SAND2007-5707P

Low-Cost, MesoScale Parts Fabricated from Nanocrystalline Metals

LDRD Project 39493

SNL Team Members

David Gill (PI) 02455 – MesoScale Machining and Analysis

Pin Yang (PM) 02454 – Mechanical Properties/Metallurgy

Aaron Hall – 01813 – Cold Spray Consolidation, Physical Metallurgy

Timothy Roemer – 01813 – Cold Spray Consolidation

Tracy Vogler – 01647 – Shock Wave Consolidation (gas gun)

University Partners

Srinivasan Chandrasekar – *Purdue University* – Nanostructured Powder and Foil Production (***Chris Saldana*** - graduate student)

Naresh N. Thadhani – *Georgia Tech* – Shock Wave Consolidation Mold Design and Modeling Analysis (***Anthony Fredenberg*** – graduate student)

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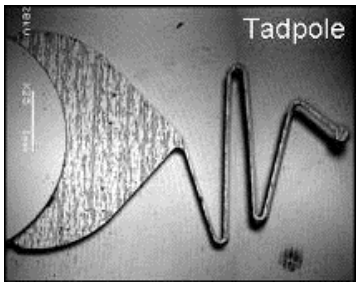
Project Overview

- **Goal: To develop methods for creating and utilizing bulk nanocrystalline metals in mesoscale NW-like parts (especially surety mechanisms).**

- **Motivation: Nanocrystalline metals exhibit very high strength and hardness, characteristics providing designers with a new suite of "super" materials for ever-smaller mesoscale surety components.**

METHODOLOGY

- **The team will study 3 methods of creating nanocrystalline material:**
  - ***Cold Spray Consolidation***
  - ***Shock Wave Compaction***
  - ***Large Strain Extrusion Machining (LSEM)***



Nanocrystalline Part

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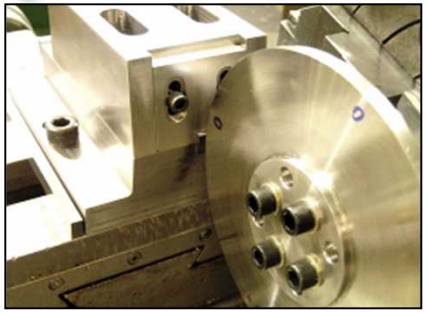
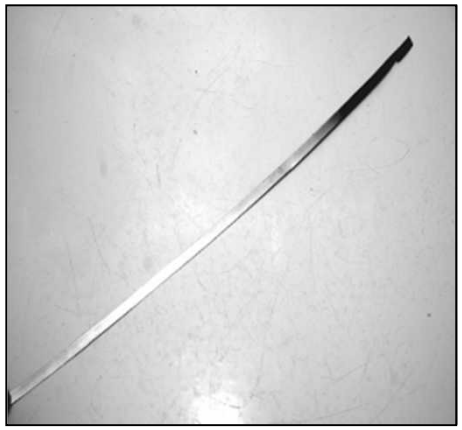
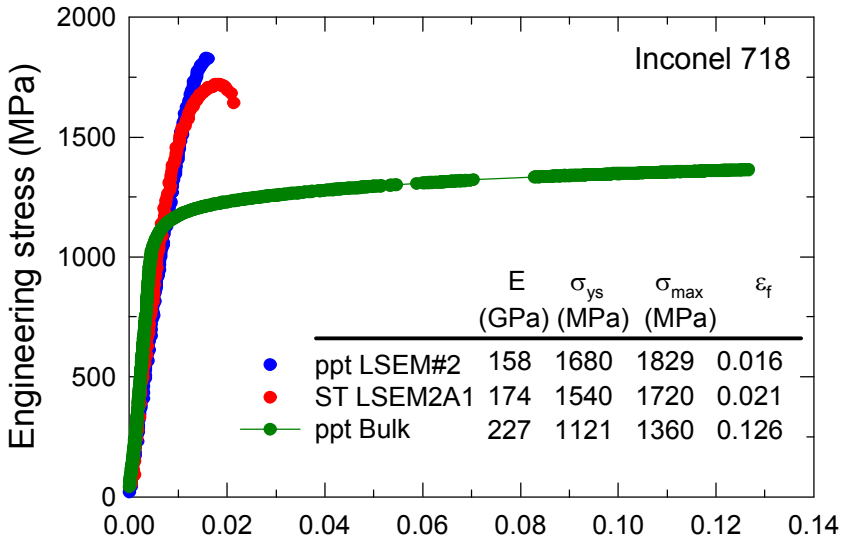
Large Strain Extrusion Machining
Nanostructured Material from Machining Chips!

