2015 DOE-NEET:
Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing (AM)

Xiaoyuan Lou (loux@ge.com)

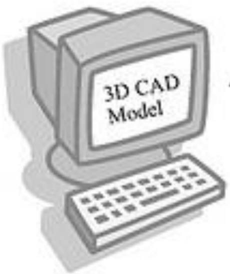
Ceramics and Metallurgy Technologies
GE Global Research, Niskayuna, NY

2015 DOE AMM Workshop, Arlington, VA
Sep. 29, 2015

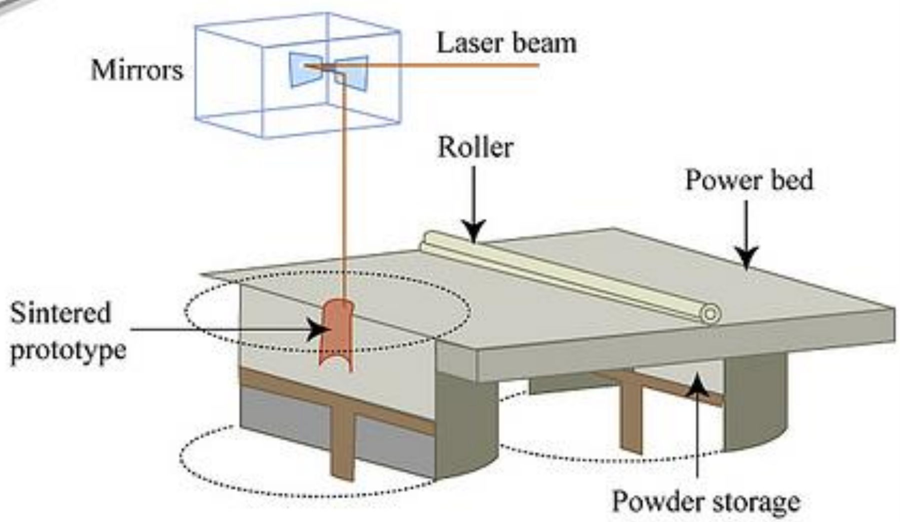
This material was prepared with the internal support from General Electric Company.

Additive Manufacturing for Nuclear Overview

Additive Manufacturing (3D Printing)

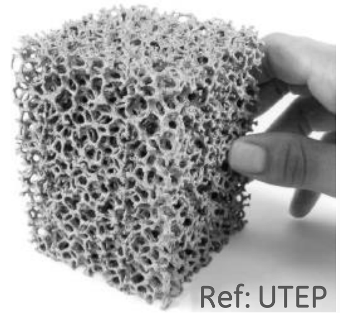


Direct Material Laser Melting (DMLM)

