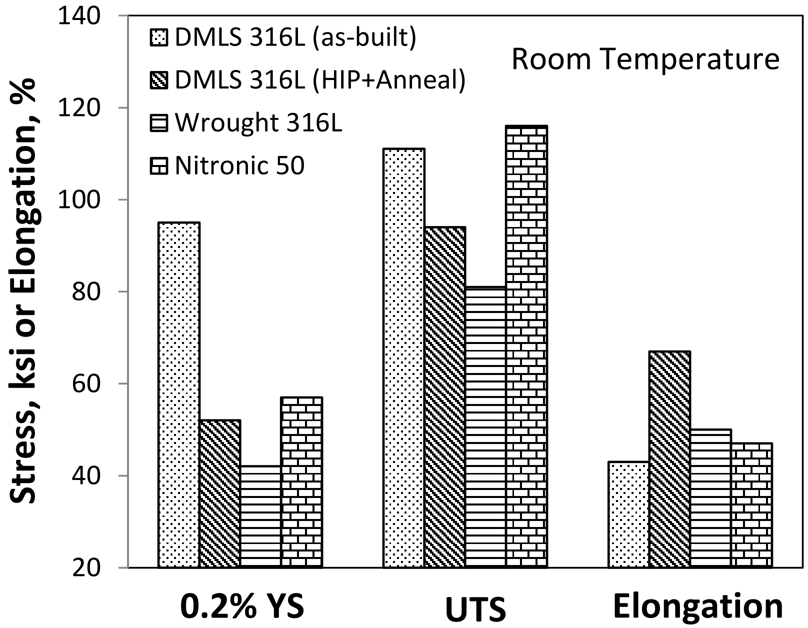
<u>Orientations of CT specimens for crack growth studies</u>

Earlier GEH/GRC Efforts (cont.)

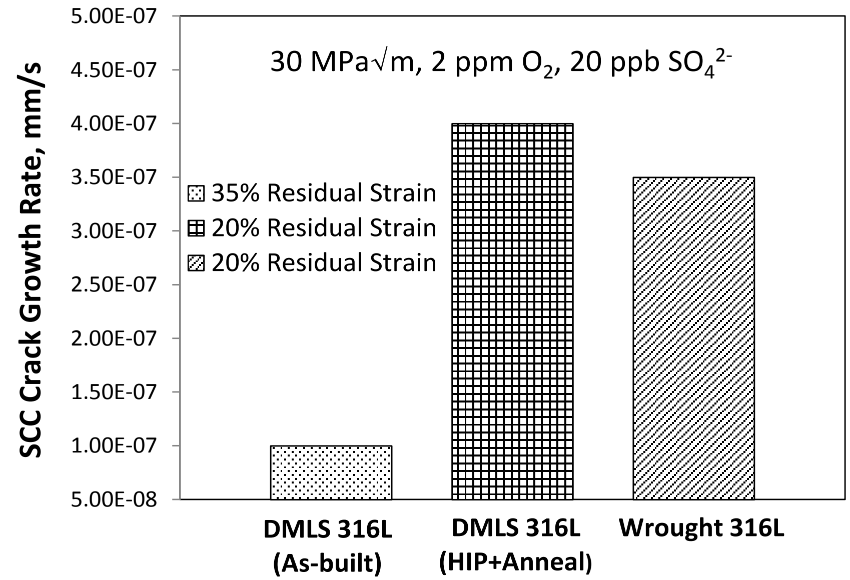


Crack growth rate of HIP'ed DMLM 316L SS at 30 MPa√m (288°C high temperature conditions)

Summary of GEH/GRC Efforts



Mechanical property comparison of DMLM Type 316L and Wrought Type 316L.