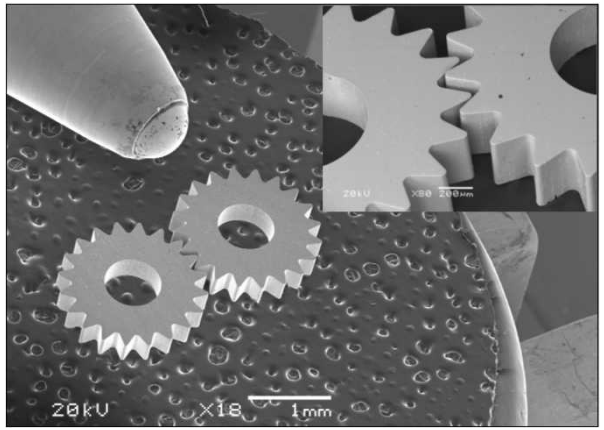




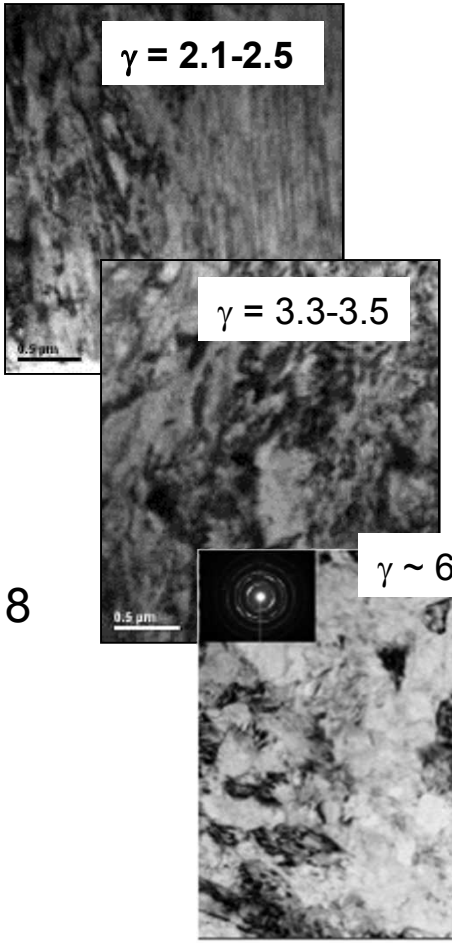
Large Strain Extrusion Machining (LSEM)



Engineering Strain for LSEM Inconel 718



First-Ever Mesoscale Parts from Nanostructured Material (shown with ball point pen tip)