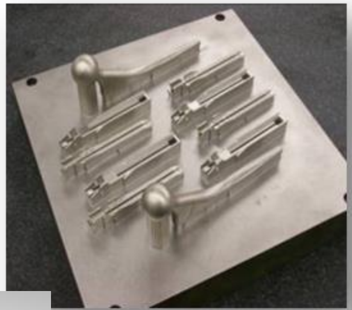


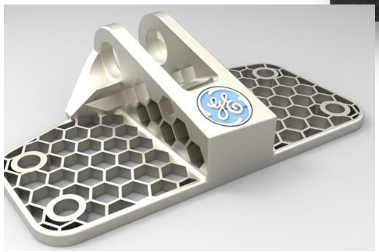
from metalbot.org

Ref. Within Labs, UK



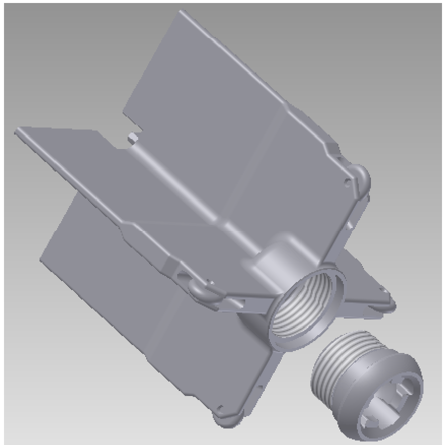
Ref: UTEP





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

Value of Additive/3D Manufacturing for Nuclear

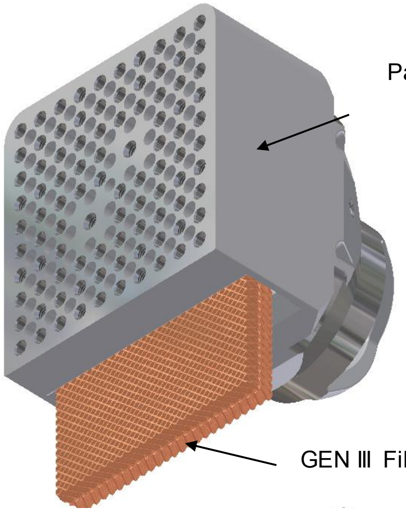


Speed of Delivery: Fast turnaround time

- Quick response to emergent needs and custom designs during outage interval
- Rapid prototyping
- Short design-to-commercialization period

Design for Performance: Fewer manufacturing limitations allow new designs for next generation reactor

- Design-driven manufacturing as opposed to manufacturing-constrained design
- Complex/expensive parts including hardfacing



Equivalent or Better Wrought Properties:
Eliminating welding in a complex structure

Enhanced chemistry control:
Powder atomization → Low Cobalt

Current Technical Gaps

High cost and high/unknown risk:

At this time, additively manufactured components generally have much higher manufacturing cost and higher or unknown risk in the reactor environment

No nuclear specified research on AM materials/processes:

Existing AM processes for most common materials, including stainless steel and Inconel alloys, have not been developed for nuclear needs.

- ❑ Stress corrosion cracking (SCC)
- ❑ Corrosion fatigue (CF)
- ❑ Irradiation resistance

Lack of specification/qualification

Need to address processing and material variability prior to codifying the material for nuclear use.

Goals of this Program – Addressing the Gaps

Lowering the overall component life cost:

Understanding and utilizing the non-equilibrium microstructure by laser process to improve the nuclear specified material properties

- ❑ Eliminating post treatment cost from HIP
- ❑ Replacing high performance alloys and welding/cladding operations
- ❑ Improving service life and reduce asset management costs.

Evaluating nuclear specified properties:

In addition to common mechanical properties, the program will evaluate the following properties for AM 316L stainless steel under various post heat treatments:

- ❑ Stress corrosion cracking (SCC)
- ❑ Corrosion fatigue (CF)
- ❑ Irradiation resistance

Developing nuclear specification for AM materials

- ❑ Understanding process variability in terms of nuclear properties
- ❑ Contributing to the development of nuclear specification for AM

Technical Concepts

Non-equilibrium Microstructure by Laser Process

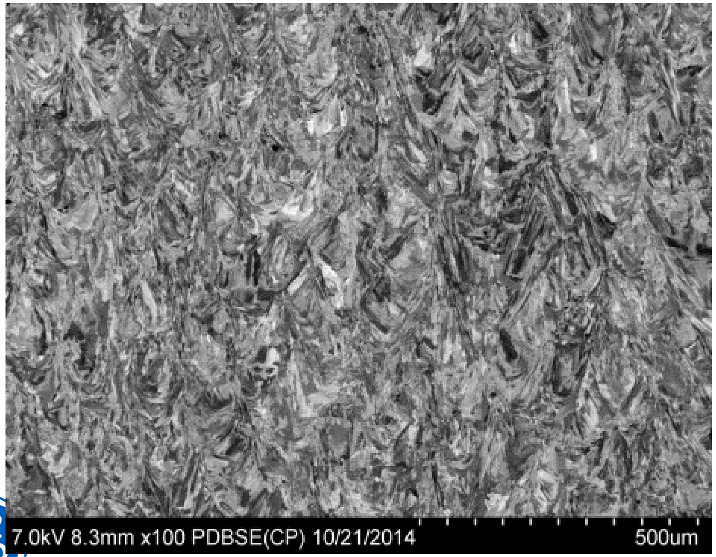
Direct metal laser melting process:

