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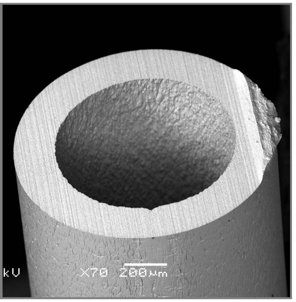

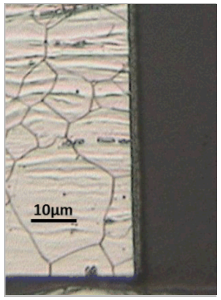

Design & Direct Machining of Mesoscale Elastic Structures

ICOMM, March 11, 2012

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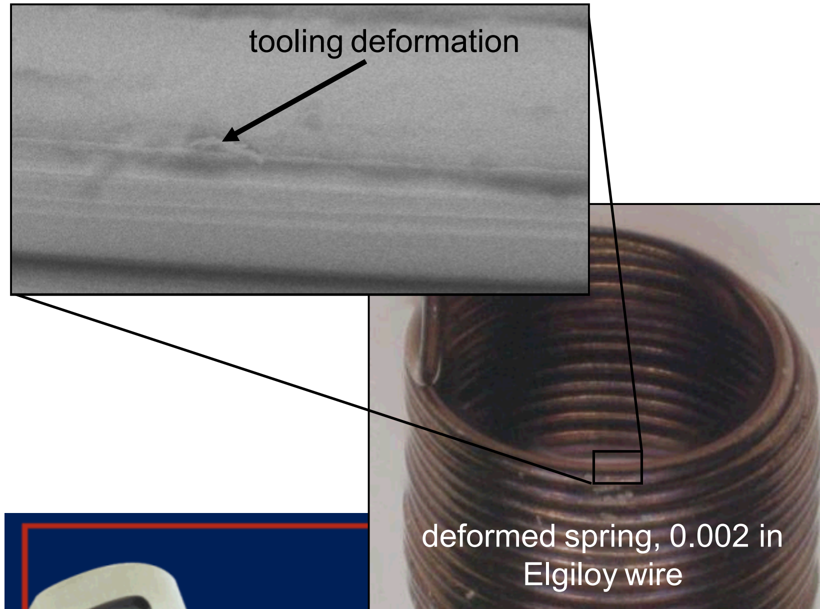
Outline

- Motivation
  - Why directly machine mesoscale elastic structures?
- Design
  - What structure best meets performance requirements & leverages direct machining?
- Fabrication
  - How are mesoscale structures fabricated?
- Performance
  - How have prototypes performed?

Motivation

- Coil winding meso springs (wire dia. < 100 µm) presents barriers to miniaturization
  - dimensional errors, tooling damage & material variability drive uncertainties
  - tolerance margins typically exceed 20%
  - design impacts counter miniaturization (increasing volume, force, power, stresses)
  - spring geometry limited by wire cross-section & material strengths

- Directly machined elastic structures present an alternative
  - reduce uncertainty margins
    - improve process accuracy
    - eliminate plasticity in processing
  - expand design space
    - unique design configurations
    - geometry driven by material form & fabrication
  - precedence
    - macro scale springs
    - medical stents



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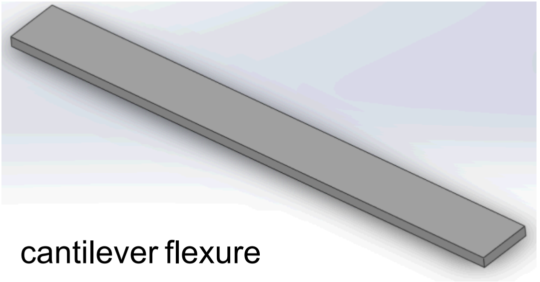
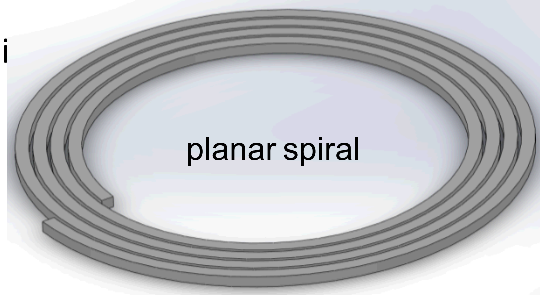
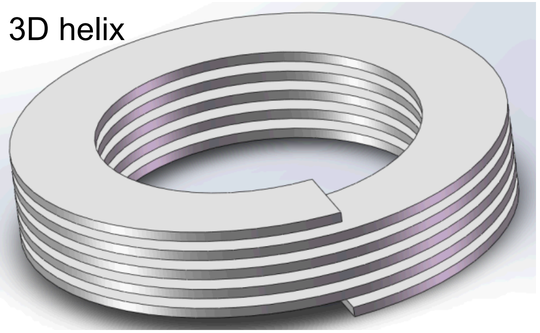
Spring Structure Design

- Objectives
  - explore design space & demonstrate mesoscale viability
  - investigate optimization & trade-offs for performance & processing
  - understand accuracy of macro scale models to meso springs
  - equivalent spring requirements
    - single start, coil wound extension spring w/50 µm wire di
    - specifications
      - stiffness from force (F1, F2) @ deflection (d1, d2)
      - working volume (min ID, max OD)
- Forms examined
  - normalized output for equivalent stiffness
    - cantilever beam flexure: unacceptable footprint
    - planar spiral spring: largest footprint, lowest natural frequency
    - 3D helical spring: best balance across requirements

form	element length	area	volume	ω_n	deflected σ	ave.
cantilever	**1**	8.18	**1**	**1**	**1**	2.44
spiral	2.74	46.36	1.97	0.63	1.45	10.82
helix	3.73	**1**	1.56	0.84	1.42	**1.78**



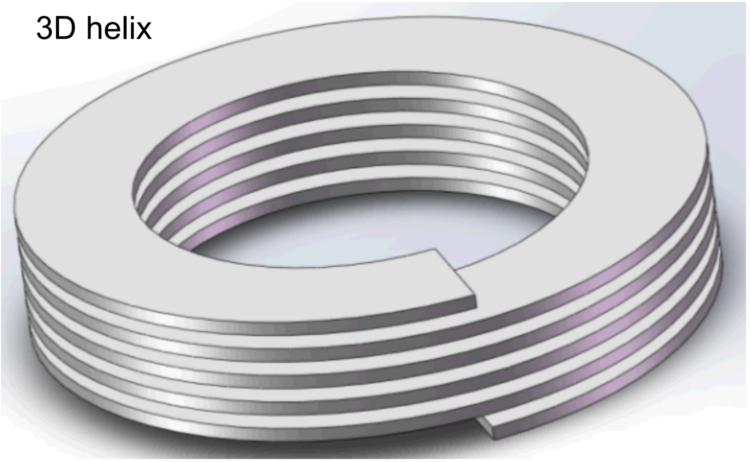




Material Selection

- Mesoscale requirements
  - isotropic mechanical properties
  - large elastic modulus
  - high yield strength
  - small grains to insure multiple grains across spring coils
  - no microplasticity, ratcheting, or low-cycle fatigue issues at operating stresses
  - long-term environmental stability
    - high temperature
    - corrosion
  - form amenable to desired spring geometry

