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Fabrication of Nanostructured Inconel 718 Alloys by Large Strain Extrusion Machining

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NNSA National Nuclear Security Administration

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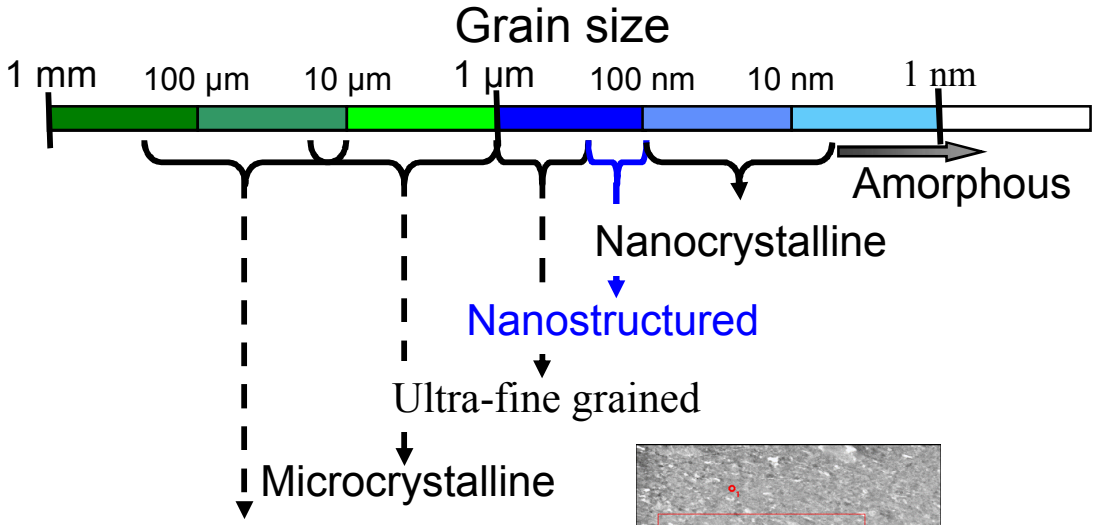
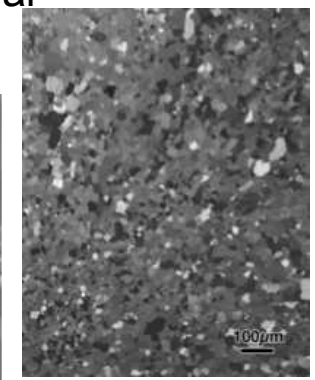
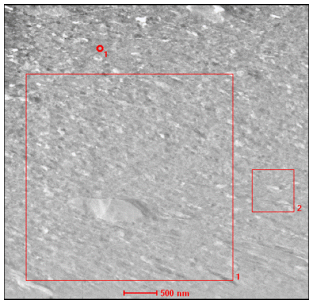
Nanostructured metals have extraordinary properties and are comprised of nanometer-sized grains.





Be- Cu



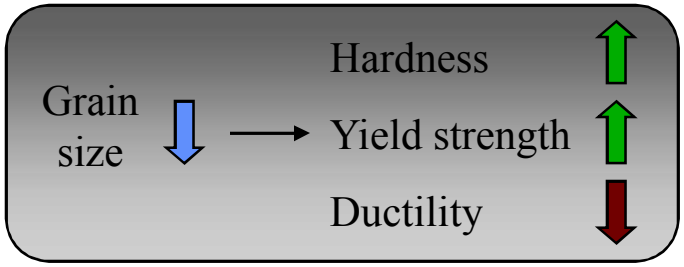
LSEM
Inconel 718

Microstructure (< 1 μm)

Nanocrystalline: < 100 nm
Nanostructured: 100 nm - 300 nm
Ultra-fine grained: 300 nm – 1 μm

The grain size affects material properties…

Increased strength $\longrightarrow$ $\tau_y \sim \tau_0 + kd^{-1/2}$



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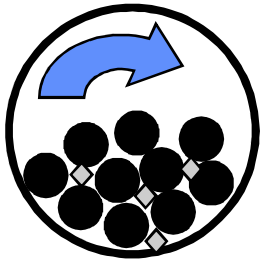
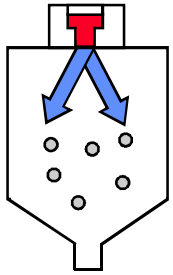
Nanostructured materials can be prepared though various processes.

Particulate



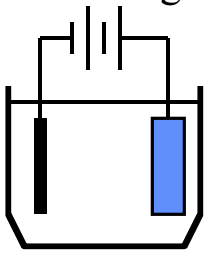
High-energy/cryogenic milling



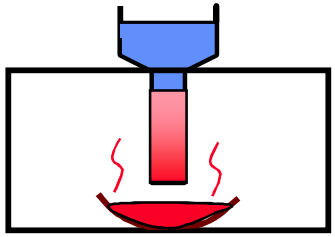
Gas atomization

Long run time
High processing costs
Limited range of materials
Low output

Film



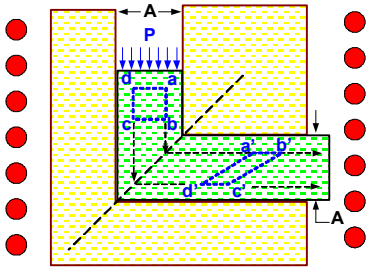
Electrodeposition



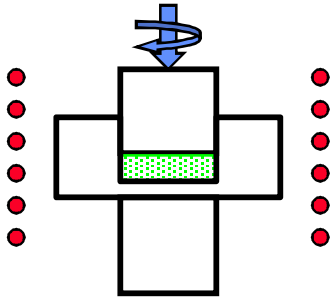
Gas condensation

Disadvantages

Bulk



Equal channel angular extrusion



High pressure torsion

Multiple passes for high strains
Limited for high-strength materials
Elevated temperatures necessary

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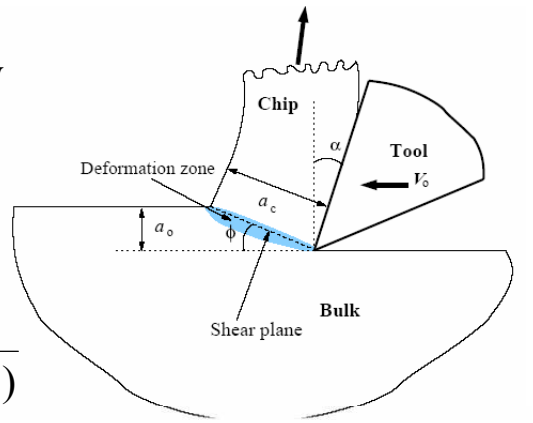
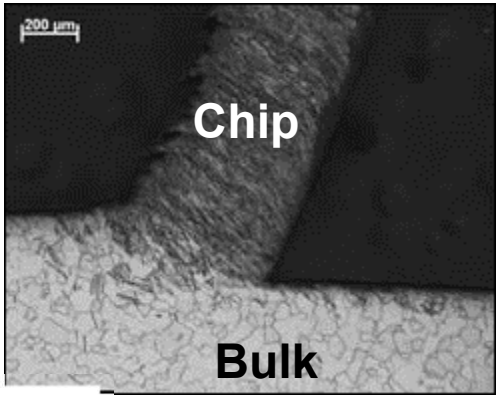
Machining is cost-effective production of nanostructured materials in any metal or alloy.