1. high local temperature
2. extremely fast cooling rate

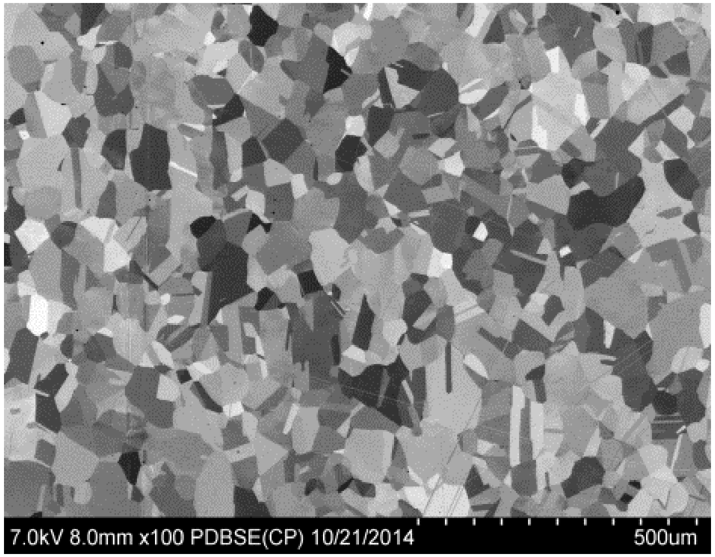
- ❑ ultrafine nanostructure
- ❑ minimum elemental segregation
- ❑ supersaturated solution
- ❑ non-equilibrium phases
- ❑ less diffusion controlled phase transformation