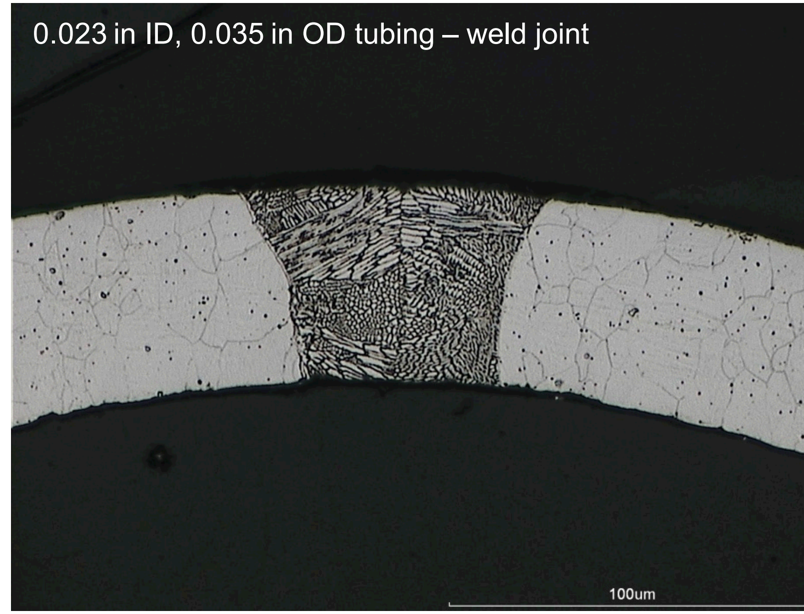
3D helix

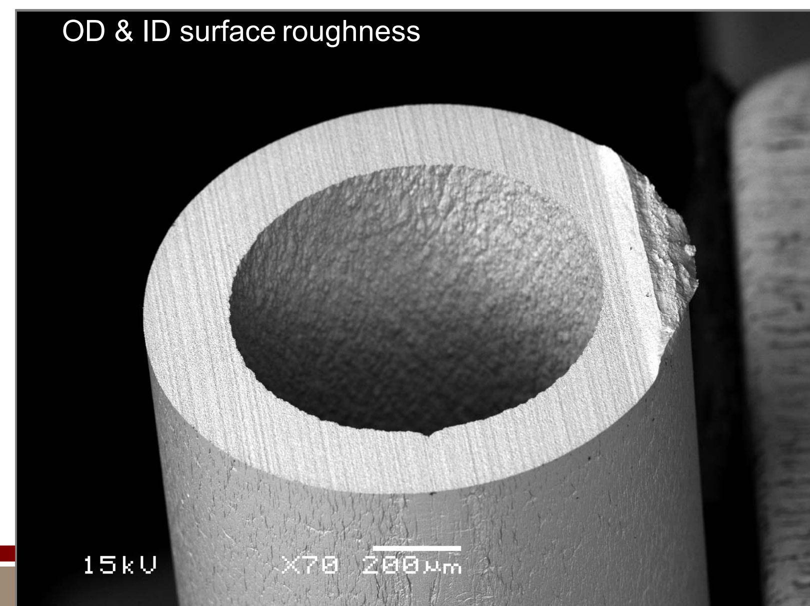


- Initial prototype material
  - 304L stainless steel hypodermic needle tubing

304L Stainless Hypodermic Tubing

- Readily available
- Well documented properties
  - isotropic
  - moderate strength (~75 ksi)
  - controllable microstructure
- Challenges
  - discrete tube sizes limit design space
  - fatigue vulnerabilities
    - rolled stock welded to form tube
    - ID surface roughness @ location of max stress





3D Helical Design

- Governing closed form equations
  - rectangular coil stiffness (Young)

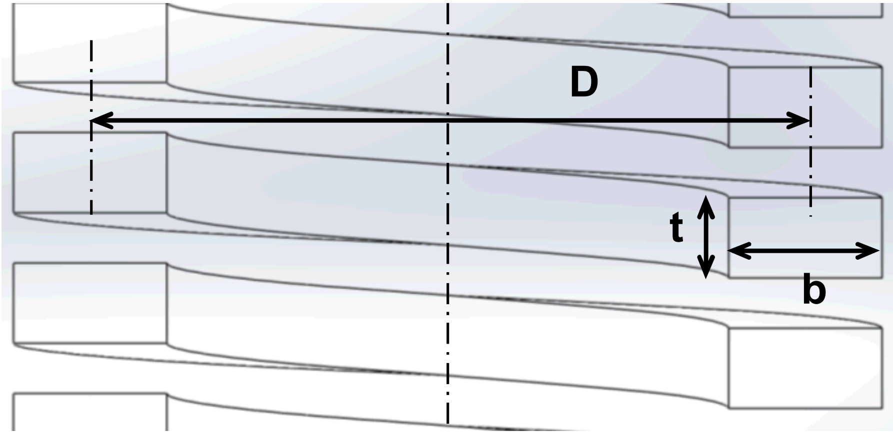
$$k = \frac{4G \cdot t^4}{3\pi \cdot D^3 \cdot N}\left(\frac{b}{t} - 0.627 \cdot \tanh\frac{\pi \cdot t}{2b} + 0.004\right)$$

  - stress under load (Wahl)

$$\tau = \frac{P \cdot D(3t + 1.8b)}{2t^2 \cdot b^2}\left(1 + \frac{1.2t}{D} + \frac{0.56t^2}{D^2} + \frac{0.5t^3}{D^3}\right)$$

  - 1st mode resonance

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{k}{\rho \cdot t \cdot b \cdot \pi D \cdot N}}$$



