Additive Manufacturing in the Nuclear Industry

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Mechanical Equipment Development

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Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Additive Manufacturing (AM) in the Nuclear Industry

Agenda

- Overview of AM technologies
- Challenges with AM
- Applications in the nuclear industry
- Component qualification
- AM at Canadian Nuclear Laboratories

AM Technologies

Terms

According to ASTM Standard F2792-12a, "Additive Manufacturing" is:

"*the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining*"

This is generally synonymous with "3D printing"

AM Technologies

Additive vs. Subtractive Manufacturing

- Additive manufacturing is a "bottom-up" process whereas subtractive manufacturing is a "top-down" process
- Additive offers a number of advantages
  - Reduced material waste
  - Potential to manufacture more complex geometry
  - Potential reduction in lead time
  - Potential flexibility in materials

AM Technologies

Additive vs. Subtractive Manufacturing

- There are also some disadvantages associated with AM
  - Poor surface finish, post-processing requirements
  - Complexities with material properties
  - Build rates
  - Equipment cost
  - Component size

AM Technologies

Materials

- Plastics – Primarily for rapid prototyping but many end use applications
- Metals
- Ceramics
- Food, tissue, insulation, etc.

AM Technologies

General

- There are a wide variety of AM processes used in industry. These include:
  - Material Extrusion, Fused Deposition Modelling (FDM, Stratasys), fused filament fabrication, etc.
  - Powder bed fusion, Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron beam melting, etc.
  - Directed energy deposition, Laser Metal Deposition (LMD), Blown powder, etc.
  - Vat Photopolymerization, Stereolithography, etc.
  - Hybrid technologies
  - Etc.

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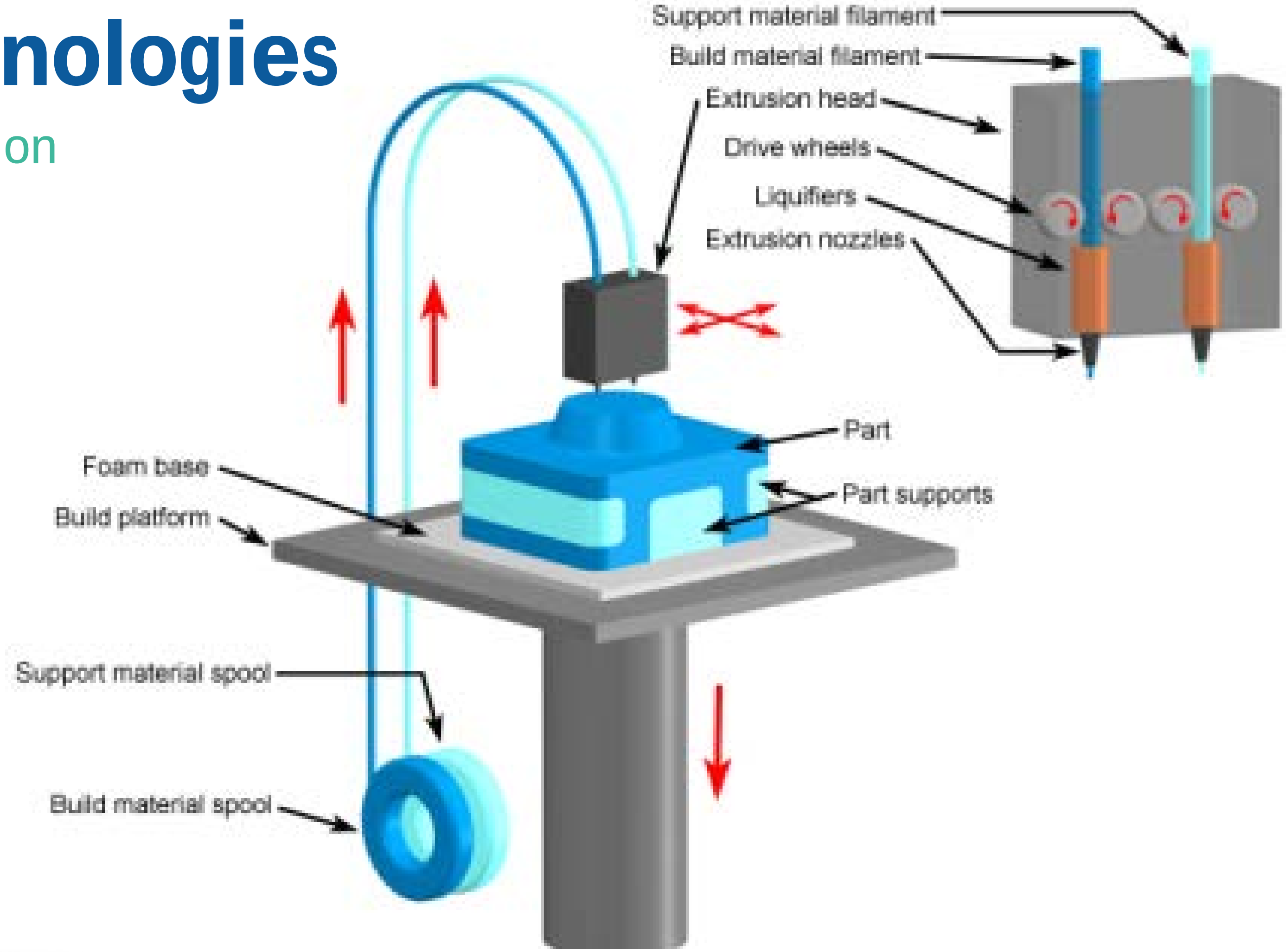
AM Technologies