Non-equilibrium structure can produce desirable effects on material's properties

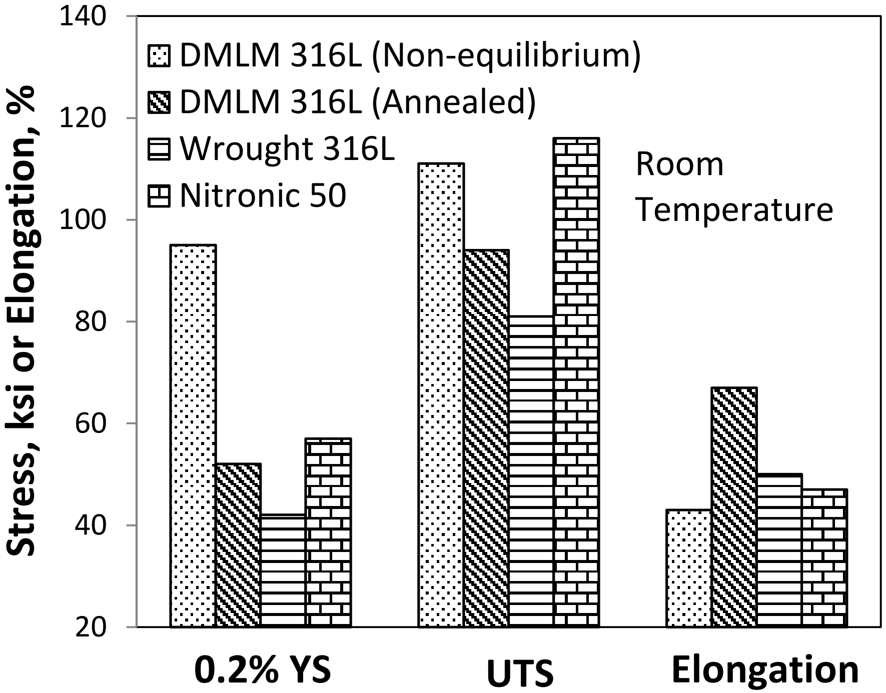
Non-equilibrium structure

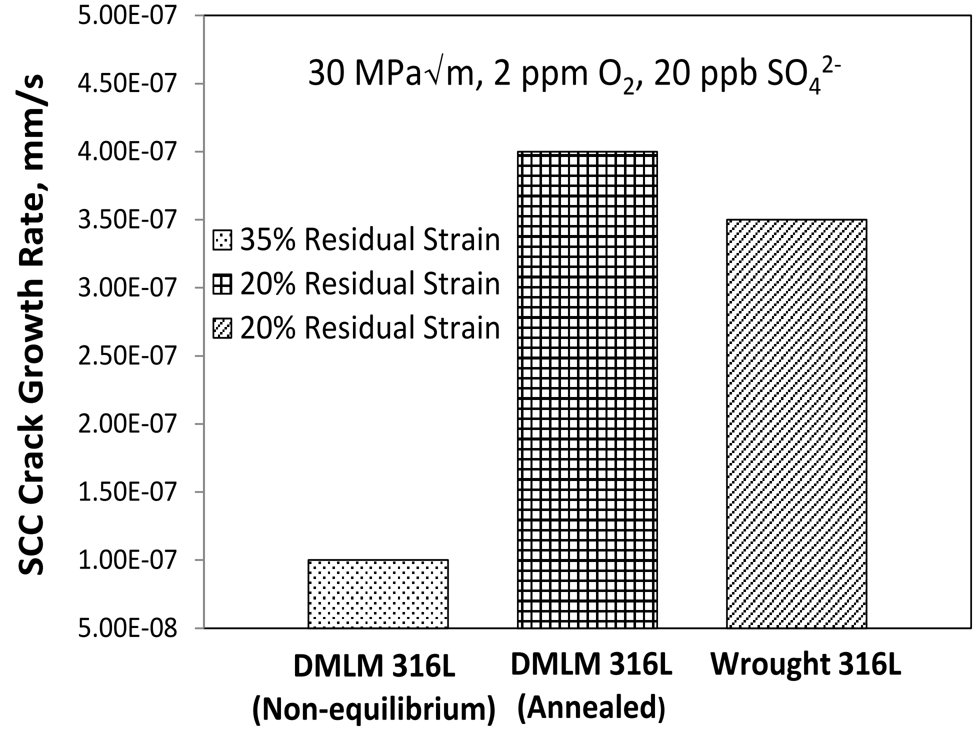


Annealed structure



Mechanical and SCC Properties

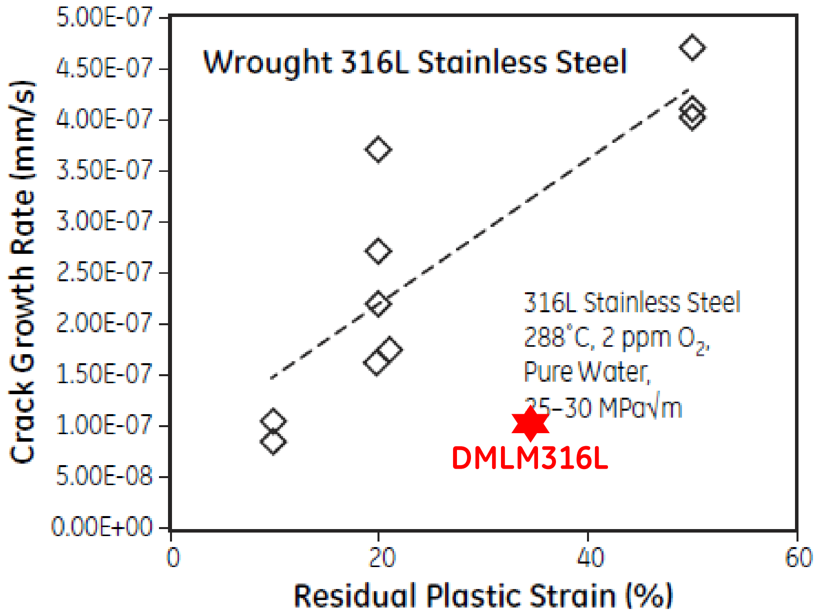