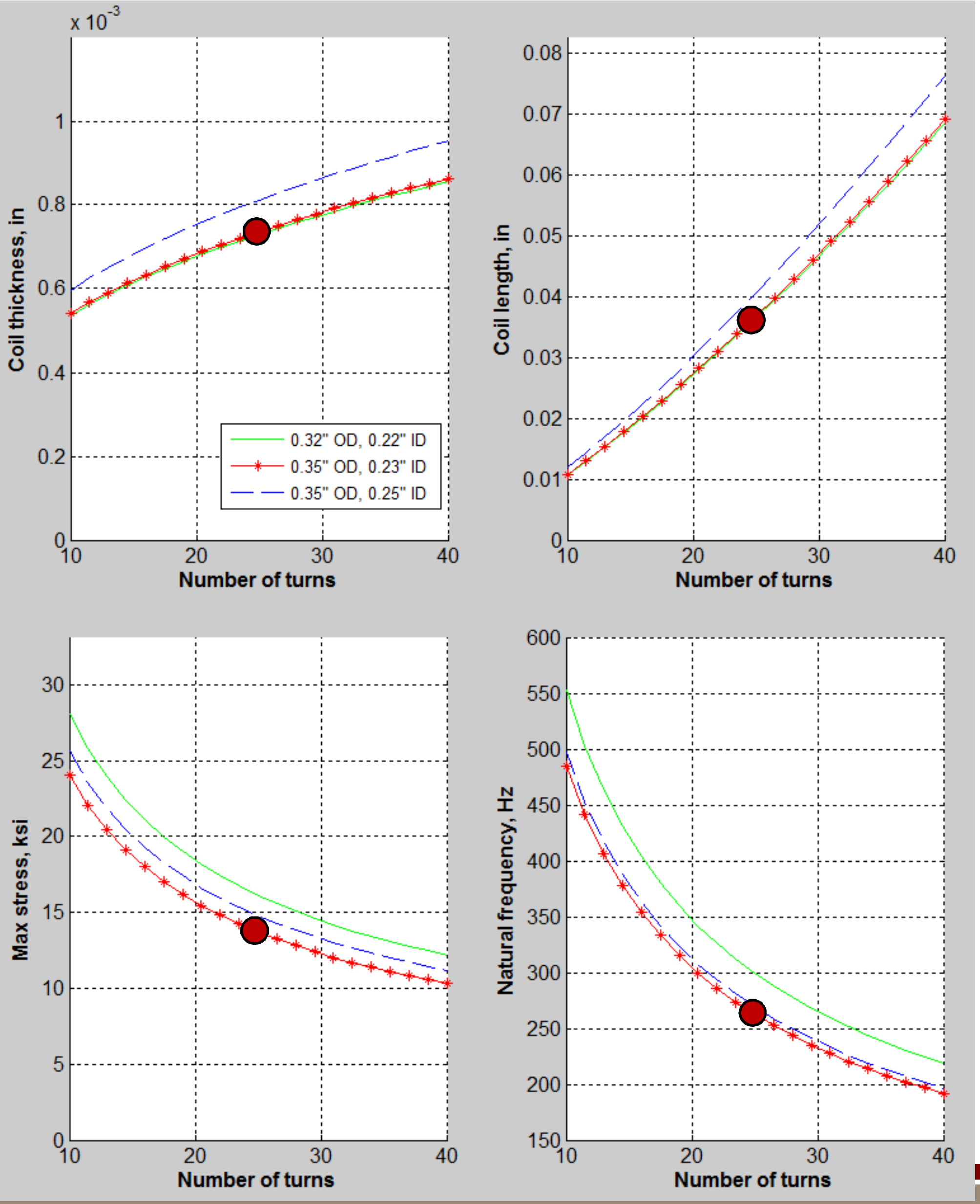
spring cross-section

- Used for “optimization” design curves
  - coil thickness, spring length, working stress & natural frequency solved numerically across range of tubing diameters & number of coil turns
  - expect to capture trends for meso structures

Design Optimization

- Design balanced
  - working stress
  - machinable coil thickness
  - minimum active coil length
  - maximum 1st mode resonance

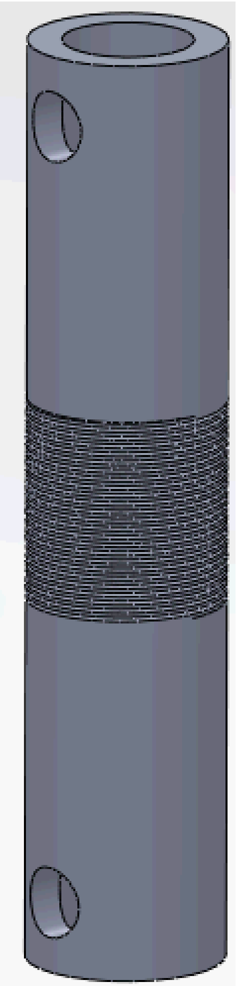
- Trends
  - increasing tubing OD & thickness
    - reduces stress
    - reduces natural frequency
    - increases fabrication difficulty
  - discretization of tube sizes limits design space



Prototype Design

- Description
  - 304L hypodermic tubing
  - 25 coils
  - 0.023 in ID, 0.035 in OD, 0.00074 in coil thickness
  - 13.7 ksi working stress
  - 263 Hz natural frequency
  - closed form agreement to FEA model within 10%

- Wound spring comparison
  - natural frequency decreased 25%
  - end geometry
    - stronger tangs
    - enables reduced length (i.e. volume)
    - enables improved and/or integrated assembly

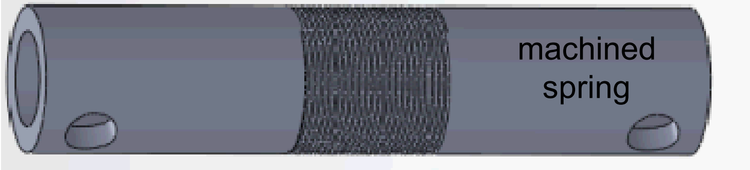


machined spring

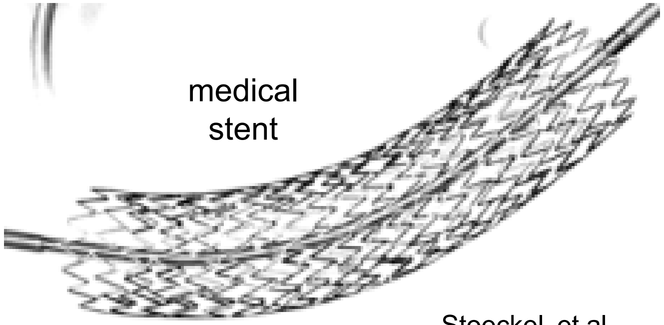
wound spring

Fabrication

- Meso scale spring requirements
  - “traditional” machining inadequate for structural elements < 50 µm
  - process accuracy = 1-5 µm
  - minimum feature “resolution” = 10-20 µm
  - minimal change in material microstructure or introduction of surface effects
  - candidate processes
    - pulse laser machining
    - µ-wire EDM



- Stent differences
  - provide primarily radial motion
  - require smaller range of motion
  - smaller aspect ratio cuts & features



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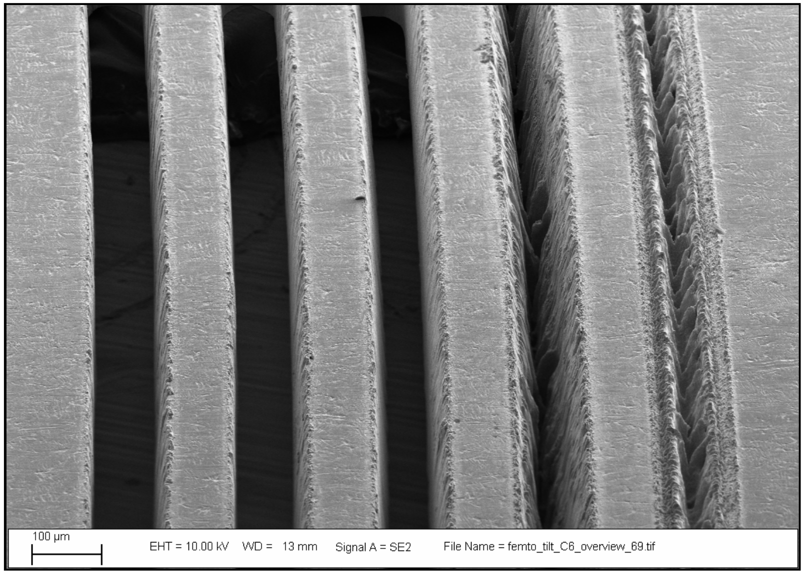
Material Impacts