Material Extrusion



AM Technologies

Material Extrusion

- Advantages
  - Well established technology
  - Complex geometry can be produced
- Disadvantages
  - Most suited to plastics

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→ Best suited for rapid prototyping applications, but some end-use applications

AM Technologies

Material Extrusion

- Advancements in Material Extrusion technology

→ Printing of metals!

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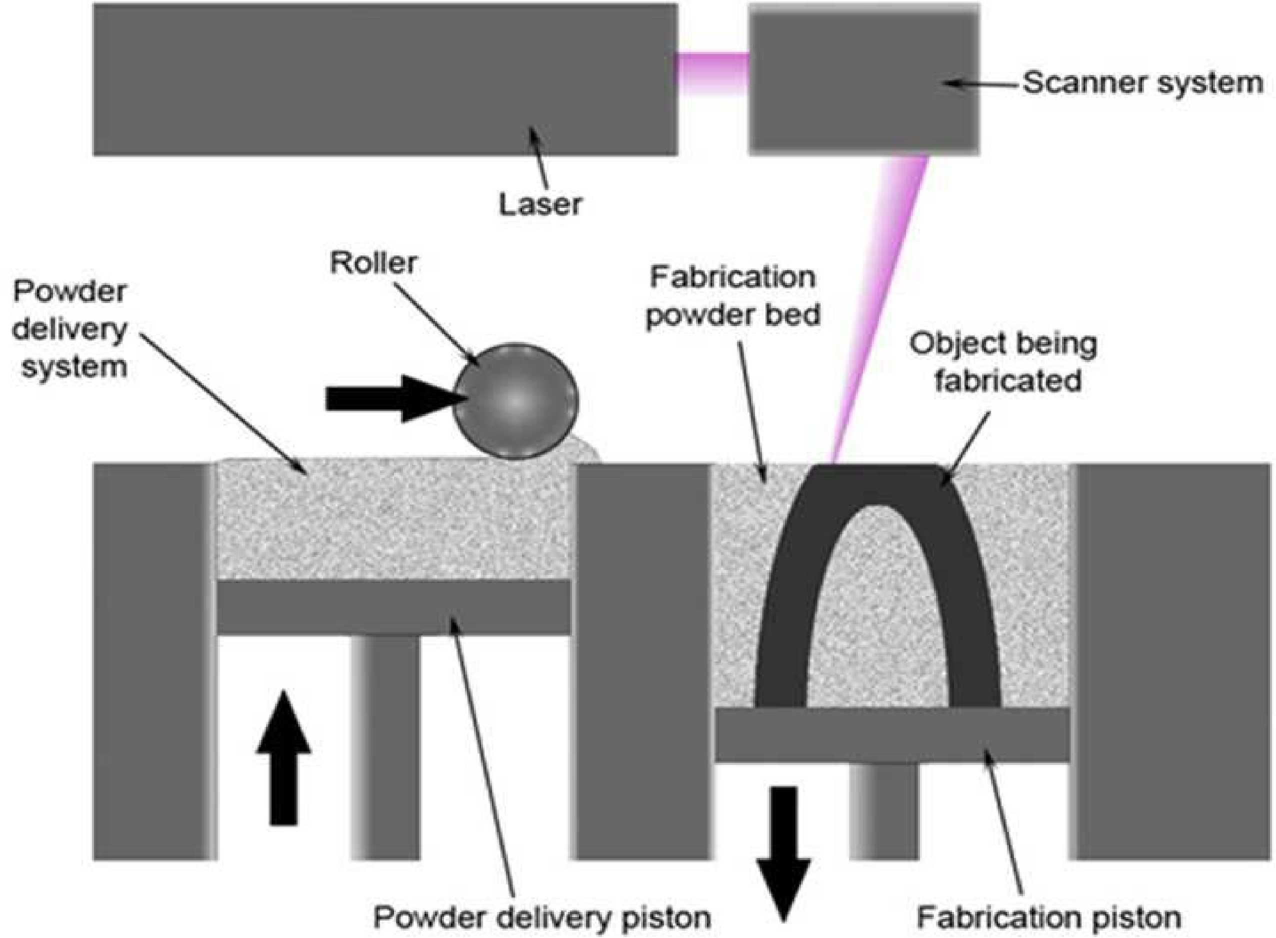
AM Technologies

