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Manufacturing Characterization of Meso-Scale Parts Made from Stainless Steel

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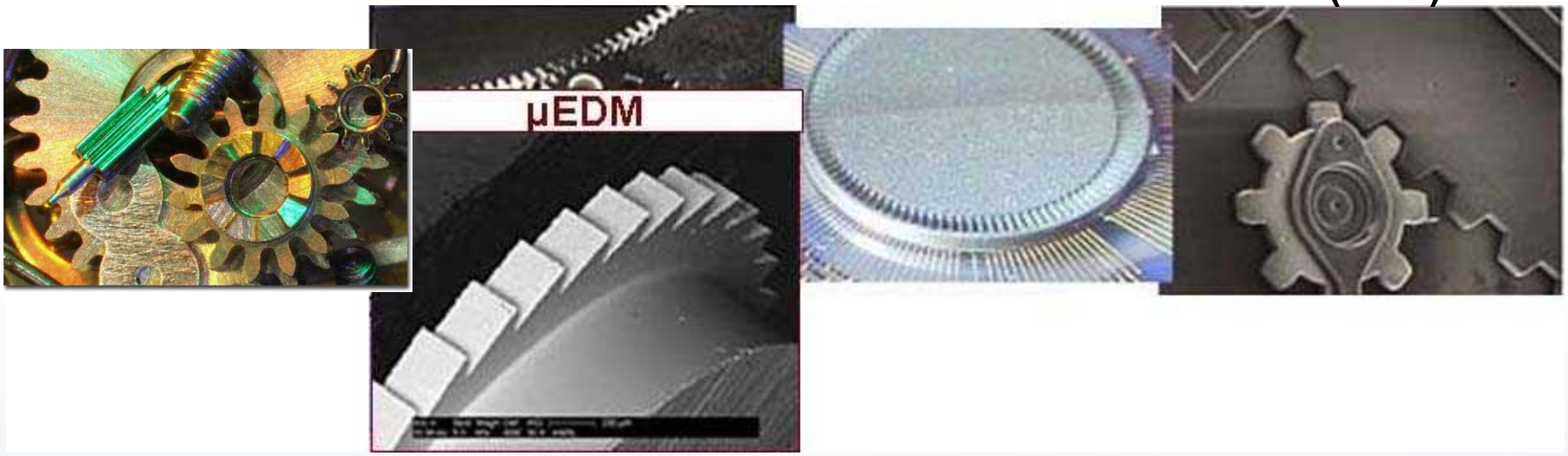
Meso-scale metal machining fills a unique manufacturing niche

Metals → Silicon

Miniature Machining | **LIGA** | **Bulk Silicon** | **Si MicroMachining (SMM)**



Dimensional tolerances decrease

± 0.X mm | ± X µm | ± 0.X µm

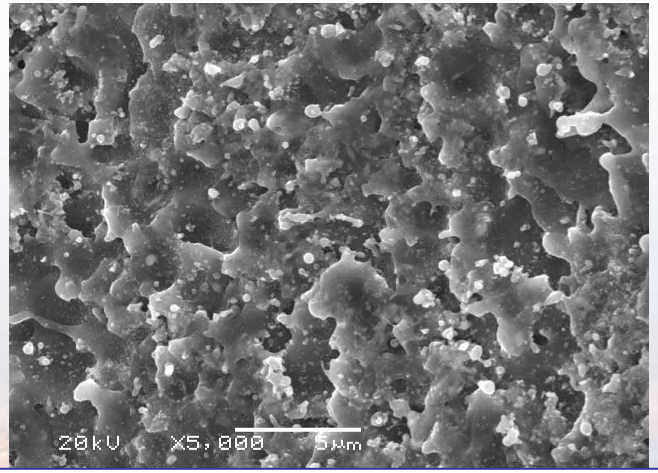
Specifically, µWEDM enables the creation of high precision metal microparts for meso-scale mechanisms.

µWEDM uses spark erosion to create small, intricate parts and achieve tight tolerances

- **Advantages:**
  - Enables machining of materials independent of material hardness
  - Applies very little force preventing part distortion
  - Minimal heat affected zone

Meso-scale stepper motor machined by µWEDM process. Stepper motor size is 10 mm x 10 mm x 5 mm.