Severe plastic deformation by machining

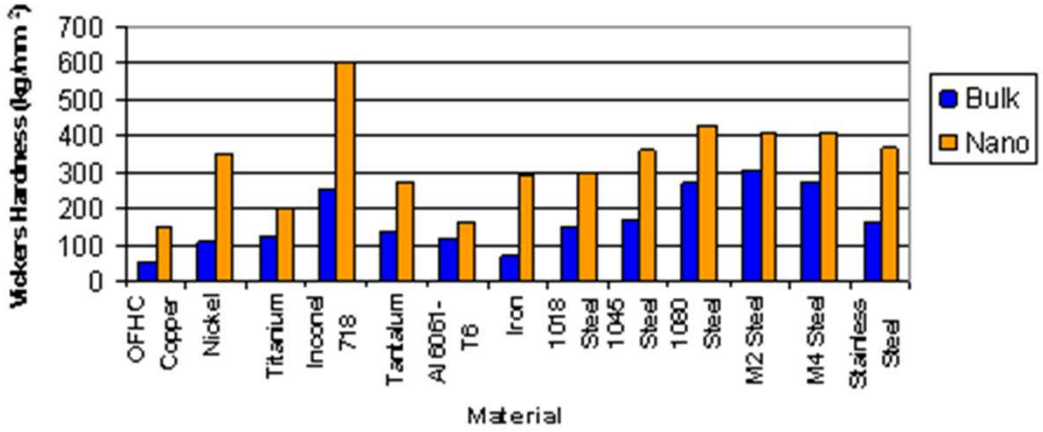
$$\gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)}$$

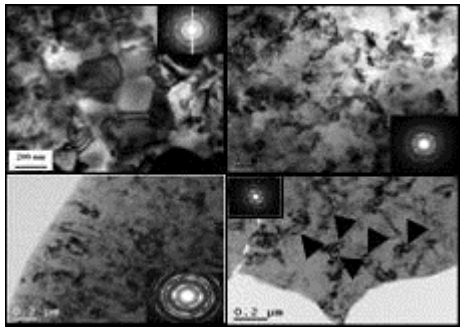




Purdue University (CMPT)

Shear strains of 1-10 in a single pass





Purdue University (CMPT)

- Machining can results in increases in hardness and strength with nanostructured grain sizes.

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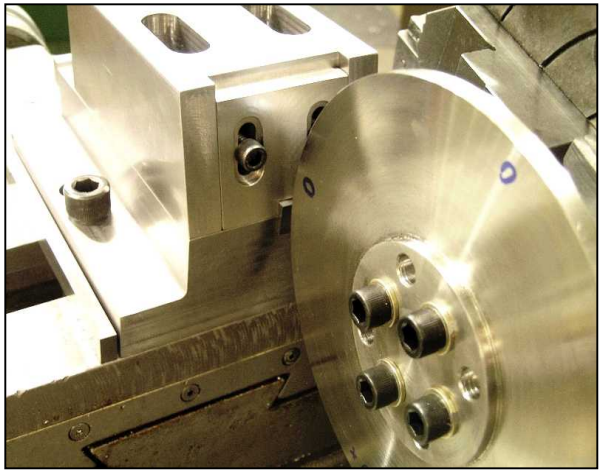
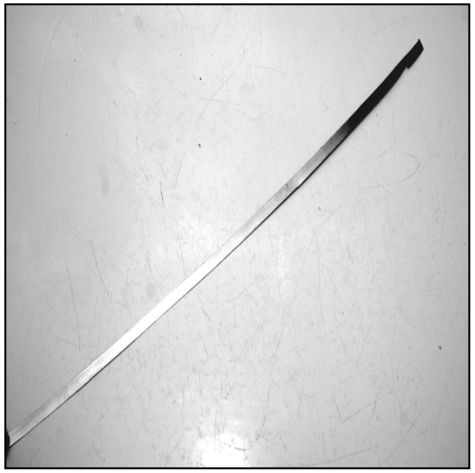
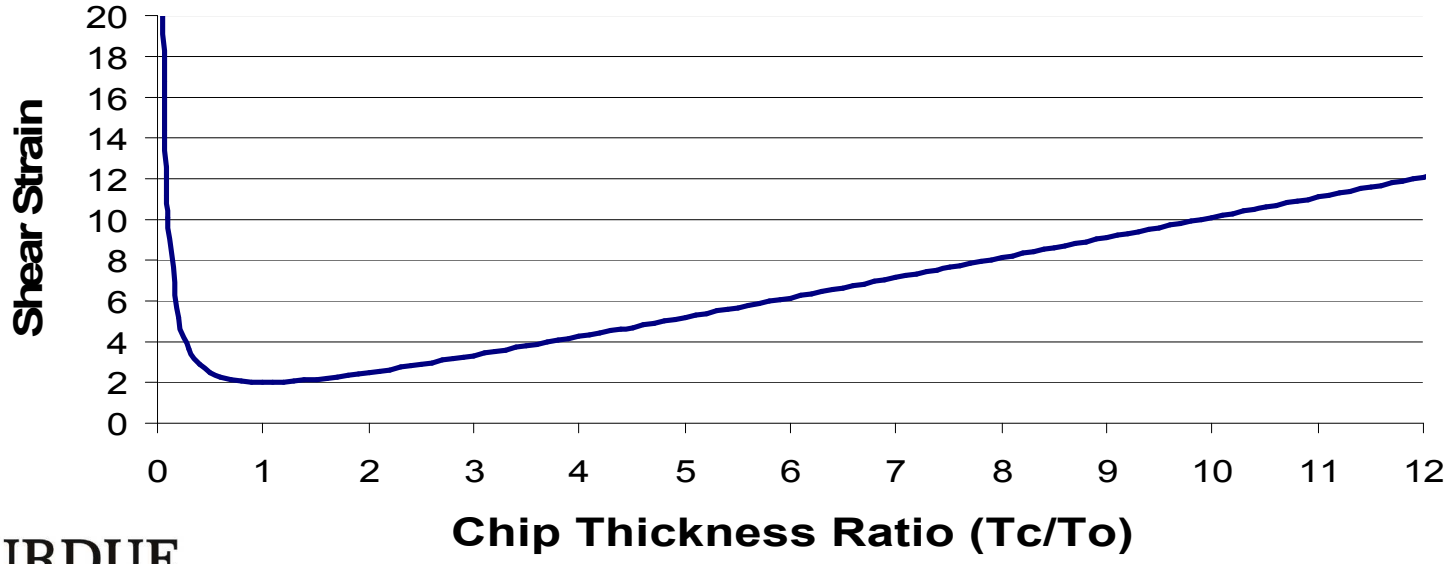
LSEM is versatile to create bulk nanostructured metals for engineer applications.