Strain Affects Grain Morphology

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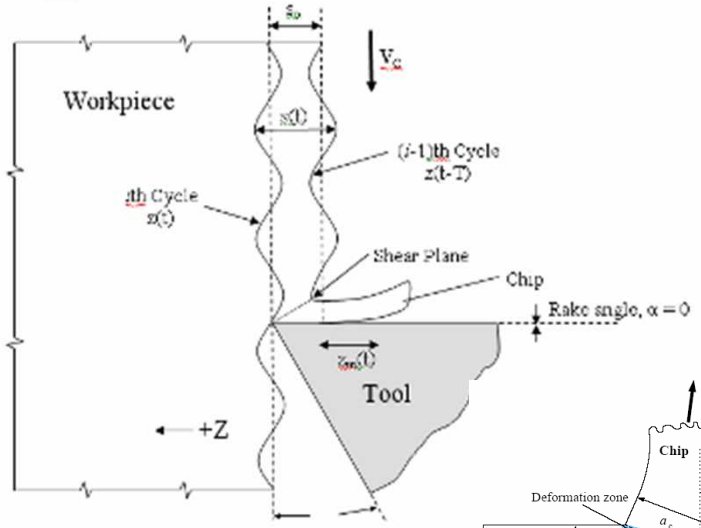
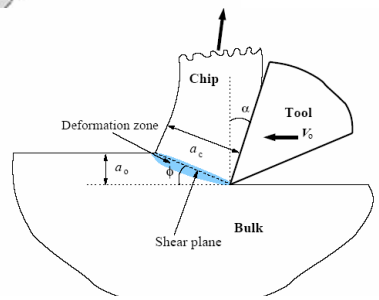
Creating Nanostructured Materials

Modulation Assisted Machining (MAM) Powder



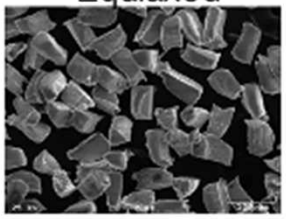
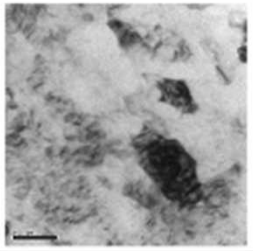
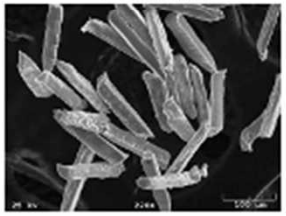
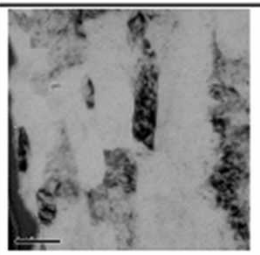
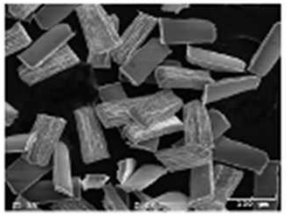
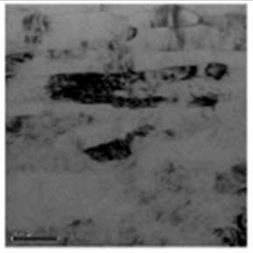
$$\gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)}$$

Theoretical Strain



Orthogonal Machining Model

Table 1. Morphology and microstructure of MAM Al 6061T6 particles

Particle Morphology	Microstructure	Size and Texture
Equiaxed 		• Equiaxed grains • Crystalline size: 100 to 300 nm • Texture: {111} and {220}
Needle 		• Elongated grains • Layer thickness: 100 to 200 nm • Texture: {200} and {220}
Platelet 		• Laminar structure • Layer thickness: 50-200 nm • Texture: {111} and {220}

Powder Characterization

- Machining Parameters Determine Particle Morphology
- Grain Morphology Follows Particle Morphology
- Utilized SNL's Unique Capability for FIB Preparation of TEM
- Discovered ultra-fine grains (100-300nm) at surface grading to um grains in interior