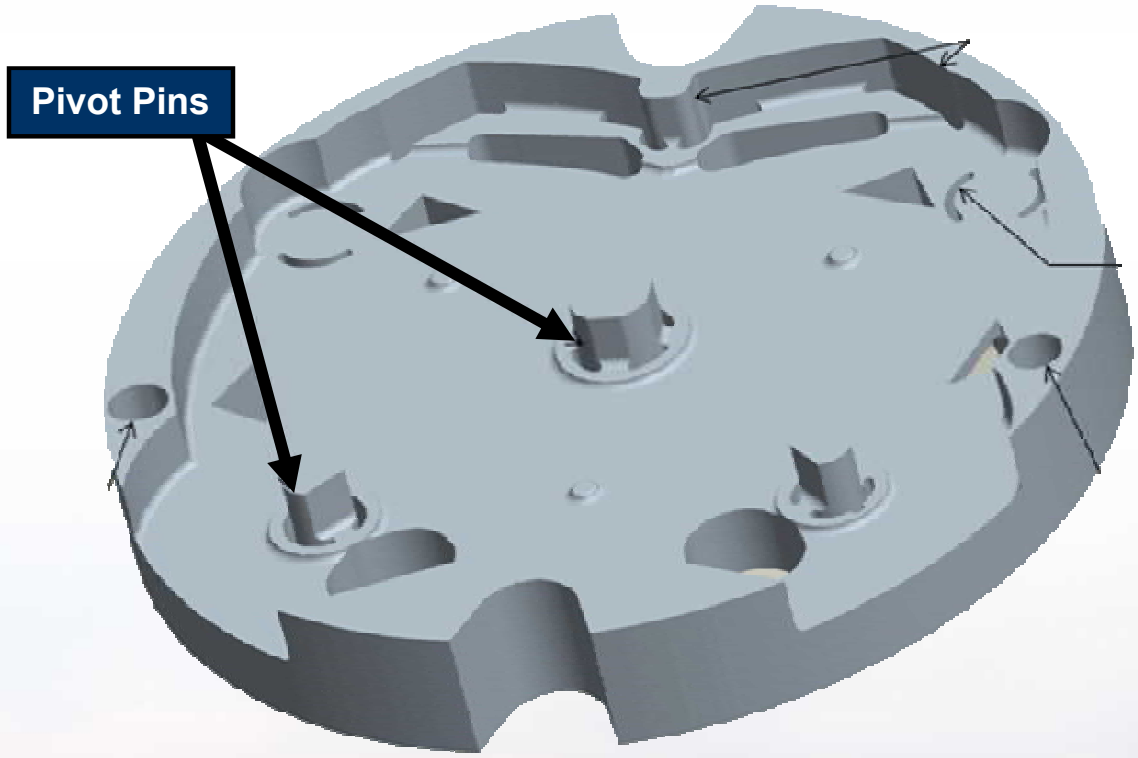
- **Disadvantage: *produces a "recast" layer on cut surfaces***
  - A thin layer (~2 microns) of re-solidified part material and traces of wire material.
  - Adversely affects:
    - Friction behavior
    - Wear particle generation
    - Coating coverage / adhesion
    - Fatigue resistance



Surface finish affects small mechanism performance, reliability and lifetime.

A “clock plate” is a mounting frame used for precision assembly of small mechanisms.