Free machining vs. Extrusion machining







T_c: foil thickness
T_o: depth of cut

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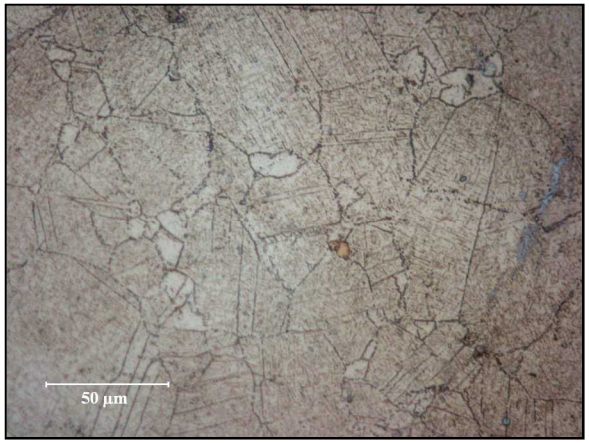
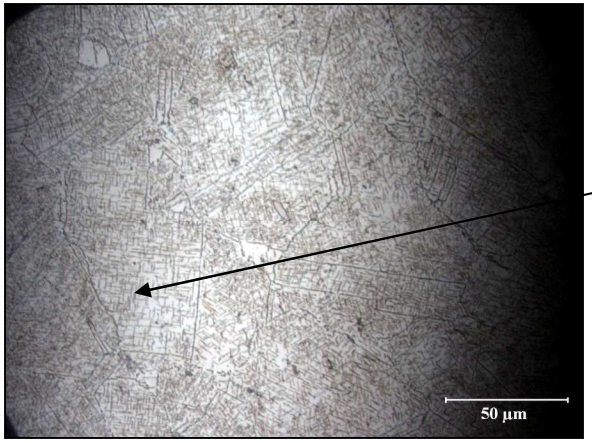
Optical Microscopy of Etched Bulk Inconel 718

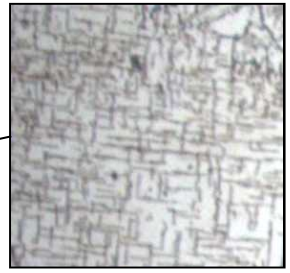
As received bulk

15HRC

(ppt hardened)





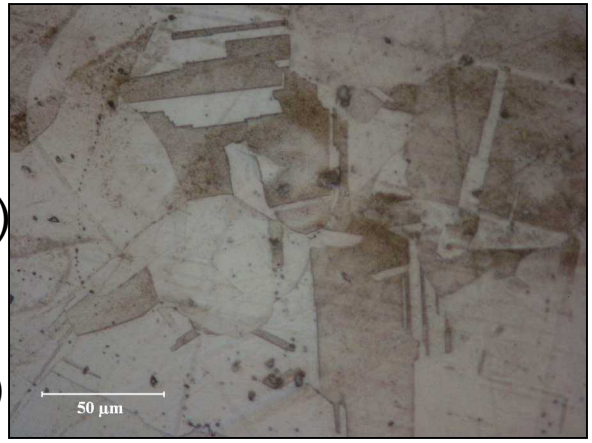


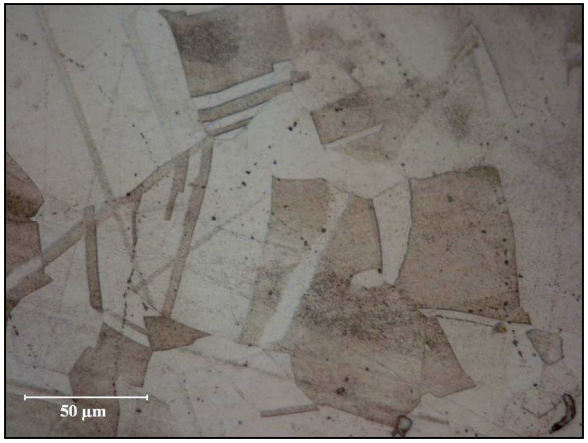
Coarse δ (Ni_3Nb) needles within grains

Annealed bulk (1037° C for 1hr)

1HRC

(solution treated)





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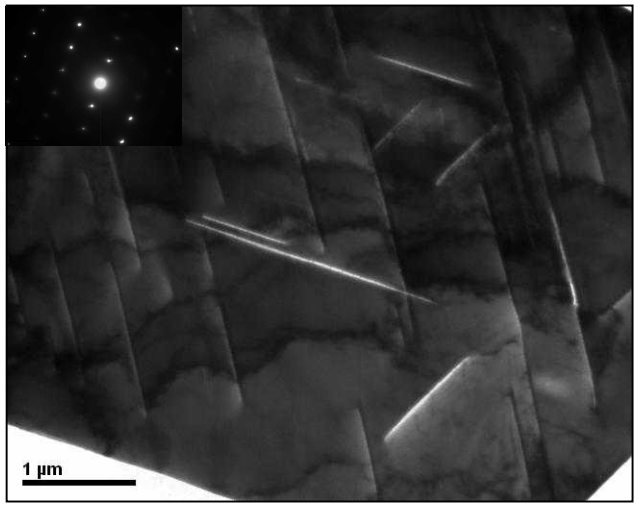
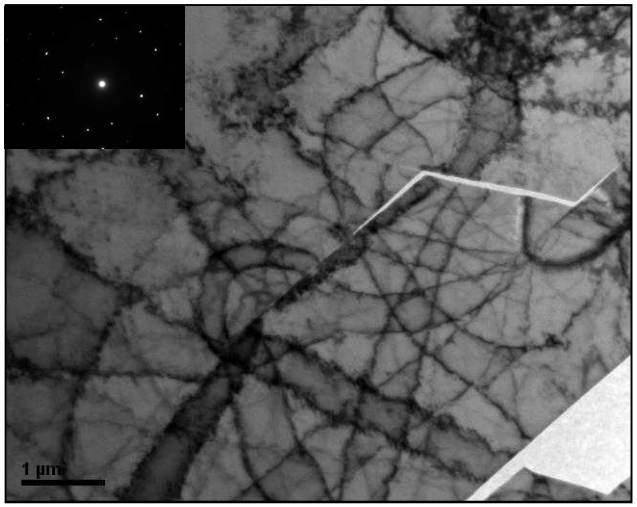
Vickers Microhardness of Inconel 718

Incoming bulk material

Annealed bulk (1037° C for 1 hr)	221 ± 7 kg/mm^2 (2.17 GPa)
As received bulk	420 ± 5 kg/mm^2 (4.12 GPa)



TEM - As received bulk Inconel 718



TEM - Annealed bulk (1037° C for 1hr)

Deformed material

Original Sandia Chip	557 ± 11 kg/mm^2	(33% increase)
γ ~ 2.1-2.5	494 ± 22 kg/mm^2	(124% increase)
γ ~ 3.3-3.5	562 ± 11 kg/mm^2	(154% increase)