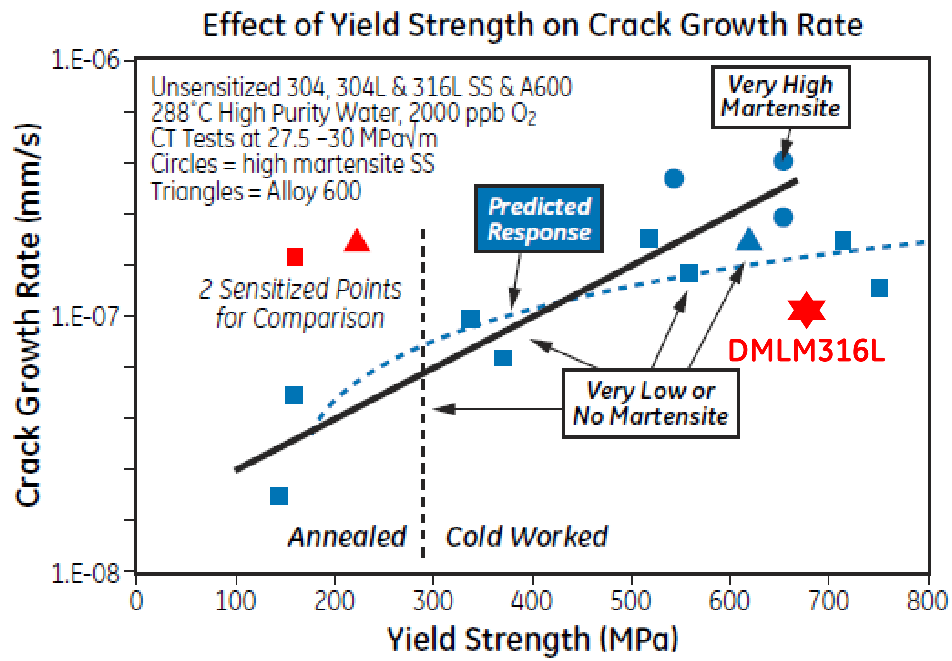
- ❑ Non-equilibrium DMLM 316L stainless steel shows higher strength, reasonable ductility and lower stress corrosion crack susceptibility in high temperature water
- ❑ Mechanical properties are very close to Nitronic 50 alloy