- Process damage is critical for mesoscale structures
  - surface layers & microstructure can approach feature sizes
    - subtractive processes generate heat affected zones, recast, internal stresses, etc.
  - design models assume bulk properties & continuum material behavior

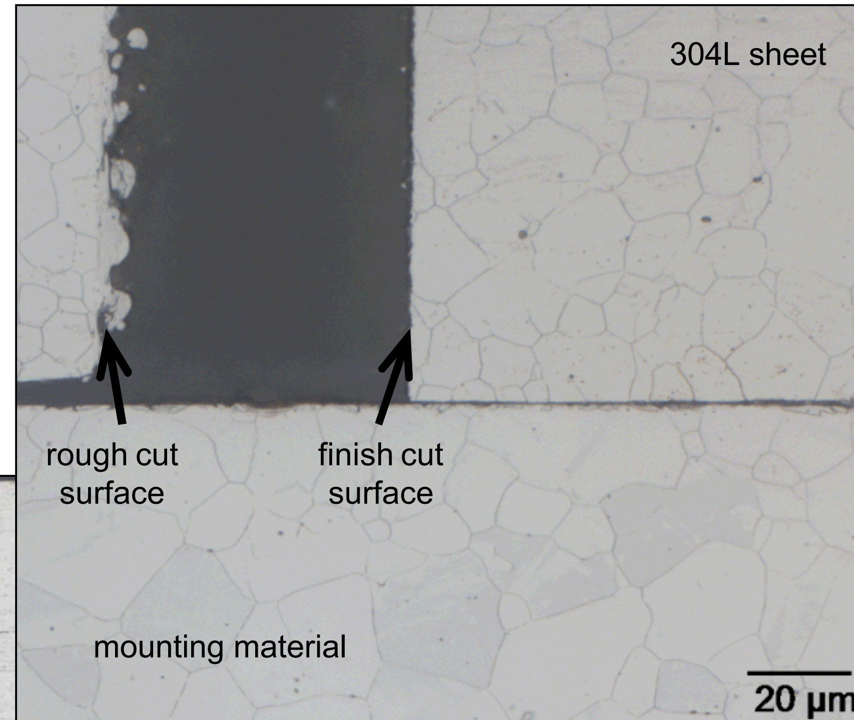
- Process experiments
  - cut 250 µm thick 304L sheet
    - fs & ns pulsed laser machining
    - µ-EDM
    - variable process parameters
  - investigating
    - heat affected zone
    - cut geometry
    - surface quality

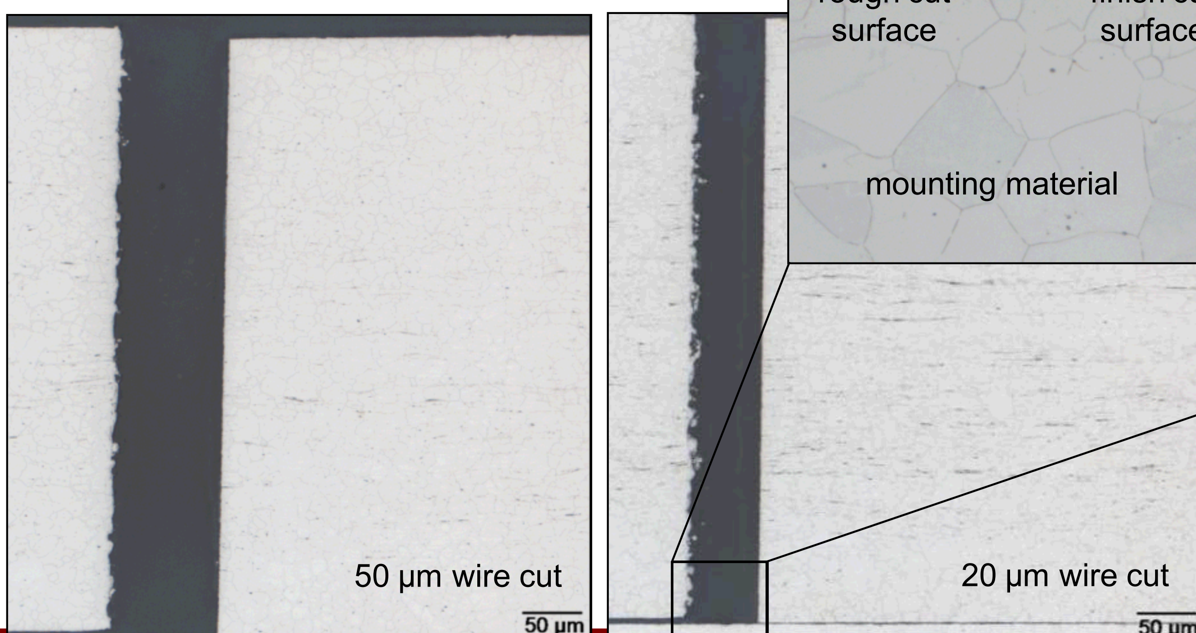


100 fs, 1 kHz, 0.49 mJ, 20 passes, 0.1-5 mm/sec

µ-Wire EDM

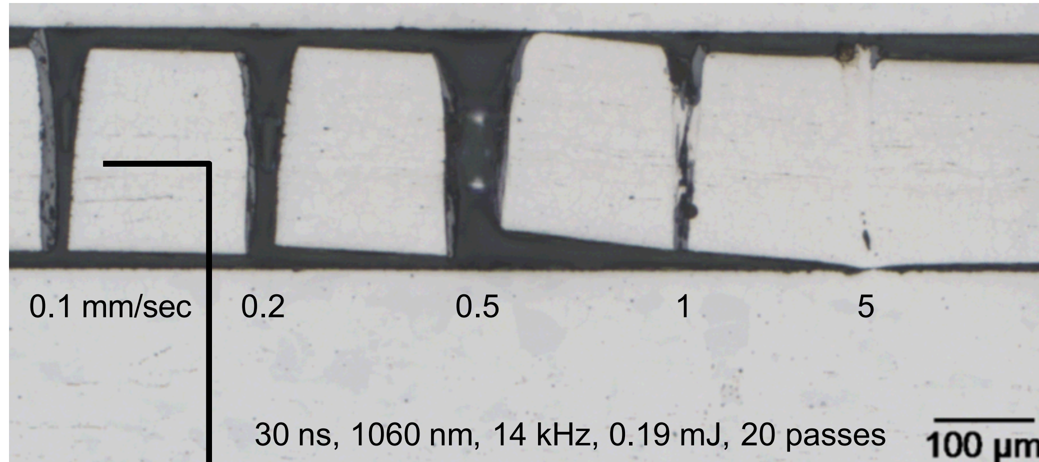
- Agie Vertex F µ-wire EDM
  - 1 rough pass, 8 finish passes
  - “turn & burn” required for helical cutting
- Varied tungsten wire diameters
  - minimal difference except for feature size
  - min feature size ~30-40 µm
  - straight sidewall geometry