Powder Bed Fusion



AM Technologies

Powder Bed Fusion

- Advantages
  - Large investment in development in the industry
  - Complex geometry
- Disadvantages
  - Size of printed component generally limited
  - Surface finish is poor and post processing is generally required

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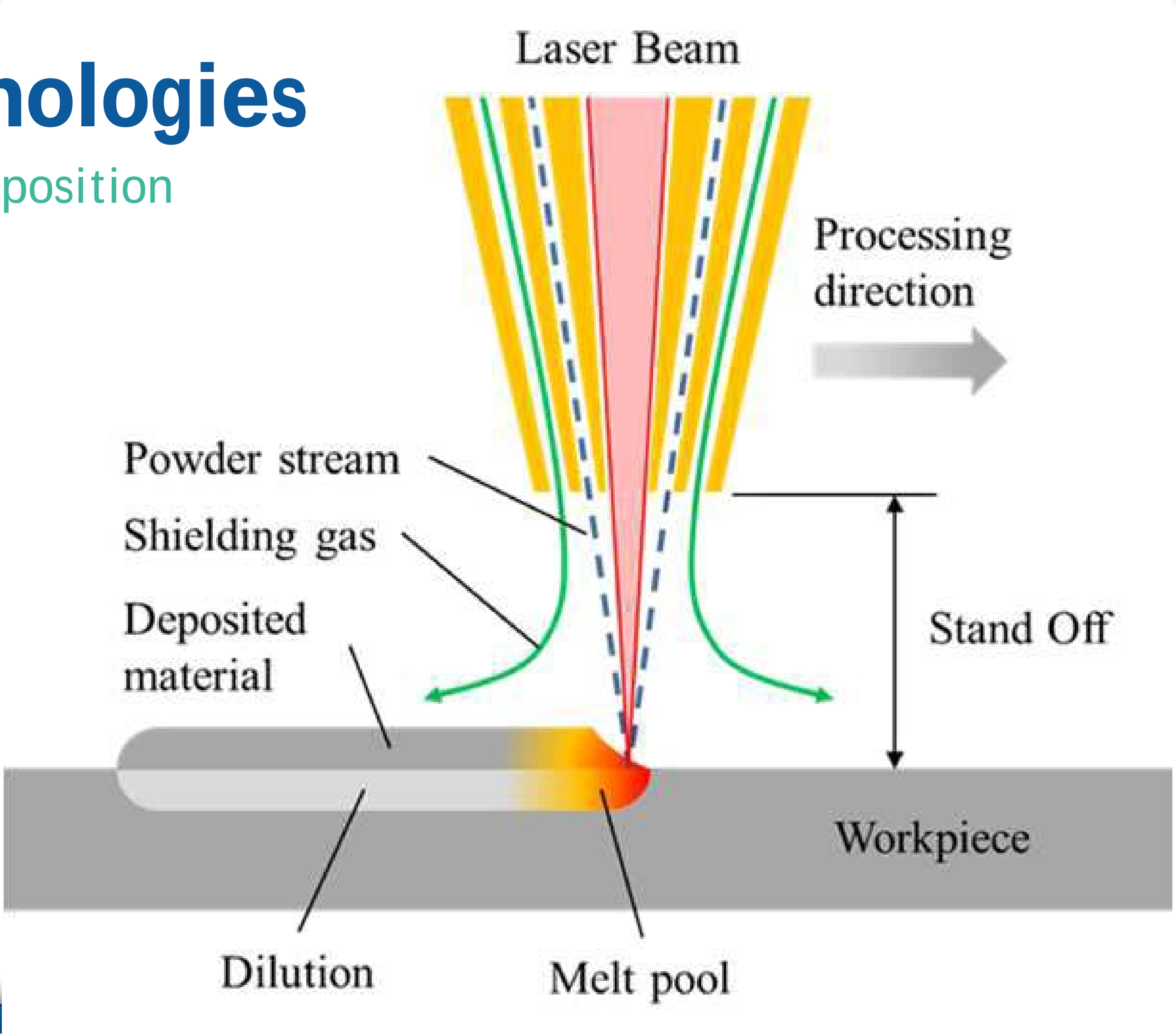
AM Technologies

Direct Energy Deposition



AM Technologies

Direct Energy Deposition

- Advantages over powder bed fusion
  - Much less metal powder is used
  - Deposits are fully fused to the substrate
  - Lower heat input
  - Generally better microstructures due to low heat input and high solidification rate
  - Very large or small parts are feasible
  - The composition of the component can also be changed more readily throughout the component

AM Technologies

Direct Energy Deposition

- Disadvantages
  - Overhung features are more difficult
  - Process complexity
  - Slow build rate
  - Expensive infrastructure
  - Safety issues associated with the use of inert gas, metal powders and a high power laser