Stress Corrosion Cracking of Austenitic Stainless Steel

Residual Strain vs. SCC



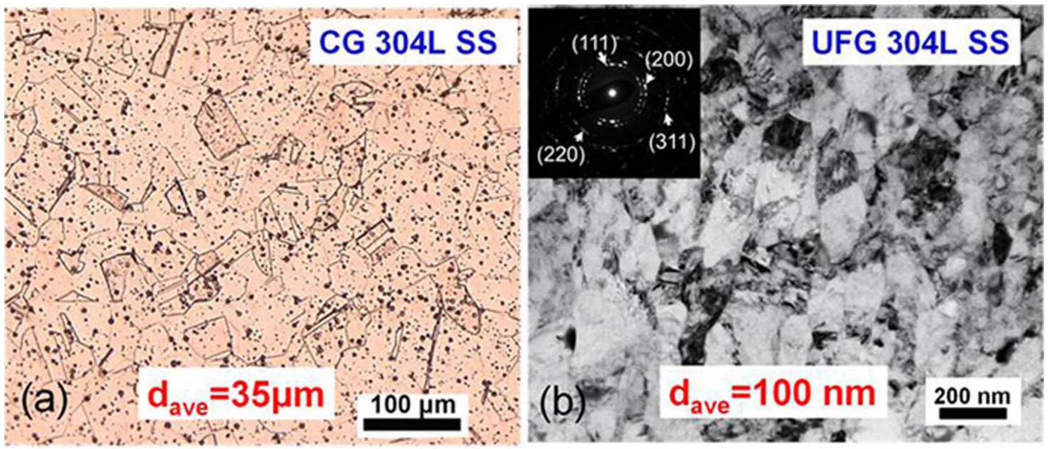
Yield Strength vs. SCC

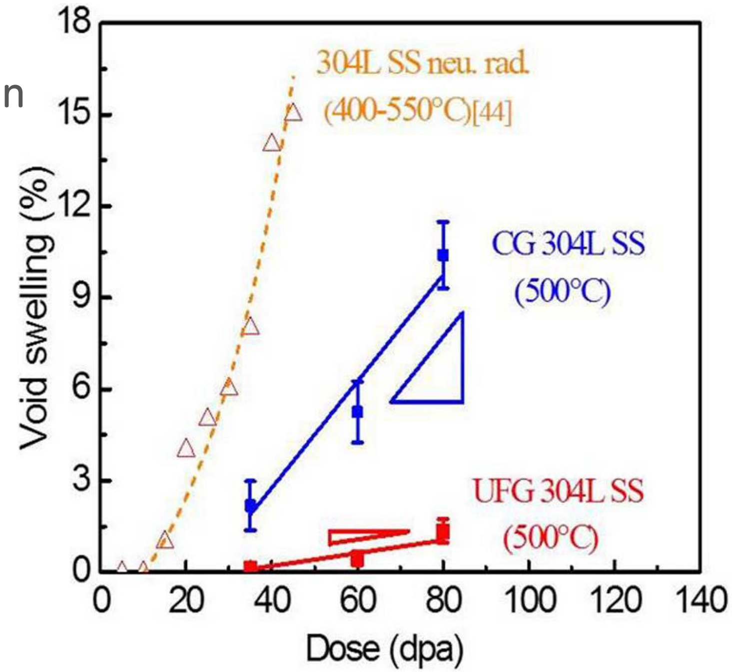


- ❑ For conventional austenitic stainless steel, SCC susceptibility generally increases with strength/cold work.
- ❑ The SCC behavior of non-equilibrium DMLM 316L vs. annealed DMLM 316L stainless steel is contradictory to the conventional theory, which is due to its unique microstructure.

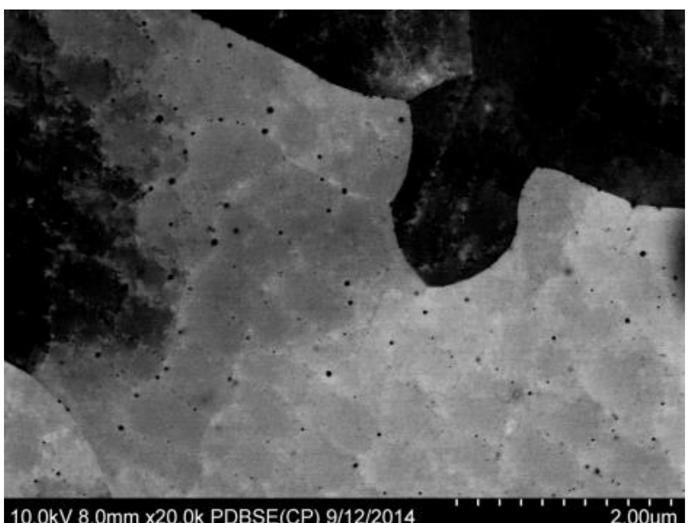
Irradiation Resistance of Nanostructured Austenitic Stainless Steel

Irradiation comparison: Coarse grain vs. ultrafine grain austenitic stainless steel by Equal Channel Angular Pressing





C.Sun, et al., Scientific Reports 5, Article number: 7801 (2015)



Understanding and controlling the nanostructure and ultrafine precipitates in DMLM stainless steel can lead to super irradiation resistant stainless steel

Program Outline

Teams, Approaches, Deliverables

Understanding and controlling the DMLM non-equilibrium microstructure to improve material's nuclear performance:

high strength, high SCC resistance, high irradiation tolerance

Program Team

GE Global Research

- 40 years of experience in environmental degradation of nuclear materials
- Industrial leader of advanced manufacturing and material technology