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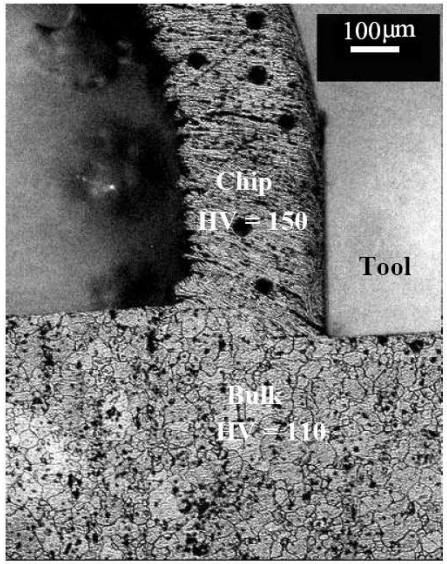
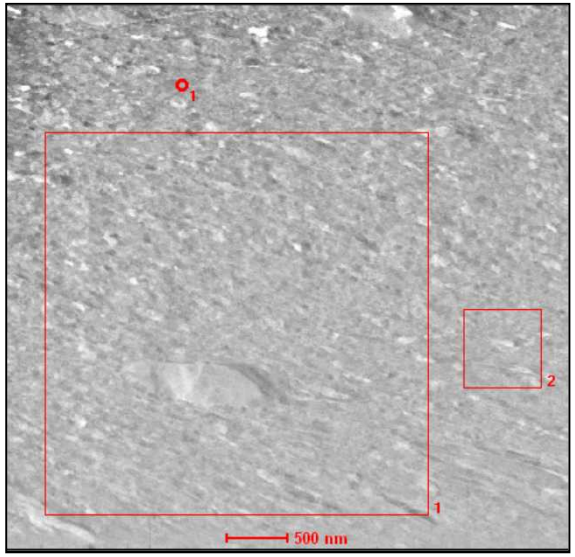
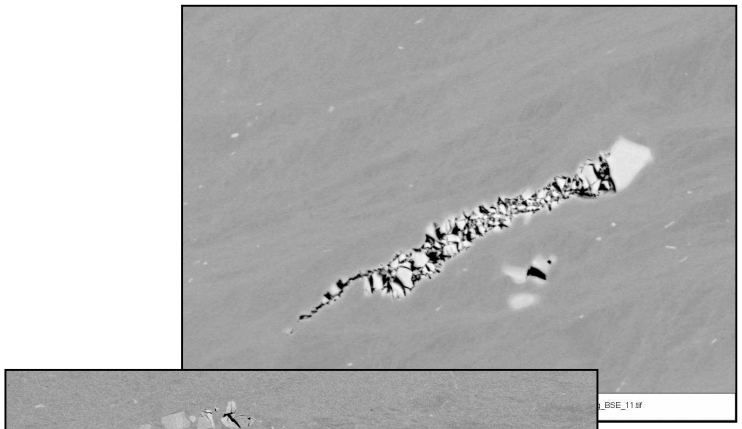
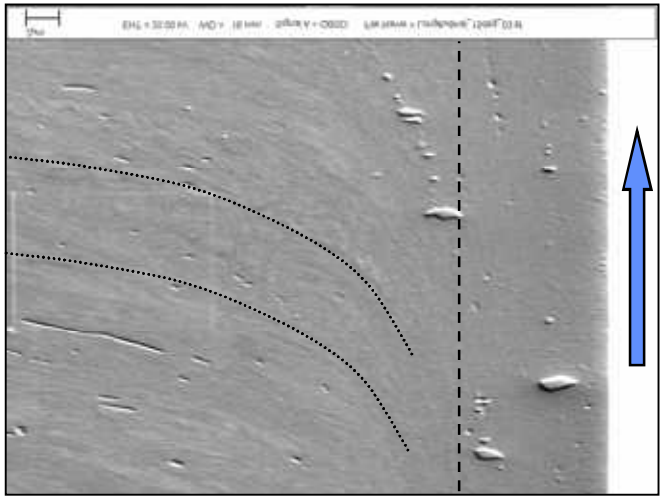
Microstructure of LSEM Inconel 718





Nb rich carbide





TiC

- Microscopic defects were created by LSEM process.

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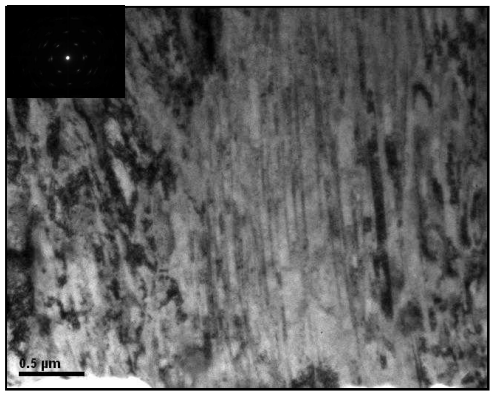
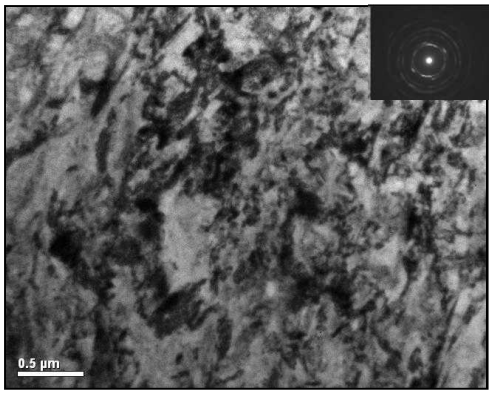
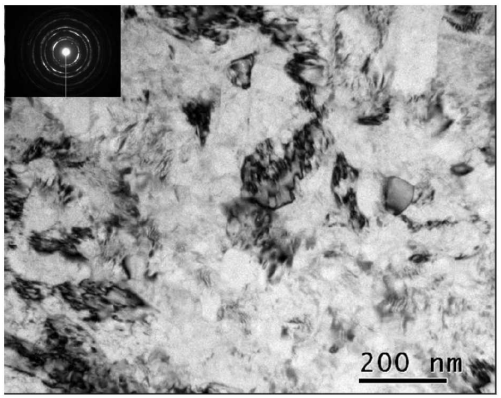
Different microstructures and properties can be created by Large Strain Extrusion Machining.