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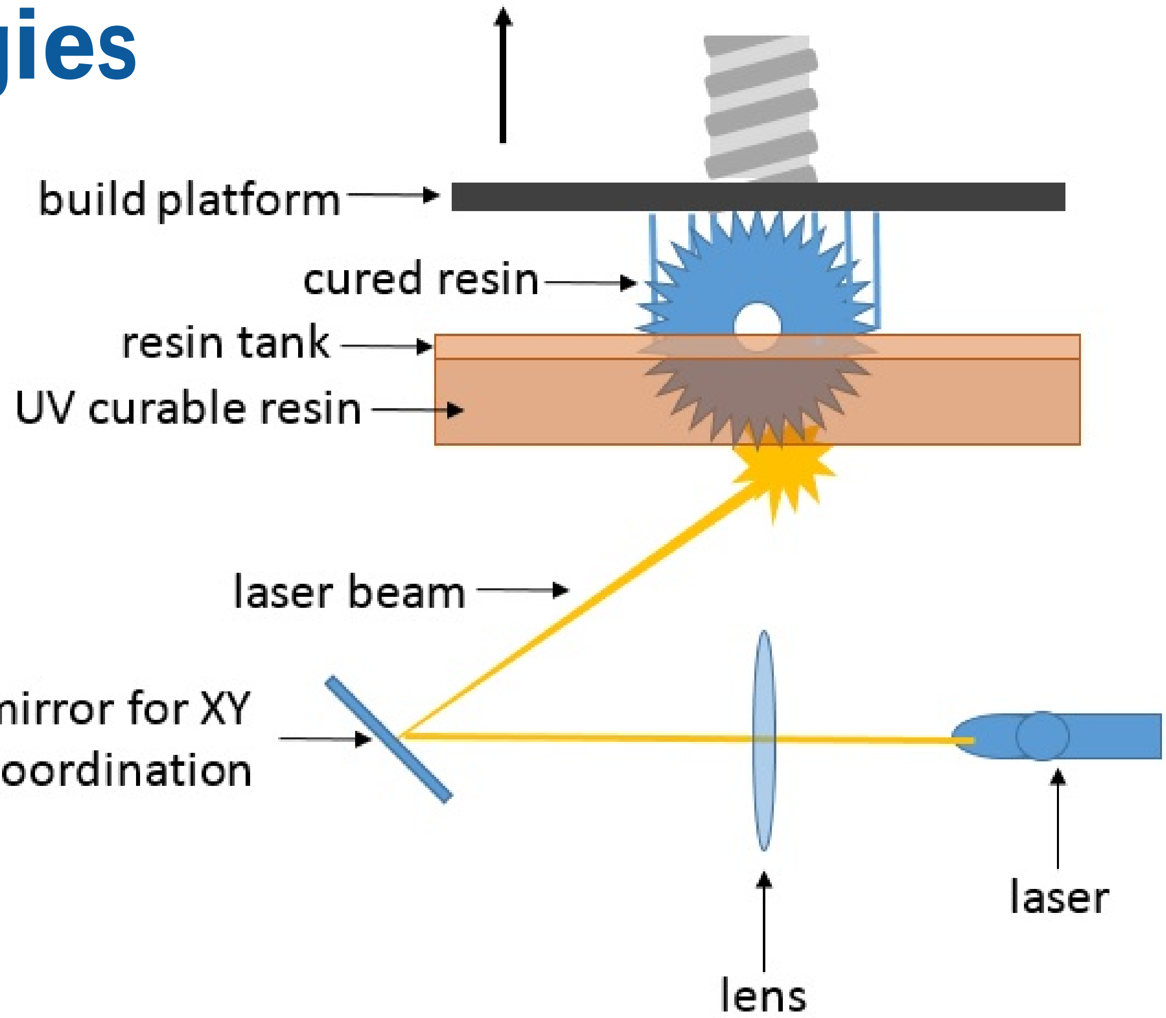
AM Technologies

Vat Polymerization



AM Technologies

Vat Polymerization

- A wide variety of materials can be printed including ceramics and metals
- Ceramic and metal printing involves a debinding and sintering step

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Challenges with AM

Just push “print”?

- Process is largely component-dependent
- Moving from research to practical implementation
- Equipment expense
- Print orientation
- Safety
- Mass production
- Non-destructive examination
- Component Qualification
- Poor surface finish, post-processing requirements
- Component size

Applications in the nuclear industry

A blank slate!

- Tooling
- New reactor design
    - Advanced components
        - Variable properties
        - Embedded sensors
    - Efficient designs
- Repair
- Replacement components
- Fuel
- Prototyping and visualization

Component Qualification

General

- As AM-related Standards are not yet mature and new AM technologies are continuously being developed, it is difficult to outline a “one size fits all” Qualification process.
- A program would need to be developed for each specific application and would no doubt include an analysis of:
  - Residual stresses
  - Microstructure
  - Mechanical performance
  - Corrosion resistance
  - Comparison to traditionally-manufactured material
  - Etc.