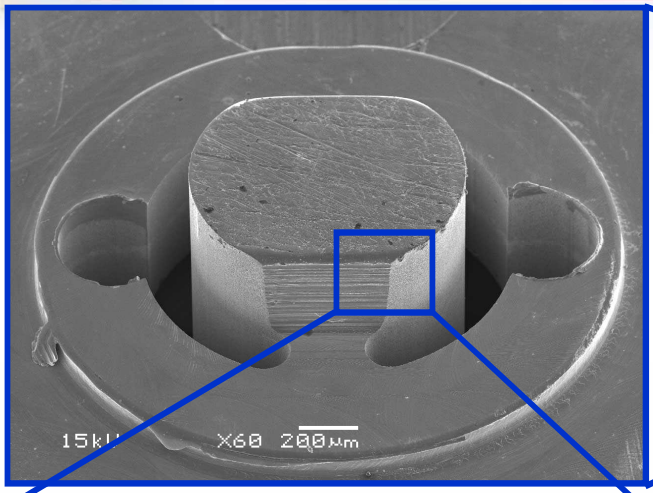
SIZE

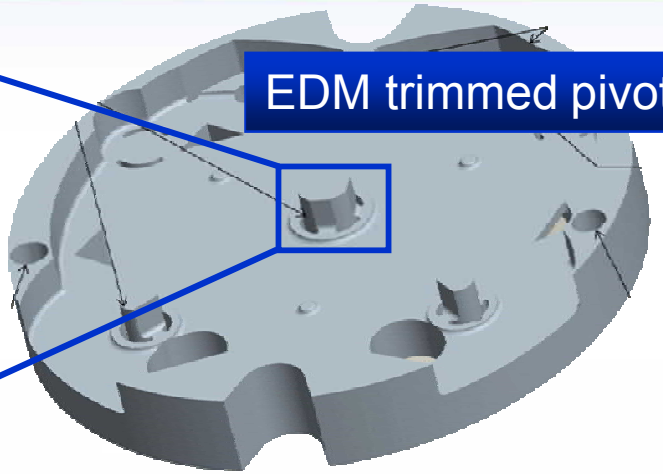


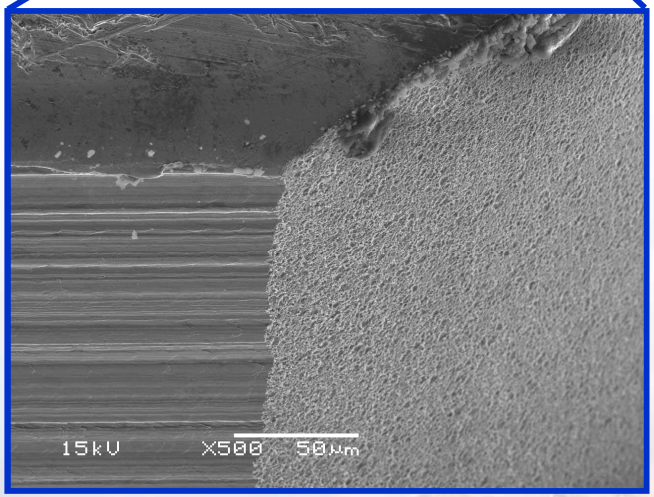
PRECISION

In conventional clock plates, registration features such as pivot pins are manually inserted, reducing mechanism precision.