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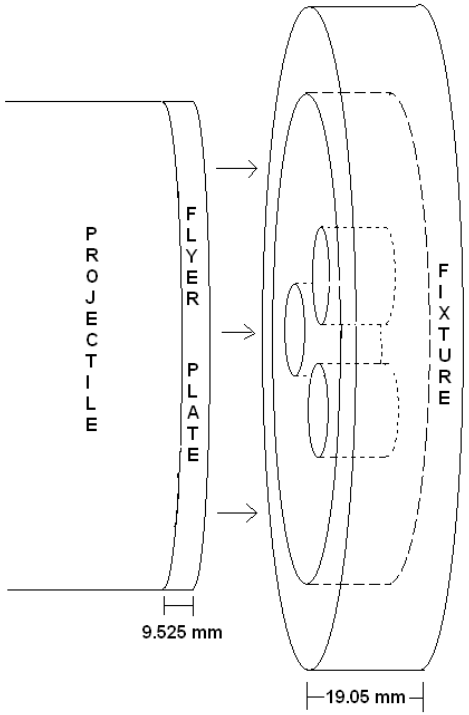
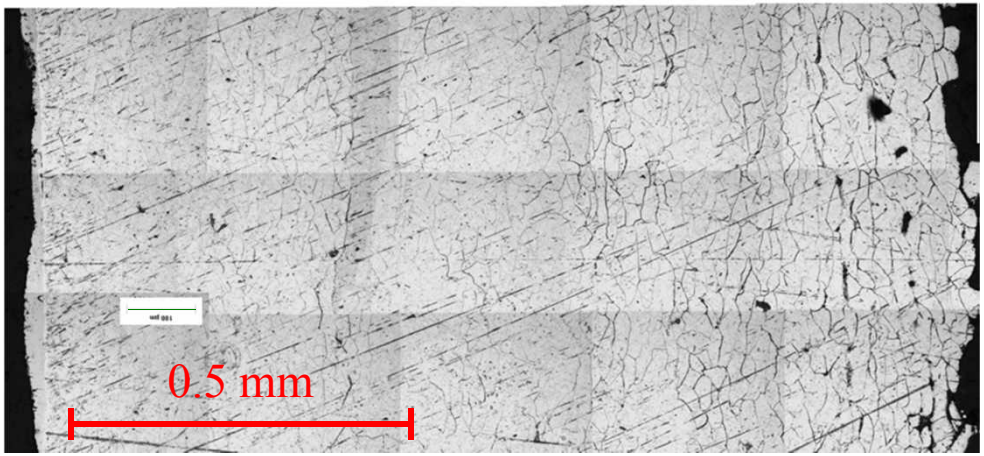
Shockwave Consolidated Nanostructured Metals

Shock Thermodynamics Applied Research

Single Stage Gun 100mm



Recovered Capsules



- steel capsule in Al holder
- 69% initial density
- complete compaction estimated for 650 m/s based on static data
- 98% density achieved for needles; hardness maintained
- incomplete compaction and porosity toward rear face