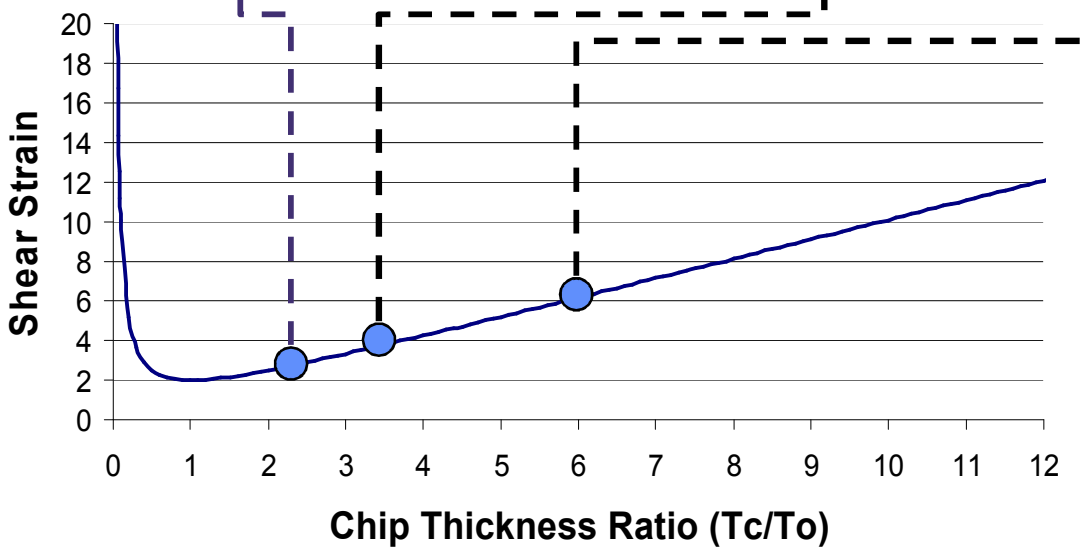




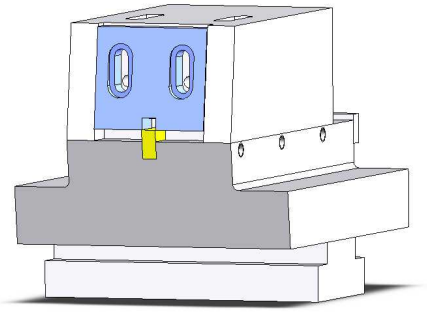
γ = 2.1-2.5; 494±22 kg/mm^2

γ = 3.3-3.5; 562±11 kg/mm^2

$\gamma \sim 6$



Machining chips from annealed bulk material



Variable foil thickness (T_c)

- Increasing strain results changes in the microstructure.

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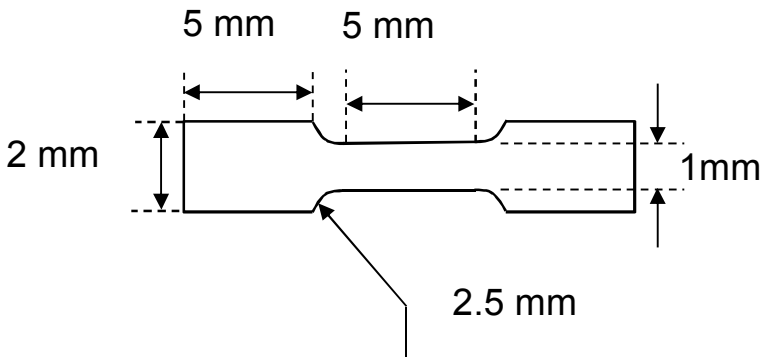
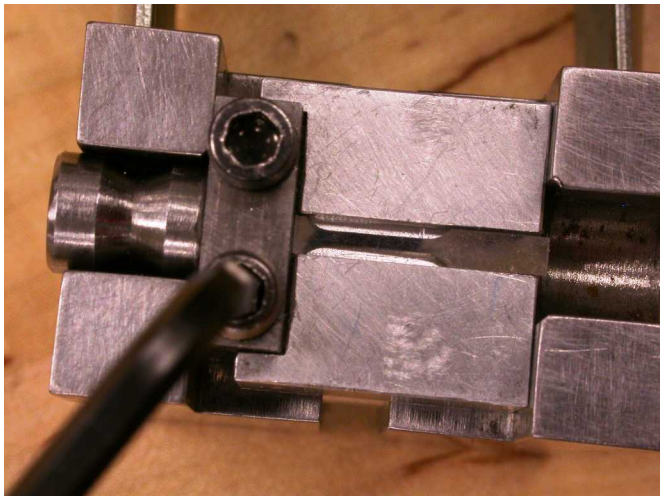
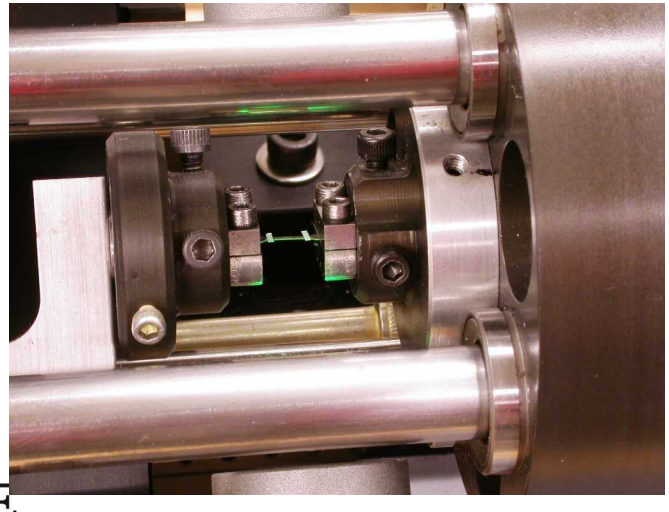
Micro-Tensile Tests







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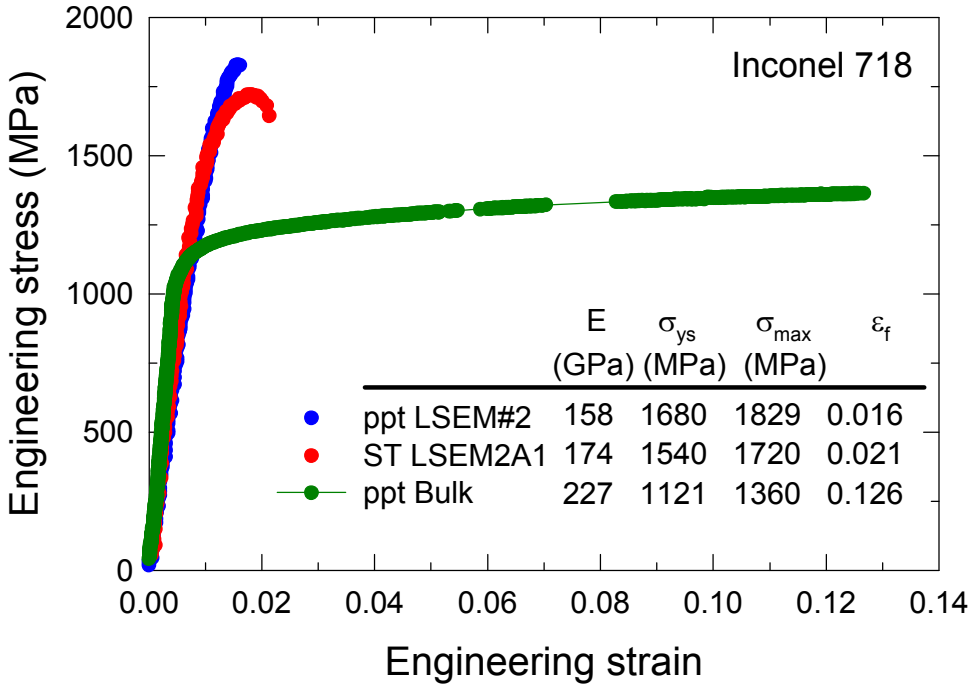
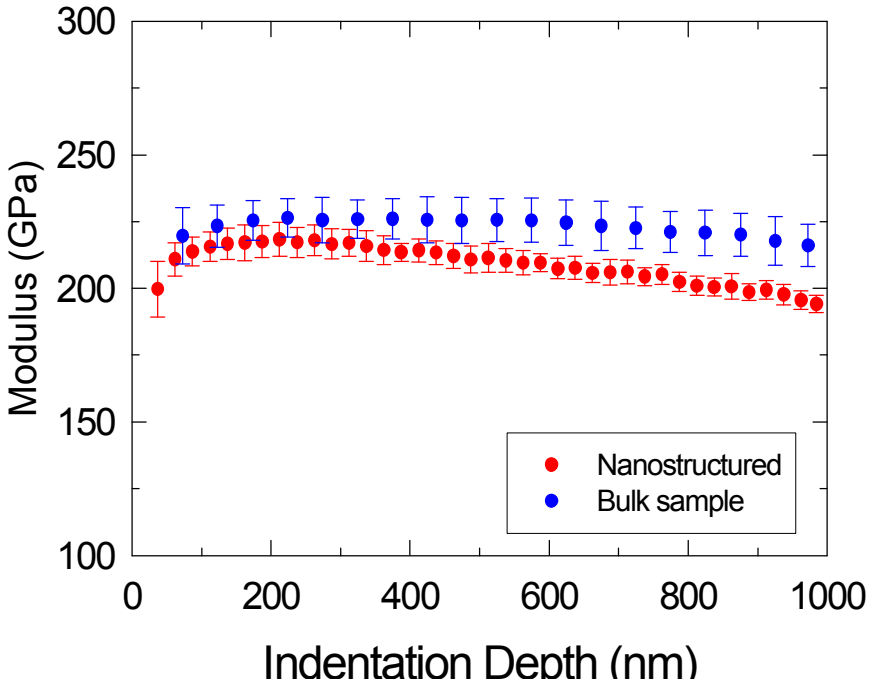
Extrusion machining greatly enhances material hardness and strength.