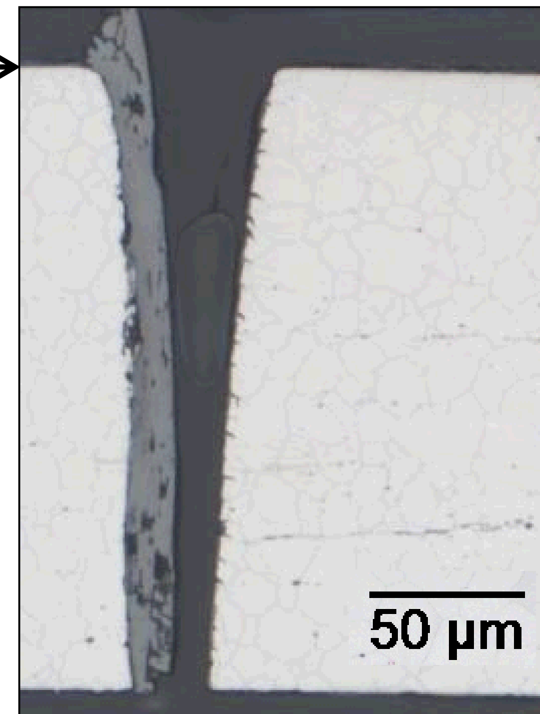




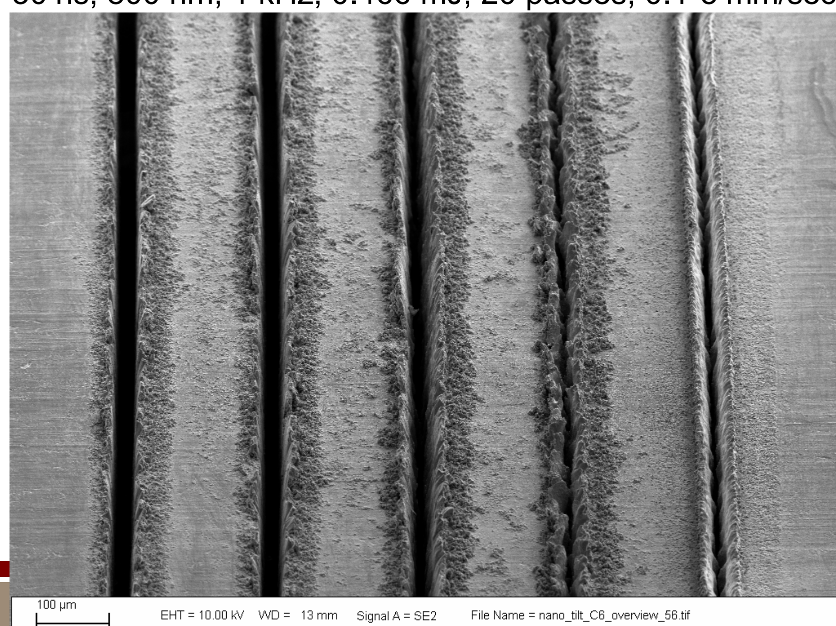
Ns Pulsed Laser

- Parameters examined
  - power, pulse rate
  - feed rate, number of scans
  - wavelength
- Damage
  - significant HAZ & recast
  - material distortion due to stresses
  - unacceptable for mesoscale structures



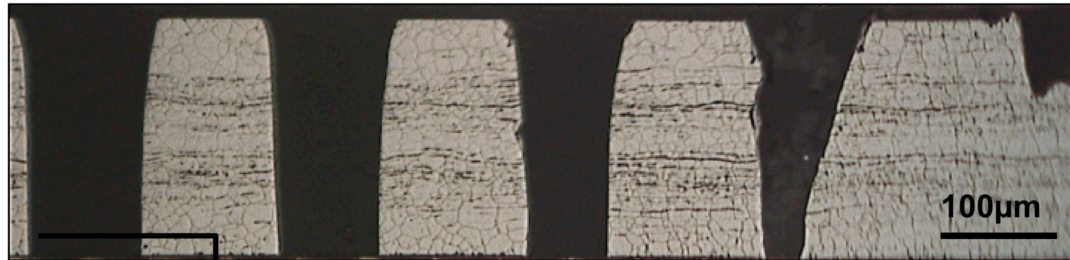


30 ns, 800 nm, 1 kHz, 0.466 mJ, 20 passes, 0.1-5 mm/sec



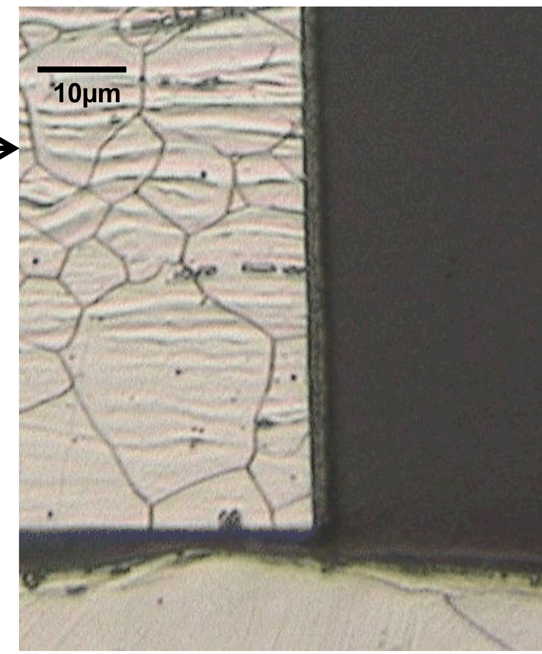
Fs Pulsed Laser

- Fs pulses provide better cutting
  - less thermal damage & recast
  - straight sidewalls
  - high power & slow velocity improve cut depth & quality
  - extra cuts cleanup surface
- Selected prototype process