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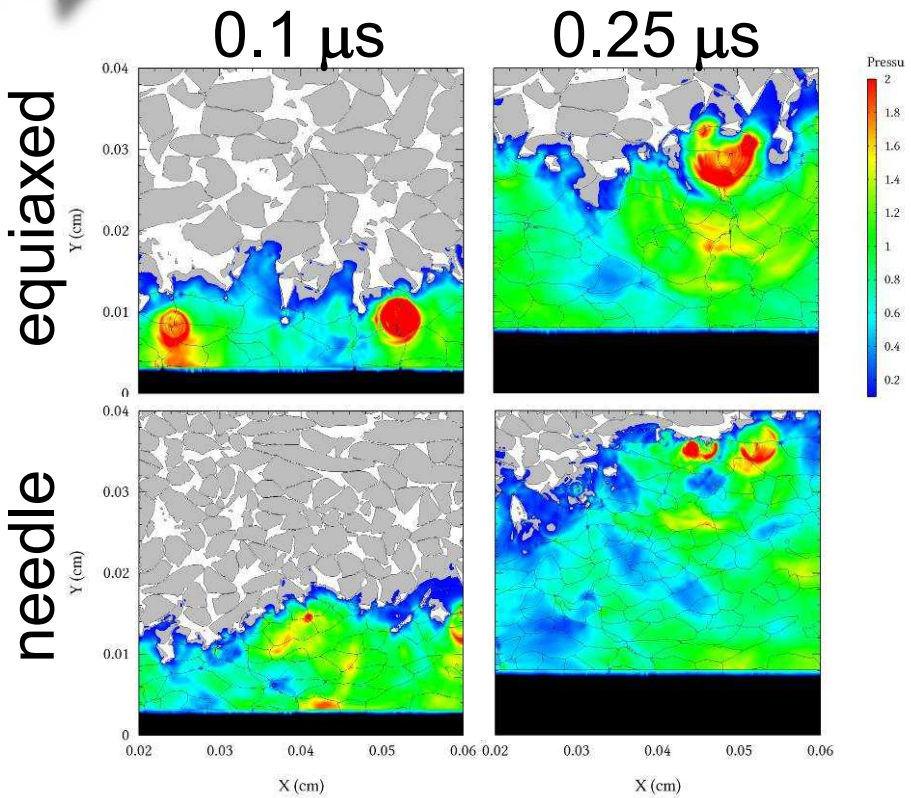
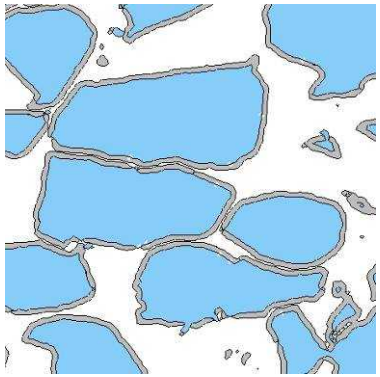
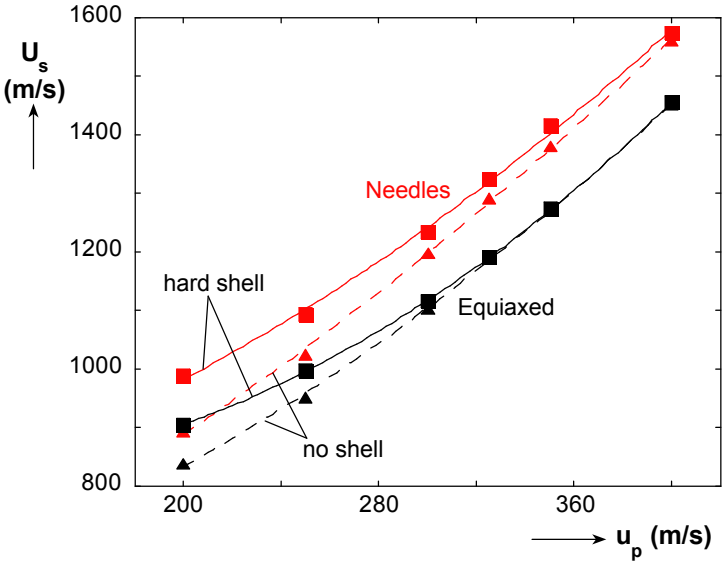
Shockwave Consolidation Modeling



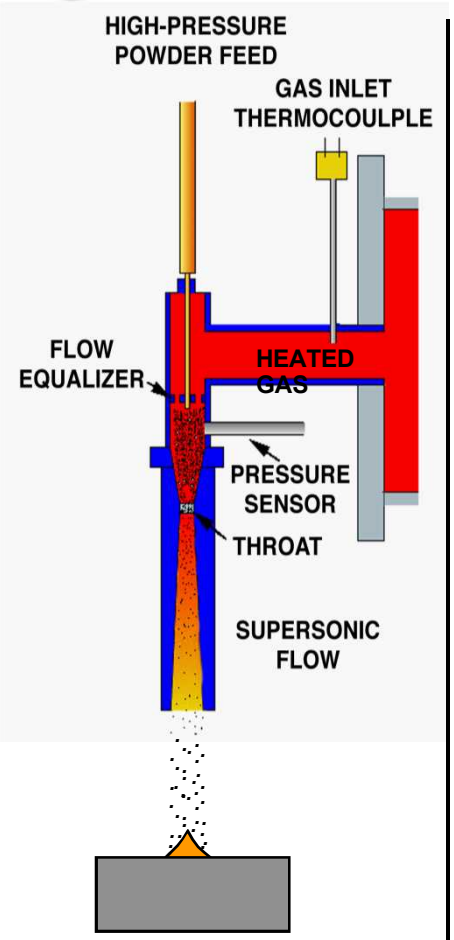
- experimental microstructures imported into CTH
- examine complex nature of wave through real powder structure
- determine effects of morphology on compaction
  - final density (to guide experiments)
  - deformation characteristics (improve bonding and prevent grain growth)