AM at Canadian Nuclear Laboratories

General

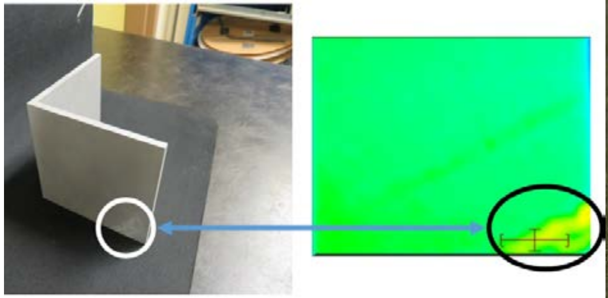
Over the past several years, CNL has been developing its AM capabilities as it is applied to nuclear components and fuels. This has led us to:

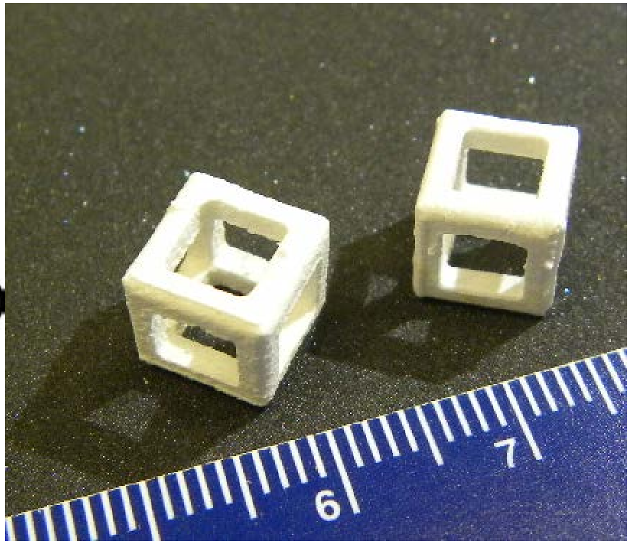
- Technical progress in targeted areas
- Strategic partnerships
- Expanding in-house facilities
- Produce a technology roadmap document to set goals and lay out the path to achieving those goals

AM at Canadian Nuclear Laboratories

Branches of Development

- Metal printing (with a focus on nuclear material)
- Non-destructive examination of AM components
- Printing of nuclear fuel





3D Metal Printing

Collaborations and Partnership

CNL has partnered with select organizations to advance its additive manufacturing knowledge and capabilities. Specifically, CNL has partnered with the University of Waterloo and National Research Council Canada on specific projects related to the deposition of Zirconium on various substrates. CNL is also a proud member of The Welding Institute (TWI) and is working to leverage the work on additive manufacturing that TWI is doing with their partners and members.

3D Metal Printing

Strategic Partnerships - Highlight

- Work with the University of Waterloo was focused on the deposition of Zirconium and investigated the influence of:
  - Powder feed rates
  - Travel speeds
  - Auxiliary shielding gas
  - Shielding gas on cladding contamination
  - Geometry control
- Tests were performed on both as received and recycled metal powder
- Tensile test specimens were cut from deposited material for testing

3D Metal Printing

Strategic Partnerships - Highlight

- A good understanding of the influence of various deposition parameters for Zirconium was gained.
- We were successful in depositing Zirconium and producing solid material that behaved similarly to conventionally-produced solid material.

Material / Powder Type	Orientation and/or location	Young's modulus (GPa)	YS (MPa)	UTS (MPa)	Elongation at UTS (MPa)	YS/UTS	Strain at fracture (%)
Substrate	Rolling	87.3	634	660	7.59%	0.960	13.8
Recycled	C1	93.0	611	731	2.53%	0.836	2.7
Recycled	C2	79.0	-	652	0.99%	-	1.2
Recycled	B	74.4	573	706	7.54%	0.811	8.2
As-received	C1	67.4	569	696	9.90%	0.817	16.3
As-received	C2	83.0	590	750	8.82%	0.787	9.4
As-received	B	88.8	578	718	8.53%	0.805	11.4

3D Metal Printing

Facilities

- In addition to the facilities that CNL has access to through its partners, CNL is establishing its own facilities.
- CNL has two LMD systems that are being installed and commissioned and will allow for rapid development and implementation of AM technology being developed and work to refine and qualify that technology.
- The AM initiatives at CNL are underpinned by well-established materials, chemistry and fuel research facilities and expertise.