Oak Ridge National Lab

- Laser melting process development

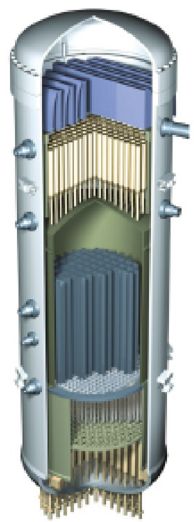
University of Michigan

- Leading lab for irradiated material research
- Environmental cracking of irradiated materials

GE-Hitachi Nuclear

- New component by DMLM
- Regulatory and commercialization plan for additive manufacturing

2-Year, $850K Program to Develop Environmental Cracking and Irradiation Resistant Stainless Steel by Additive Manufacturing



Program Objectives:

- *Understand and control the non-equilibrium nanostructure during laser additive manufacturing process to develop a SCC and irradiation resistant super 316L stainless steel*
- *With the improved performance, the technology can save life cycle cost and deployment schedule with improved plant reliability*
- *Evaluate SCC and irradiation resistance of 316L stainless steel by additive manufacturing*
- *Develop a plan for regulatory approval and commercialization*

Technical Approaches

- Understand the correlation between laser process, non-equilibrium nanostructure, and SCC/irradiation resistance
- Perform stress corrosion cracking, corrosion fatigue and irradiation tests
- Component fabrication to demonstrate the time and overall cost saving

Technical Challenges

- It may take some time to reproduce GE's material at Oak Ridge National Lab.
- Surface roughness may add another fact to IASCC crack initiation

Program Deliverables

- A novel concept and technology for additive manufacturing in nuclear application
- Technical database about SCC and irradiation resistance of additively manufactured material
- A plan for regulatory approval and commercialization

Anticipated Benefits of the Proposed Technology

An improved additive manufacturing process for stainless steel nuclear components that

- Rapidly fabricates custom designed parts
- Saves overall life cycle cost and plant management cost
- Improves the reliability of nuclear power plant

GE Global Research's world class nuclear research facility for materials degradation

- 50+ fully instrumented high temperature water SCC testing systems for crack initiation and growth study
- 14 high temperature electrochemistry systems
- All stages of alloy processing capabilities, from melting to hot/cold working to heat treatment
- State-of-the-art materials characterization facility

Program Scope

Program Activities		GRC	ORNL	UM	GEH	Year 1 Q1	Year 1 Q2	Year 1 Q3	Year 1 Q4	Year 2 Q1	Year 2 Q2	Year 2 Q3	Year 2 Q4
Task 1	**Laser Process Development for Improved Material Properties**					■	■	■	■	■	■	■	■
1.1	Correlation between laser process, microstructure and properties	●	●			■	■	■	■				
1.2	Optimize 316L stainless steel with improved nuclear performance	●	●							■	■	■	■
1.3	Nuclear component fabrication and evaluation	●	●		●					■	■	■	■
Task 2	**Microstructure and Mechanical Characterization**					■	■	■	■	■	■	■	■
2.1	Microstructure characterization	●	●			■	■	■	■	■	■	■	■
2.2	Tensile property	●	●			■	■	■	■				
2.3	Fracture resistance	●				■	■	■	■				
Task 3	**Environmental Degradation Evaluation**					■	■	■	■	■	■	■	■
3.1	Stress corrosion crack growth	●				■	■	■	■	■	■	■	■
3.2	Corrosion fatigue crack growth	●				■	■	■	■	■	■	■	■
Task 4	**Irradiation Resistance Evaluation**					■	■	■	■	■	■	■	■
4.1	Irradiation effects - microhardness and IASCC susceptibility			●		■	■	■	■	■	■	■	■
4.2	Irradiation effects - microstructure characterization			●		■	■	■	■	■	■	■	■
Task 5	**Material Specification for Nuclear, Plan for Regulatory Approval and Commercialization**	●			●					■	■	■	■