hard 2 μm "shell" from machining process include in simulation



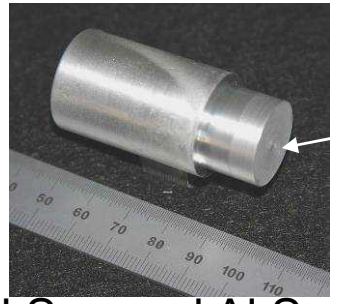


Cold Spray Consolidation of Nanostructured Metal

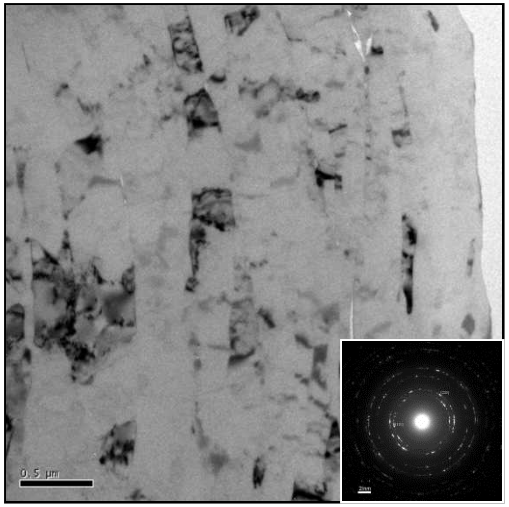


Schematic of the cold spray process

LN_2 Ball Milled, Nanostructured Powder



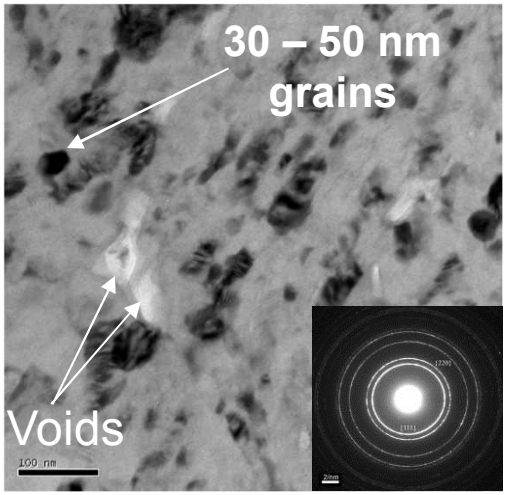
Cold Sprayed Al Sample



LN_2 Ball Milled Al 6061 Powder Has 250-300nm grains,lath-like structure w/ intra-grain porosity and no texture

Cold Spray

Process



Cold Sprayed LN2 Ball Milled Al 6061 Powder has 30-50nm grains and small regions of porosity

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Why are there nano-voids in the nanocrystalline material?

- Minimum grain size for Aluminum is ~ 20 nm
- Dislocations are unstable in Aluminum grains smaller than 18nm
- Plastic deformation is responsible for grain refinement in LN_2 ball milled and cold sprayed aluminum
- Both cold sprayed samples show grain sizes between 20 and 50 nm.
- Grain refinement through plastic deformation will not create Al grains less than ~ 20 nm in size.