µWEDM trimming of registration features can increase precision

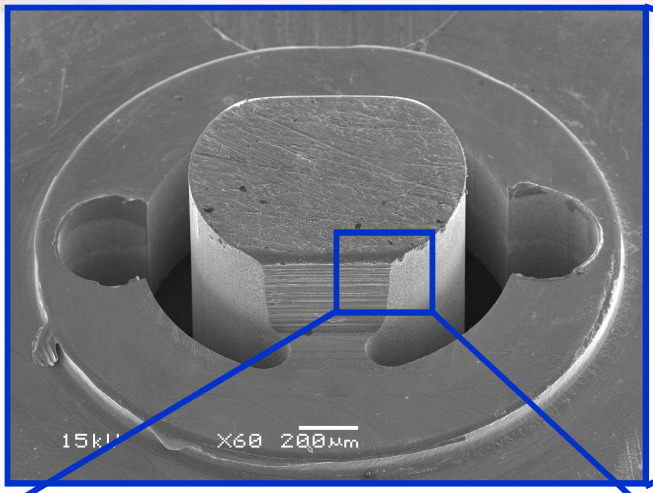


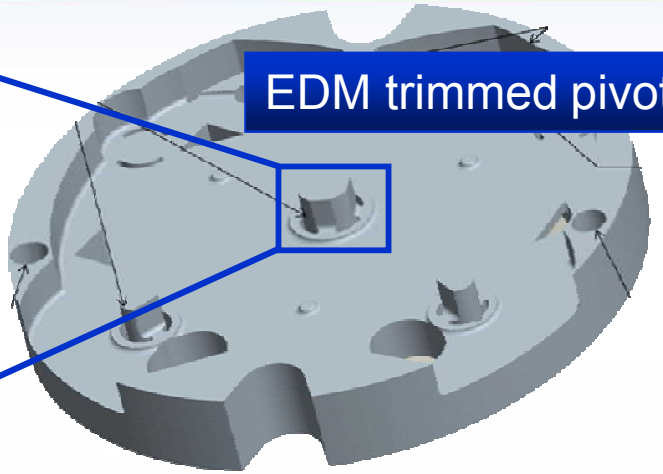


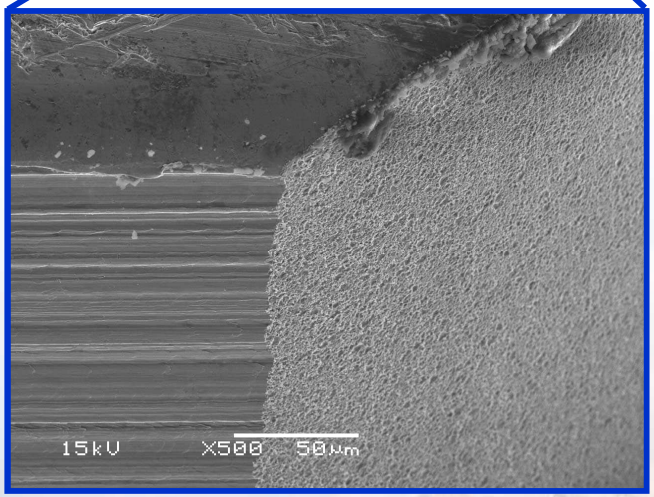


Tolerances of ±1.5 µm can be achieved using this method.

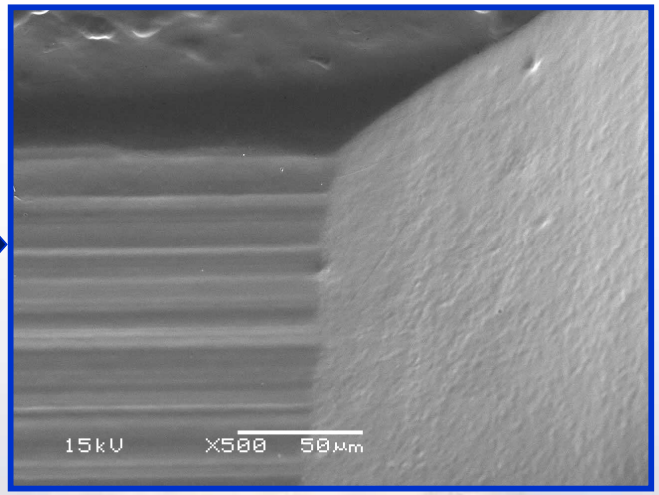
Electropolishing removes recast and improves surface finish.