- Moderate tradeoffs between strength and ductility can be made by machining conditions.

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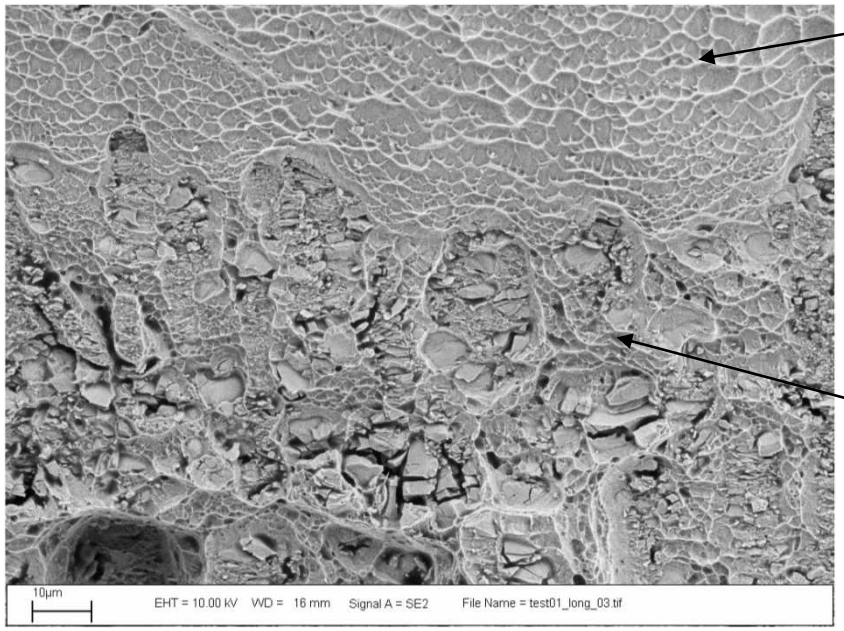
Microstructure of Fracture Surface



Dimpled rupture - ductile failure morphology

Brittle cracking and failure associated with Nb,Ti carbide particles (EMPA)

- Fracture surfaces of nanostructured Inconel 718 samples exhibited regions with both ductile and brittle failure morphologies.

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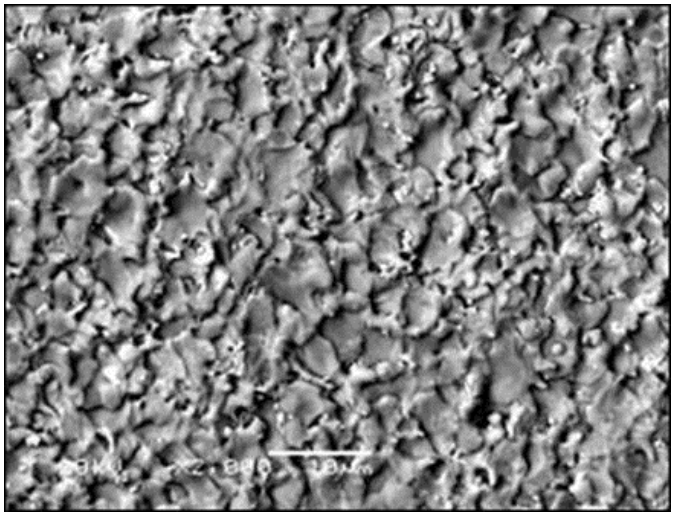
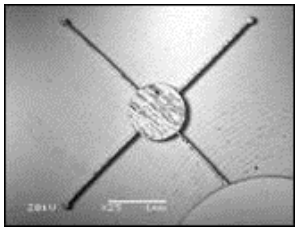
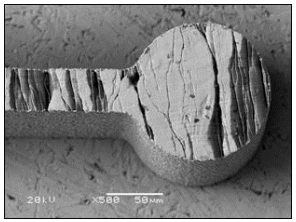
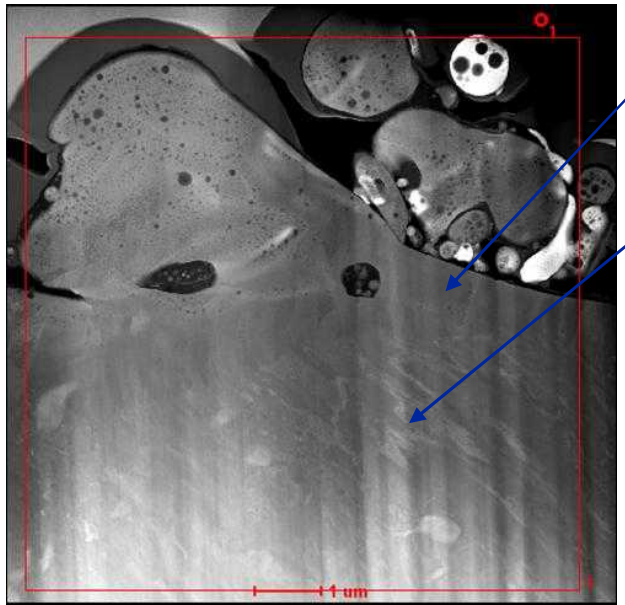
Nanostructured bulk metals can be machined into components via μ-machining methods