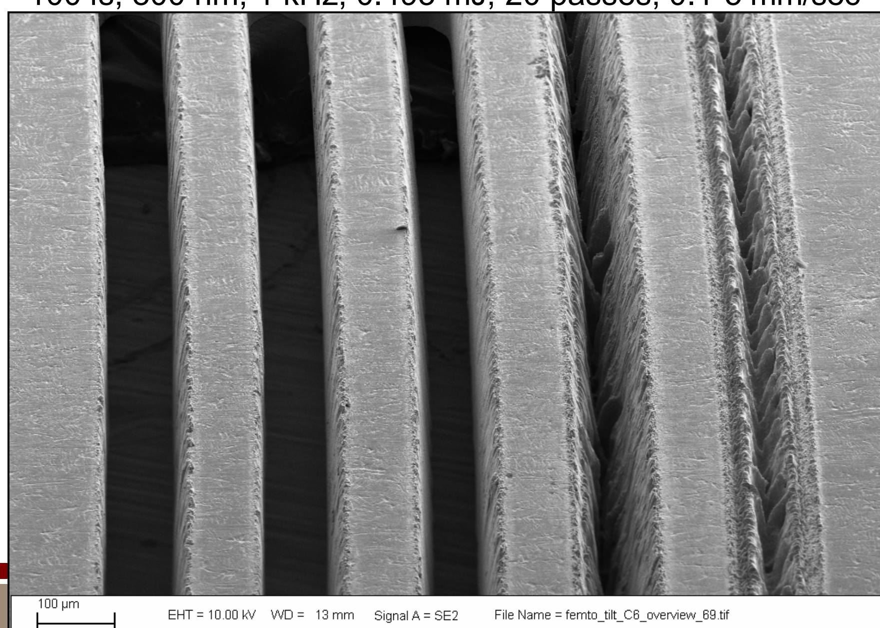


0.1 mm/sec 0.2 0.5 1 5

100 fs, 800nm, 1 kHz, 0.493 mJ, 20 passes

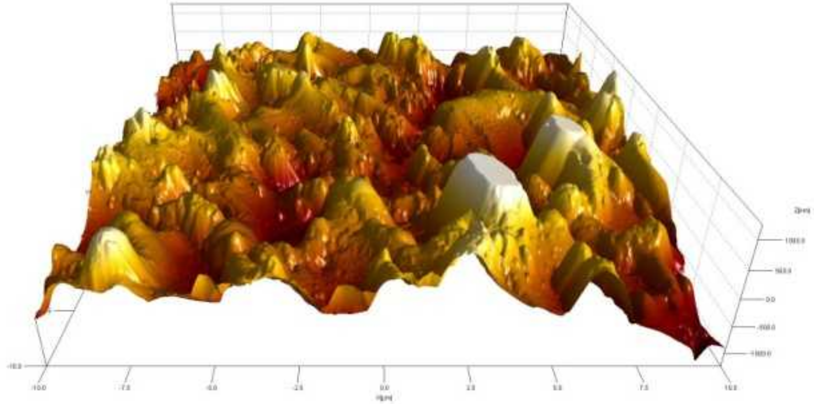


100 fs, 800 nm, 1 kHz, 0.493 mJ, 20 passes, 0.1-5 mm/sec

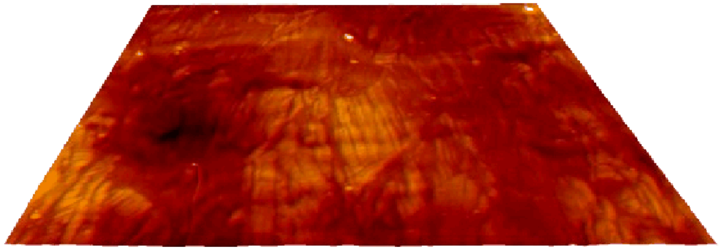


Electropolishing

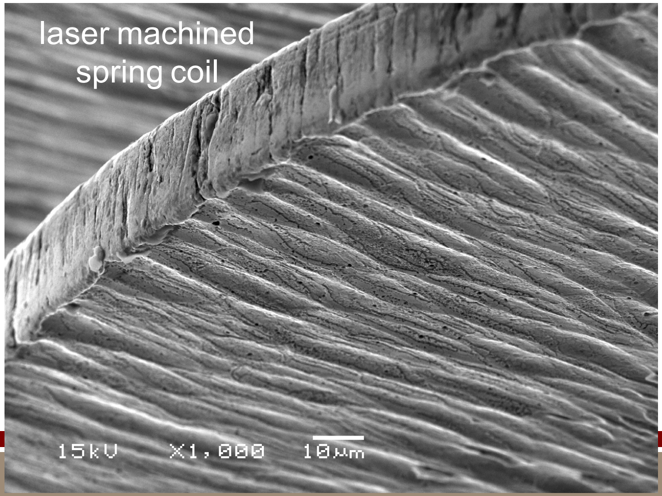
- Prompted by concern that process damage & tube roughness would reduce fatigue strength
- Optimization experiments
  - examined EP of high aspect ratio features
    - 20-30µm gaps w/aspect ratios ~5
    - thru cuts on 0.008in thick, 0.050in OD tube
    - measured throwing power, surface finish & material removal
  - presentation by colleague L. Serna
    - “Effect of Electropolishing on the Surface Topography of Micro-Wire Electrodischarge Machined Simulated Coil Gaps”, ICOMM 2012