EP

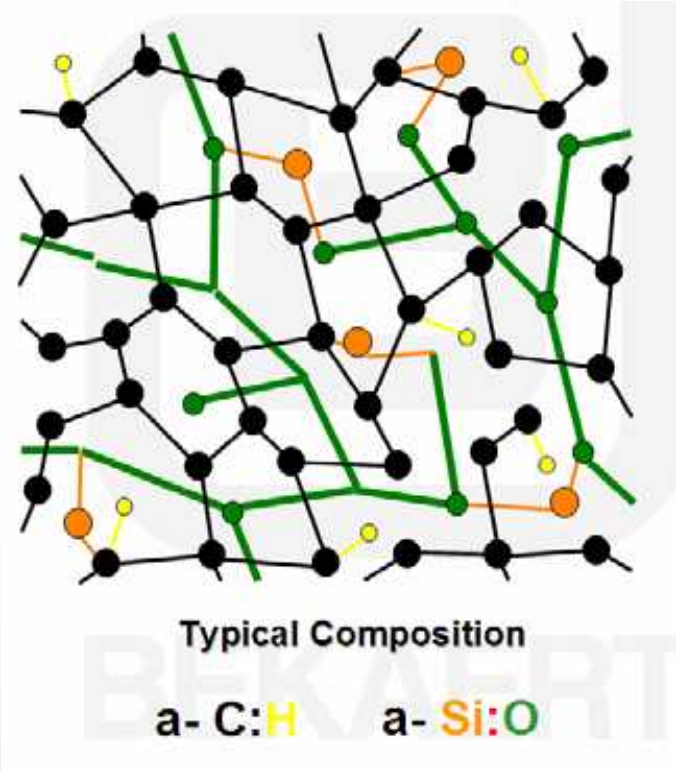


Electropolishing introduces tolerance uncertainty.

Diamond-like Nanocomposite (DLN) coatings are used for low friction applications

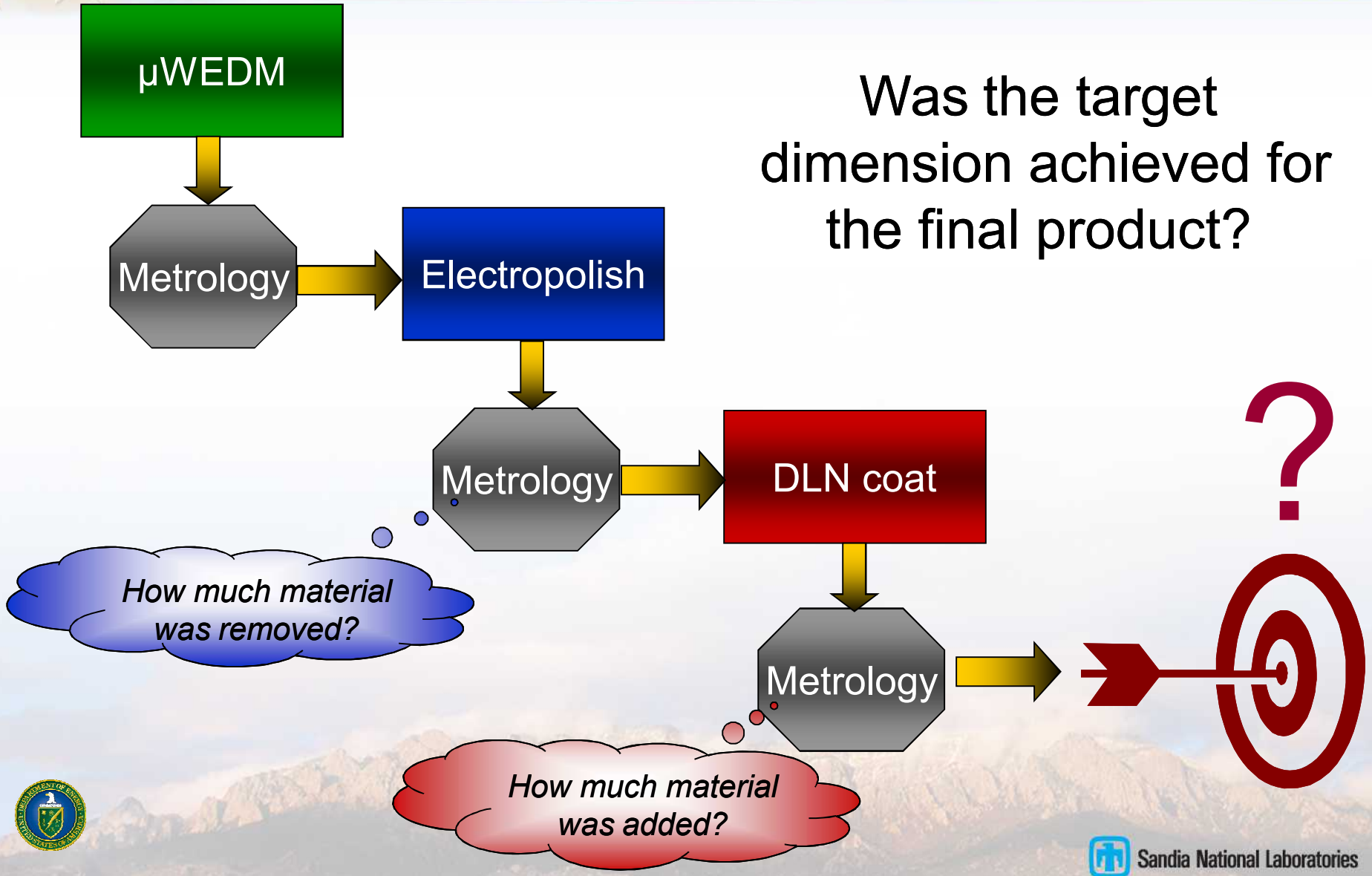
- **Proprietary thin films (2 to 4 microns)**
  - low friction and wear [9,10].
  - high hardness
  - high corrosion resistance
  - high temperature stability