SCC crack growth rate comparison of DMLM and Wrought Type 316L

Mechanical and SCC behavior essentially the same for DMLM and wrought Type 316L

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On-going GE Global Research Led NEET (DOE) Program

- Combined Program Team of GE Global Research, University of Michigan,
- ORNL and GE Hitachi
- Top Level Objectives :
  - Addressing Technical Gaps in AM Materials
  - Lowering the overall component life cost
  - Developing nuclear specification for AM materials
- Four main tasks:
  - Task 1: Evaluating commercial AM stainless steel
  - Task 2: Optimizing commercial AM stainless steel
  - Task 3: Advanced AM stainless steel for SCC and radiation
  - Task 4: Component demonstration & nuclear specification

Support fundamental understanding and development of AM material for nuclear applications

Overview of the NSUF INL-DOE-GEH Program

NSUF Additive Manufacturing Program

- Top Level Objectives :
- Provide focused research opportunities and dedicated industry engagement: realize the full potential of nuclear through advanced technology
- Optimizes public-private partnership headquartered at INL
- The program is needed to accelerate commercial readiness for implementation of innovative technologies

GEH/INL/DOE Additive Manufacturing Programs

- <u>Specific NSUF AM Program</u>:
- GEH wants to use innovative additive manufacturing (AM) to make components for in-core use
  - Near term applications for Type 316L
  - Alloy 718 offers potential for long term benefits
- Need to assure customers, regulator that AM materials respond to irradiation just like wrought materials
- GEH makes the AM materials and NSUF irradiates them, tests them, characterizes them
- GEH and INL validation will help the industry implement Additive Manufacturing in Nuclear Industry

Program Scope

The following material preparation details will be provided to support the program:

- Two materials will be evaluated: Type 316L stainless steel and Nickel base Alloy 718
- Conventional material powder alloy compositions
- DMLM specimens will be made by GE Power (Greenville facility)
  - Same batches will be used for un-irradiated and irradiated assessments
- Both vertical and horizontal sample orientation will be evaluated
- Material processes and heat treatments will employ LWR industry standards; all materials will be HIP'ed

GEH Un-irradiated Scope

Following material preparation by GEH, basic mechanical properties will be measured:

- Type 316L stainless steel:
  - Vertical and horizontal tensile tests: RT and 288°C C
  - Vertical and horizontal low cycle and high cycle fatigue test at RT
    - Multiple strain levels
  - Microstructural characterization
- Alloy 718:stainless steel:
  - Tensile tests: RT and 288°C: potentially two heat treatments
  - Low cycle and high cycle fatigue test at RT
    - Two strain levels
  - Microstructural characterization

Irradiated Scope (INL)

- Using AM specimens processed by GEH, INL will irradiate the specimens in ATR
- INL efforts will be focused on assessing the effects of irradiation
  - Fracture toughness and crack growth rate tests will provide best indications of changes
- INL Testing: efforts will be the same for both Type 316L and A718
  - Tensile testing at RT
  - Fracture toughness at RT
  - IASCC environmental crack growth rate testing at 288°C
- TEM and microstructural characterization of both alloys

The INL-DOE effort for GEH (customer) will support the use of Type 316L in actual BWR applications

GEH/INL/DOE Additive Manufacturing Program

- Long term benefit of NSUF AM Program:
- Additive manufacturing program will set the stage to use AM for core applications prior to developing irradiated test data
  - Direct comparison expected to confirm that controlled AM material can be compared to wrought material in un-irradiated condition
    - Microstructural and test data behavior should be the same as wrought: irradiation will cause no surprises
- First use requires assuring customers, regulator that AM materials respond to irradiation just like wrought materials
- GEH and INL validation will help the industry implement Additive Manufacturing in Nuclear Industry with other materials without irradiated data in advance

Program will accelerate AM use

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Summary

3D Metal Printing/Innovation/GAIN

- Additive Manufacturing provides many advantages:
  - Speeds up Innovation
  - Design-driven manufacturing as opposed to manufacturing-constrained design
  - Specialized materials
- Nuclear industry has more difficulty in incorporating new materials, designs
  - Costly validation, limited facilities
- Collaboration between NSUF and GEH will facilitate more rapid use of Additive Manufacturing for In-core Applications

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