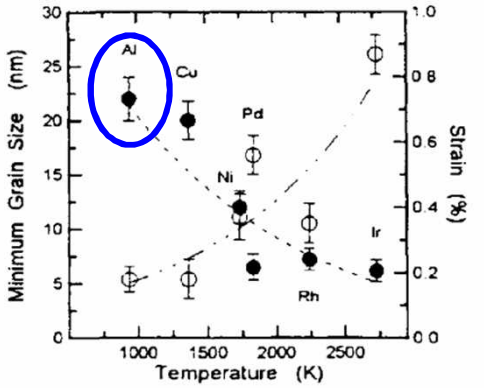

Figure 1. Minimum average grain size (filled symbols) and atomic-level strain (open symbols) for ball-milled fcc metals versus melting temperature.

J. Eckert, Relationships Governing the Grain Size of Nanocrystalline Metals and Alloys, *NanoStructured Materials*, 1995, 6(1-4), p 431-416

Heterogeneous void nucleation is the likely cause:

- Within precipitates
- At interfaces
- At grain boundary triple points

Both 5083 & 6061 contain precipitate forming elements

Aluminum nitrates are known to form in LN2 ball milled aluminum.

Bulk Nanocrystalline Al Was Created Using Cold Spray!!

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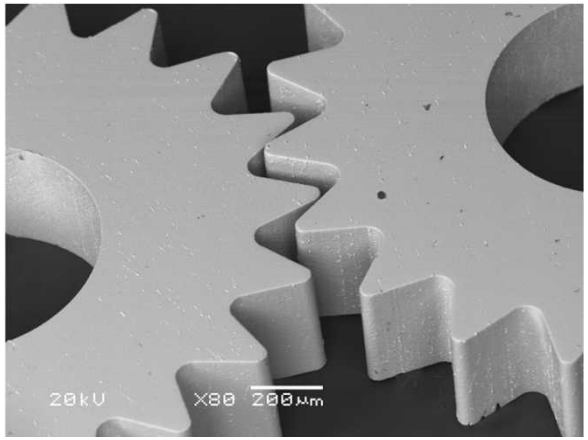
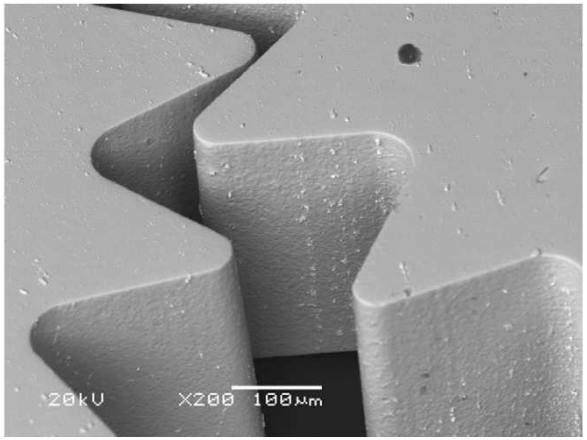
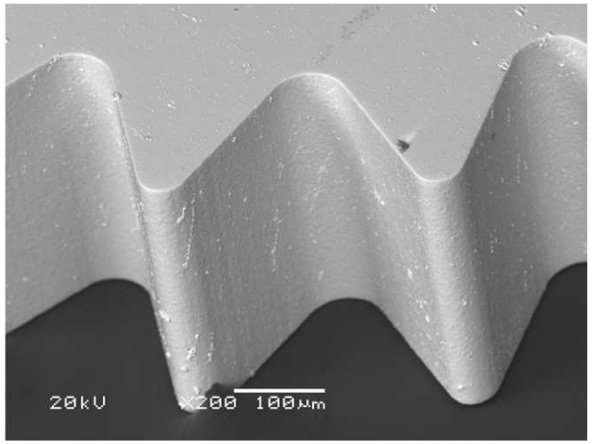
Conclusions

- Nanostructured Material Created by Several New Methods Has Been Analyzed
- Bulk Nanostructured Material Has Been Created Using Cold Spray and Shock Compaction
- Cold Spray Nanocrystalline Material Has Reached the Lower Limits of Grain Size!
- Mesoscale Parts Were Created Using LSEM Chips







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