- **Structure and composition**
  - C, H, Si, O
  - Random networks of diamond-like C:H networks and glass-like Si:O networks.
  - Interpenetrating network structure prevents growth of graphitic carbon at high temperature, enhancing film adhesion and reducing internal film stress [11].



Bekaert Advanced Coating Technologies

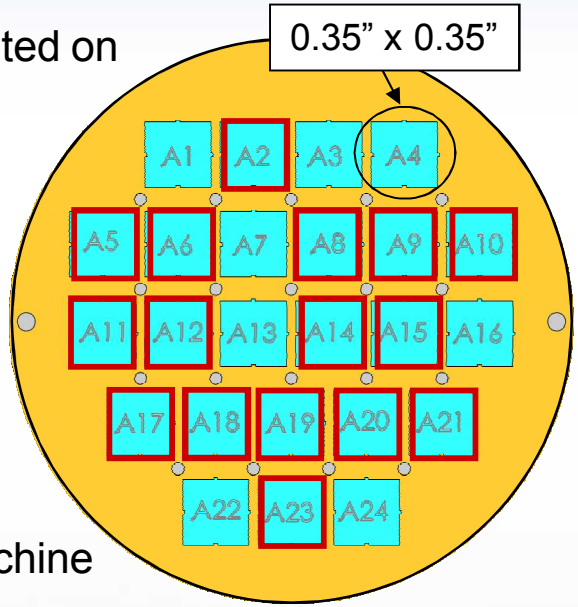
A three step manufacturing process was characterized.

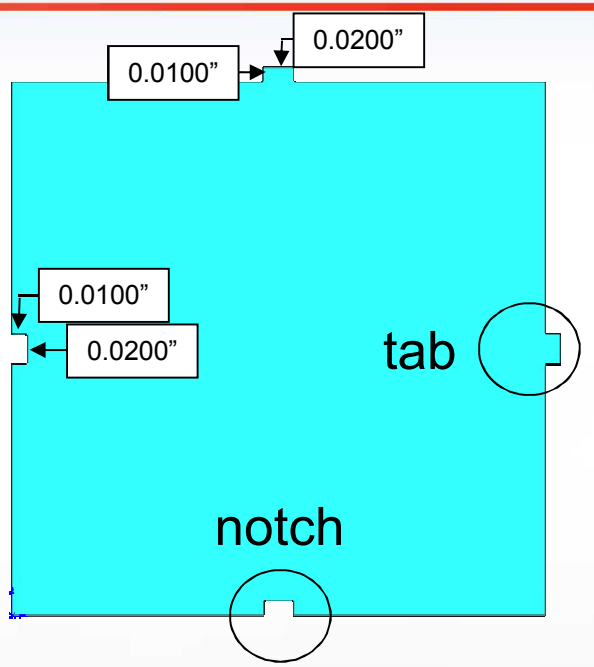


Was the target dimension achieved for the final product?

Tabs and notches were used for statistical analysis of dimensional tolerance stack up.