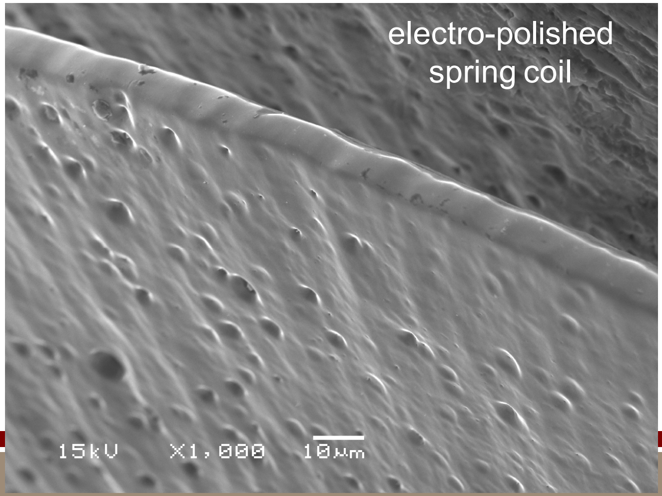


µ-EDM surface, R_a = 254nm



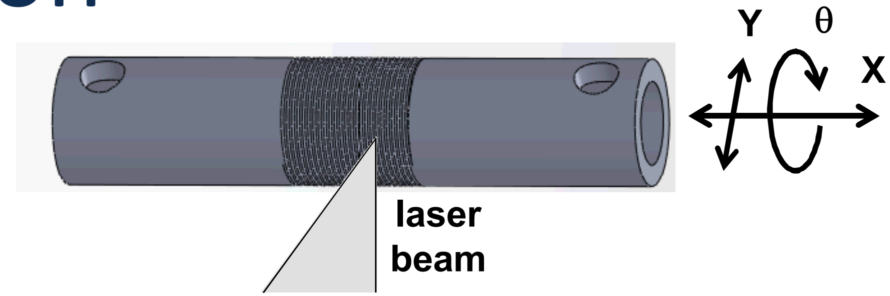
electropolished, R_a = 20nm

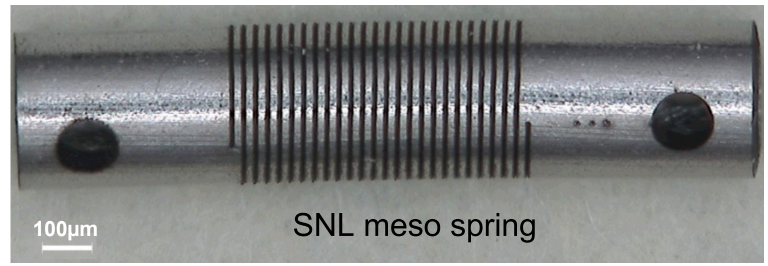




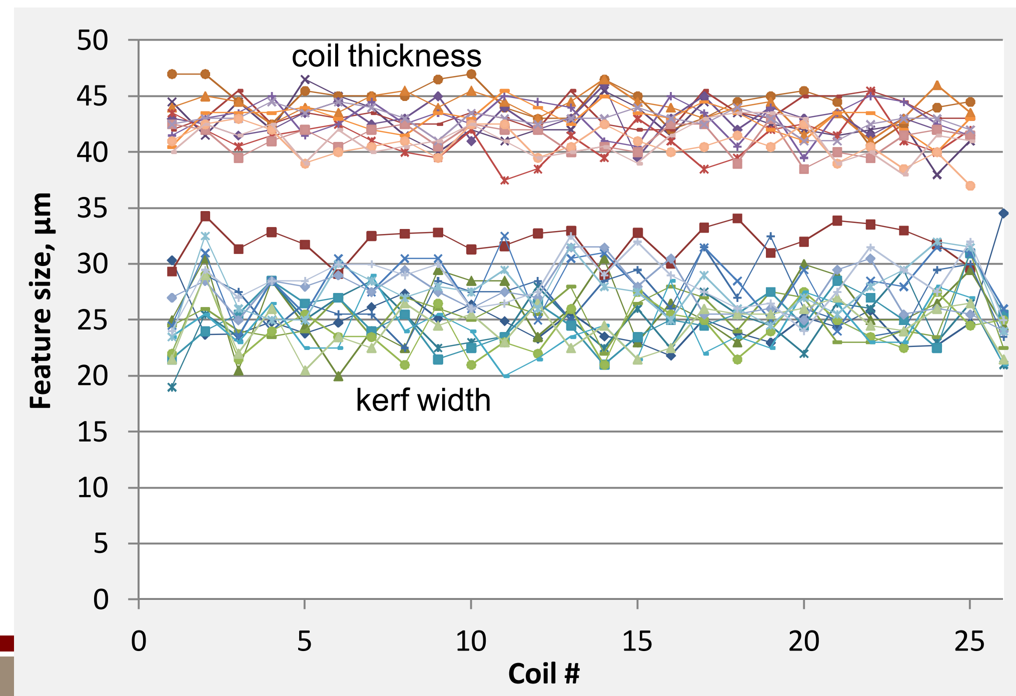
Prototype Fabrication

- Prototype fabrication
  - Spectra Physics Hurricane fs laser
  - process description
    - stationary beam
    - tubing translates in XY, rotates about θ





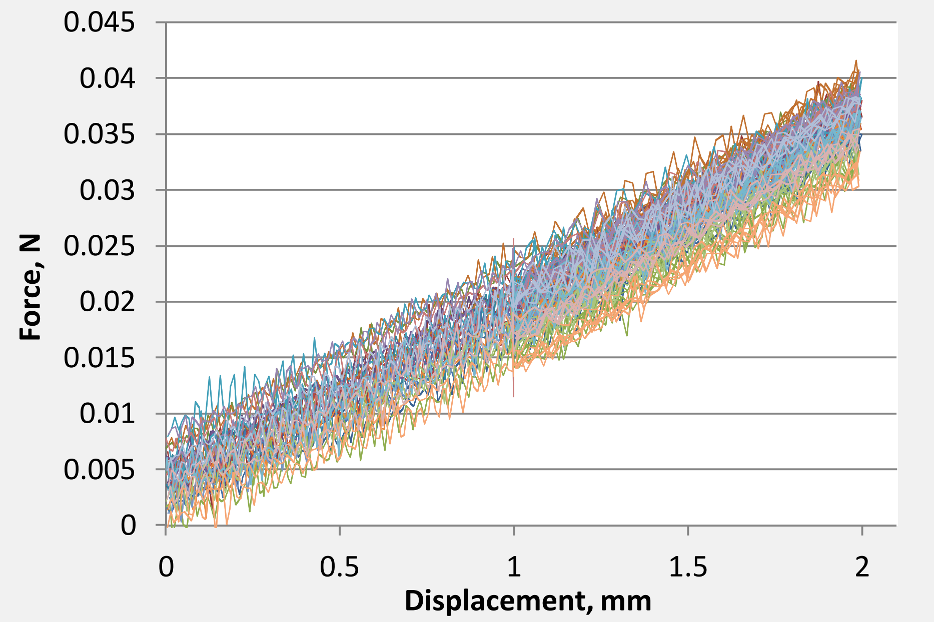
- Process repeatability
  - 19 prototype parts
  - coil thickness
    - spec = 40µm
    - average = 42.5 µm
    - range = 10.0µm
    - std dev = 1.9 µm
  - kerf thickness
    - spec = 25 µm
    - average = 26.0 µm
    - range = 15.6 µm
    - std dev = 2.8 µm