μ wire EDM

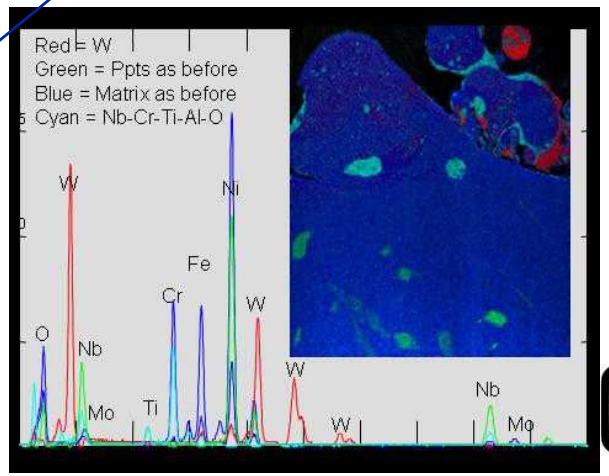








1 μm recast layer (coarser microstructure)
Nanostructured Inconel



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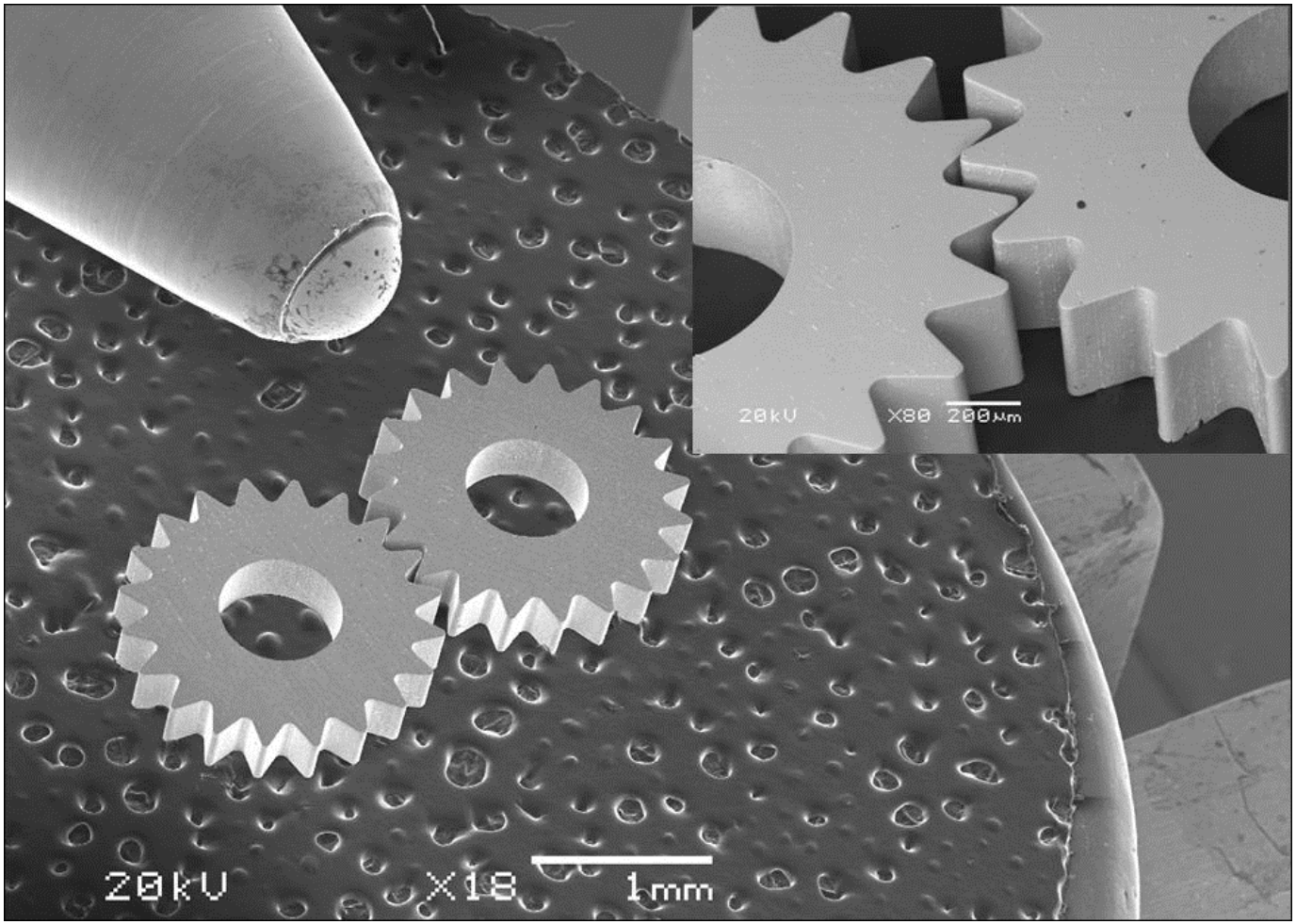
Prototype meso-scale component was made from nanostructured metals by μ wire EDM.



Meso-Scale, nanostructured Inconel 718 gears

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Summary

- Bulk nanostructured Inconel with high-strength was successfully fabricated by the extrusion-machining process.
- Increasing strain in LSEM process results in microstructure and mechanical property changes.
- μ-EDM is a viable process to fabricate meso-scale, nanostructured engineering components.

Acknowledgement

- Michael J. Rye and Paul G. Kotula – TEM sample preparation and investigation.
- Joseph R. Michael – SEM study
- Michael P. Saavedra – μ-wire EDM
- Alice C. Kilgo – Sample preparation
- David T. Schmale – Micro-tensile test
- Lysle M. Serna- Electropolishing
- Funding – LDRD program, Sandia National Laboratories