3D Metal Printing

Facilities

Commissioning is underway on a laser cladding system that can be used for versatile R&D and the development of techniques to be employed on a full-function commercial system

3D Metal Printing

Facilities

- Procurement is underway for an industrial LMD Printer with the following features:
  - 5 axis CNC motion system
  - 500 x 500 x 500 mm working envelope
  - 2 powder feed units
  - 500W Nd:YAG laser
- The system will have capability to produce parts, but will also provide flexibility for additional development work.

3D Metal Printing

Related Technology Development – NDE of AM components

- To complement CNL's work on additive manufacturing, development related to the non-destructive examination (NDE) of components manufactured by AM is also a focus.
- CNL has expertise in all methods of NDT and is developing ground-breaking technology to allow for in-process monitoring of laser melting using thermographic/infrared methods.

3D Metal Printing

Related Technology Development – NDE of AM components

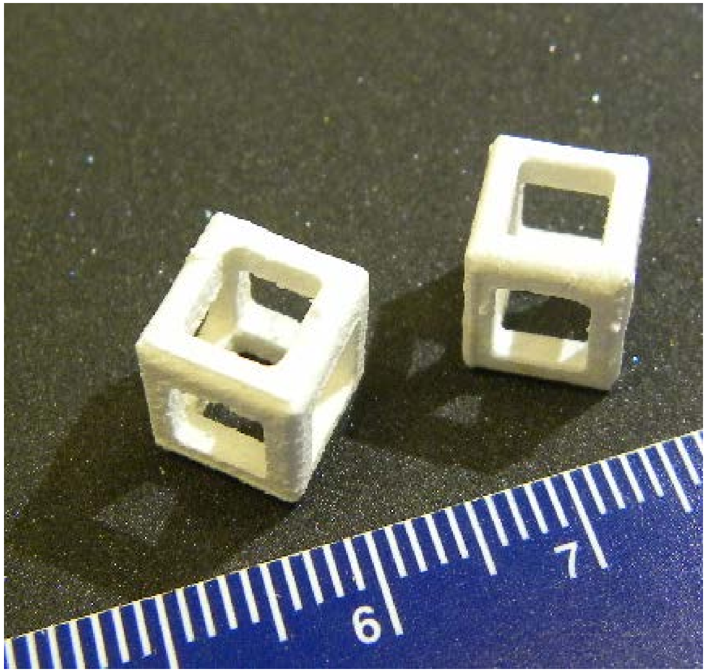
- Two key things change with AM components vs. conventional material that affect the ability to perform NDE:
  - Flaws form through different mechanisms and in different orientations
  - The fundamental NDE parameters (e.g., electrical resistivity for eddy current, speed of sound and acoustic attenuation for ultrasonics) vary with material composition, density, heat treatment history, etc.
- Radiographic methods like high-resolution computerized tomography are most commonly used in industry to inspect AM parts.

Additive Manufacturing of Nuclear Fuel

- CNL has extensive expertise in the area of nuclear fuel development, fabrication and qualification with a full suite of active laboratories and hot cells to examine nuclear fuel.
- CNL believes that AM offers a number of exciting opportunities when applied to nuclear fuel design and fabrication including:
  - Better fuel performance,
  - increased safety margins, and
  - greater accident tolerance

Additive Manufacturing of Nuclear Fuel

- CNL has had success printing ceramic fuel material and work is underway to improve and refine this capability.



3D Printing

Additive Manufacturing of Nuclear Fuel

- Printing of metallic fuel is also being pursued.
- LMD offers potential improved bonding between the fuel and the cladding and solves a problem with conventional manufacturing methods.
- AM is actually a cheaper option as it replaces several operations and expensive production equipment.

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