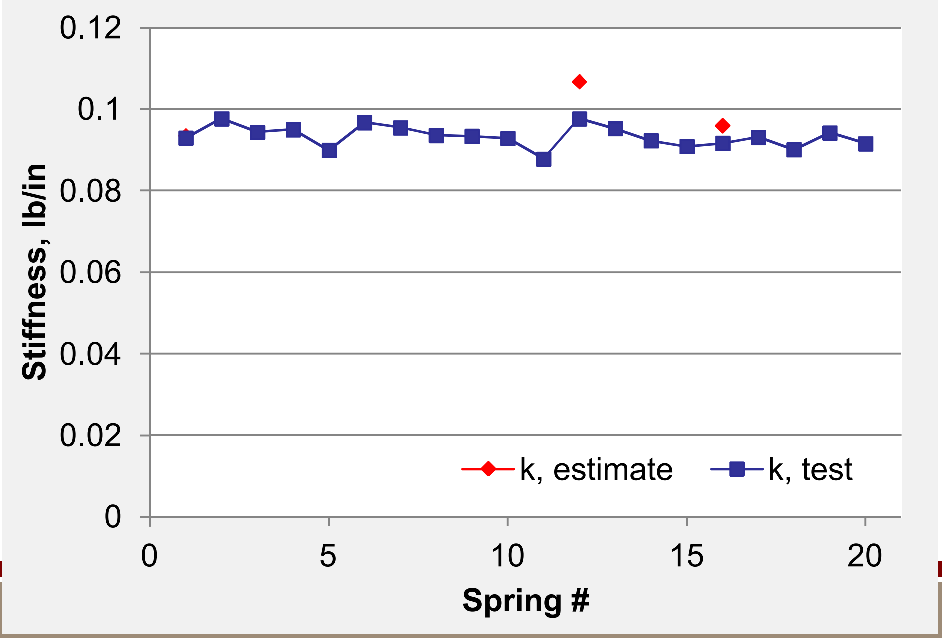


Spring Performance

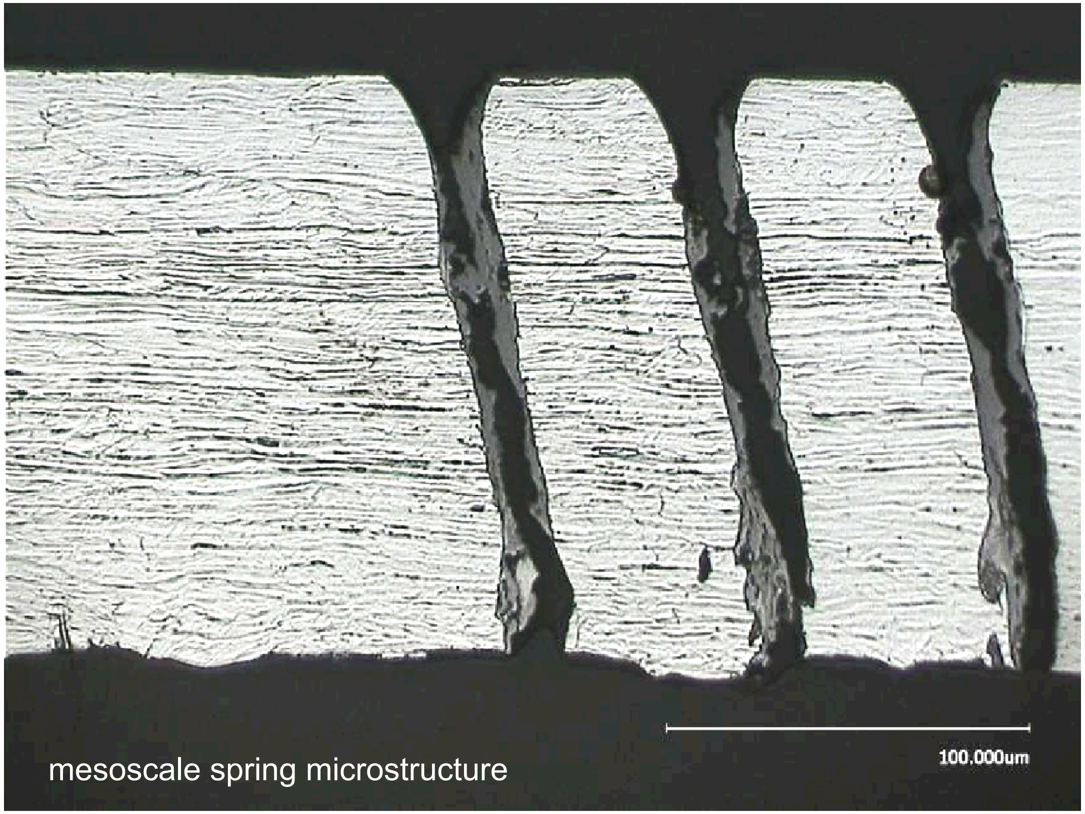
- Design models
  - proven for “macro” springs
  - assume bulk properties & continuum material behavior
  - what is accuracy @ mesoscale?

- Prototype meso springs
  - set of 20 springs
  - ~10% variability in stiffness
    - correlates directly to similar variation in coil thickness
    - normal distribution
  - closed form prediction accurate to ~5%
  - suggests minimal impact to material modulus due to processing & feature size





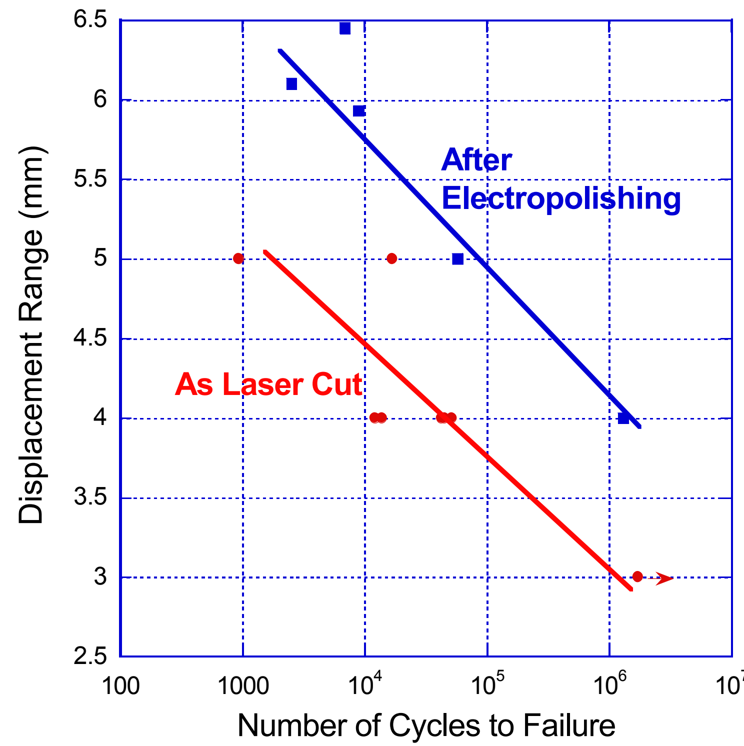
Continuum Behavior

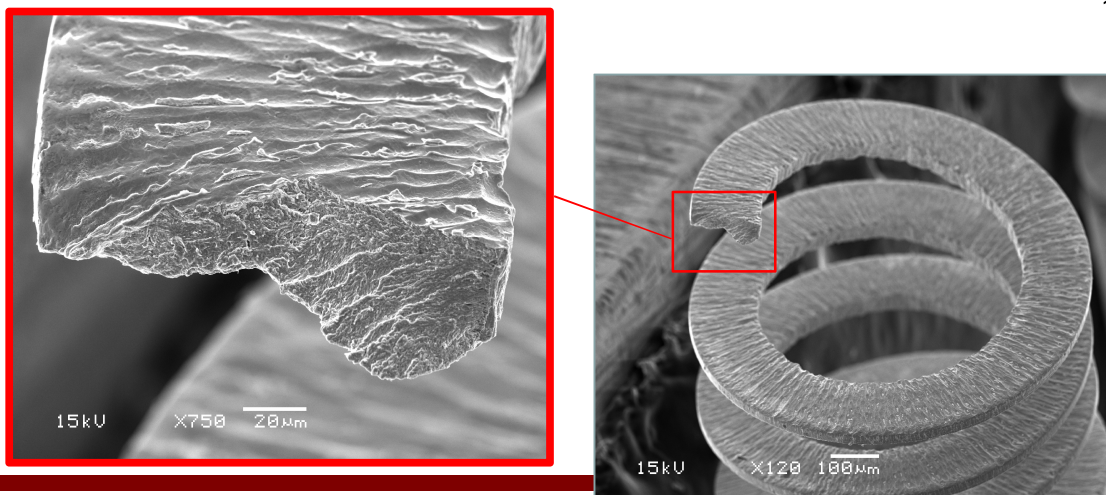


- Stiffness consistent with continuum models
  - coil thicknesses ~20-40μm
  - work hardened grain orientation is advantageous
    - multiple grains observed across coil width
  - torsion loading averages stresses across grains

Fatigue Resistance

- Pulsed laser surfaces are rough & are sources for crack initiation
- Electropolishing provides order-of-magnitude improved fatigue life





Conclusions

- Directly machined mesoscale springs have been investigated
- Design trades have been studied based on closed form solutions
- Feasibility & impact of fabrication processes have been examined
- Prototype springs have been fabricated & shown to provide stiffness variations of only 10% with model agreement within 5%

Acknowledgements

- Process operation
  - Carter Hodges, Michael Saavedra
- Design
  - Ernie Wilson, Ron Wild

- This document has been reviewed and approved for un-classified, unlimited release under SAND2012-xxxC.