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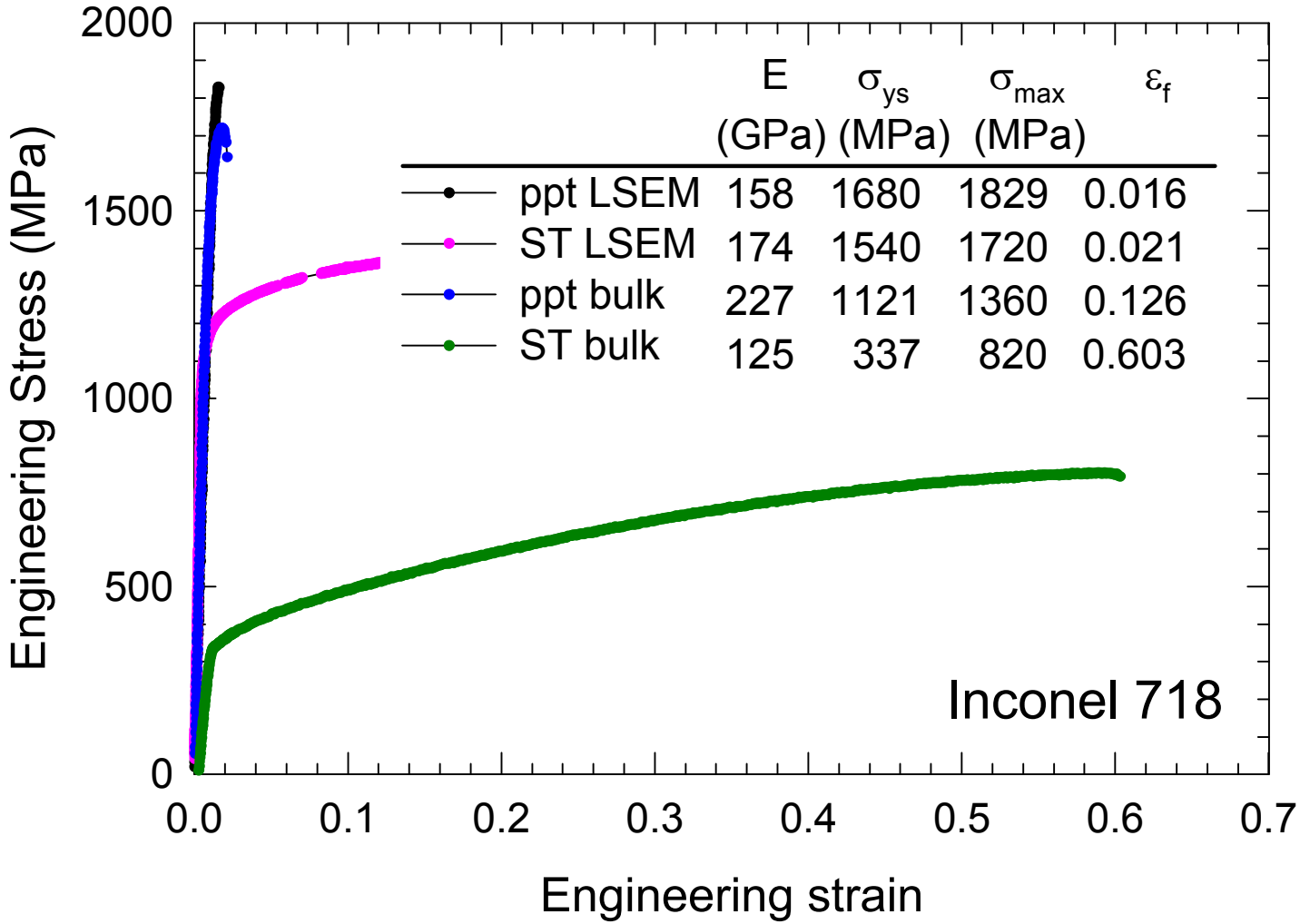
LSEM greatly increases the strength and reduces the ductility of Inconel 718 alloy.



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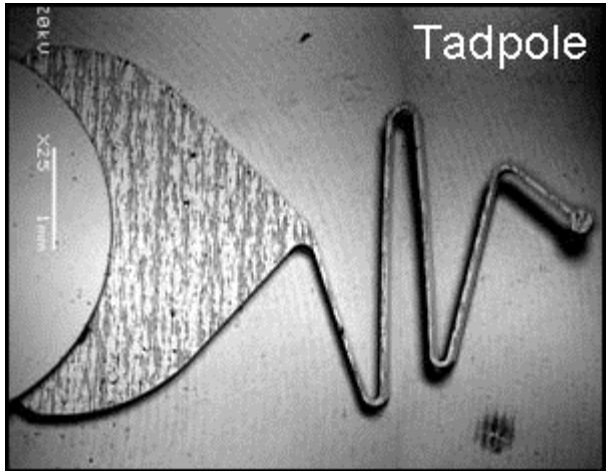
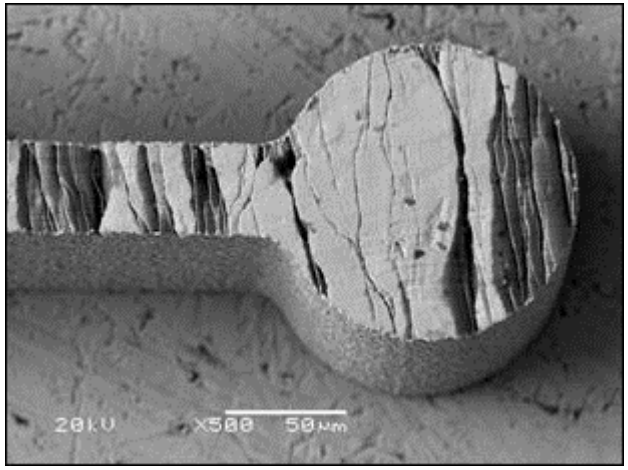
Nanostructured Materials for Meso-Scale Components

- **Objectives:**
  - **develop an effective manufacturing process to fabricate meso-scale components from nanostructured metals produced by Large Strain Extrusion Machining (LSEM).**
  - **Establish a processing-microstructure-property relationship for LSEM Inconel 718.**





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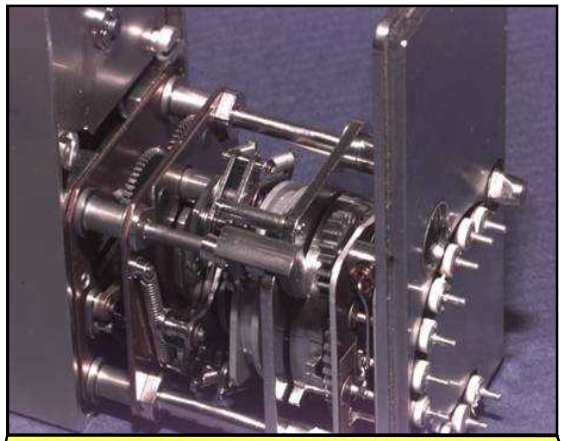
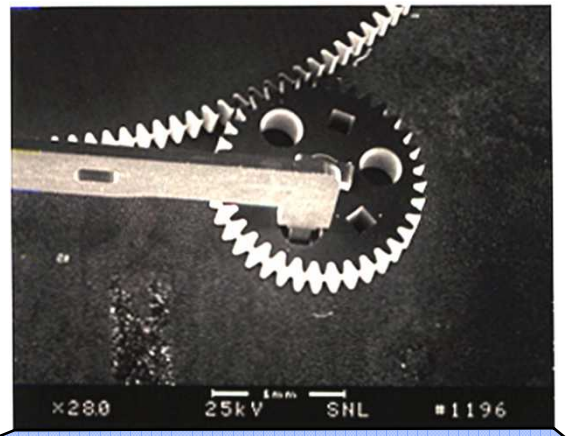
High-strength meso-scale components enable system miniaturization.

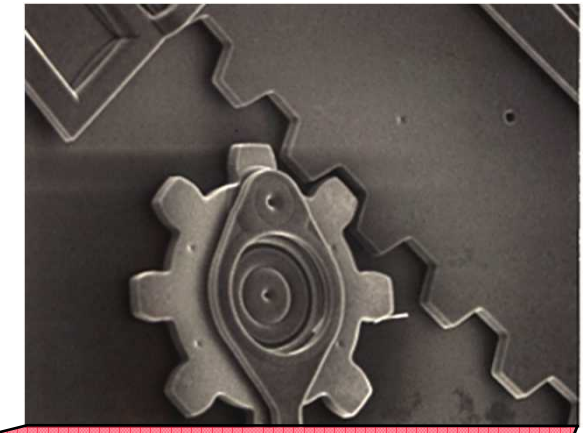
Miniature Machining

Meso Machining & LIGA

Silicon Surface Micromachining







10^{-3} 10^{-4} 10^{-5} 10^{-6}

Critical dimensions (Meters)

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