- 2 manufacturing runs were completed on consecutive days
  - Disc A and Disc B
- 24 coupons / run
- Tab and notch dimensions are 10 mil x 20 mil (254 x 508 µm)
- 16 out of 24 coupons were inspected (randomly selected)
- Optical Gaging Products (OGP) Avant 200 precision metrology machine
- MeasureMind Version 12.55 Build 10 software
- Feature width (target dimension 508 µm) was evaluated



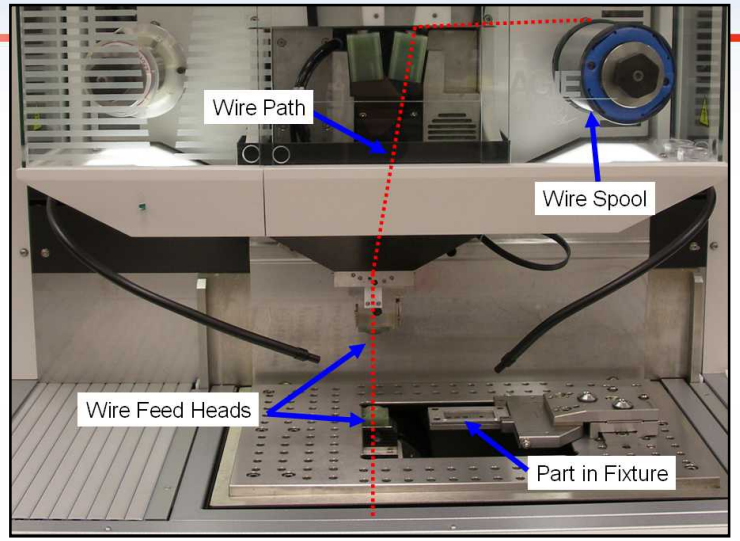


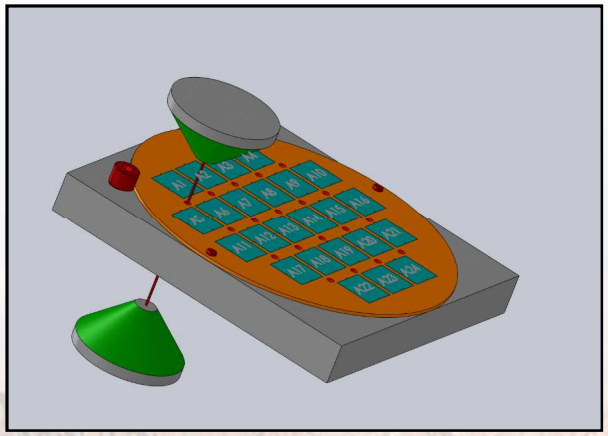
The following variables were explored:

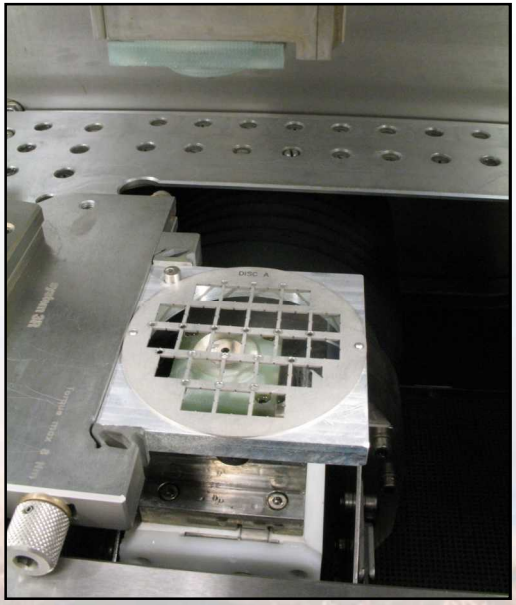
1. Within process variability – Coupons 1 through 24
2. Day-to-day (between) process variability – Disc A vs. Disc B
3. Geometry – tabs vs. notches

μWEDM Experimental Details

- Material: 21Cr-6Ni-9Mn stainless steel (Nitronic 40™)
  - 32 mil thickness
  - 30% machinability based on 100% machinability for AISI 1212 steel
- Agie Vertex 1F w/ proprietary process parameters:
  - Applied voltage
  - Circuit resistance & capacitance
- AC pulse generating circuit
- 30 micron tungsten wire
- Dielectric – deionized water
- Passes - 1 main and 3 trim
- Gap distances (microns)
  - Main pass = 416
  - Trim pass 1 = 264
  - Trim pass 2 = 191
  - Trim pass 3 = 160

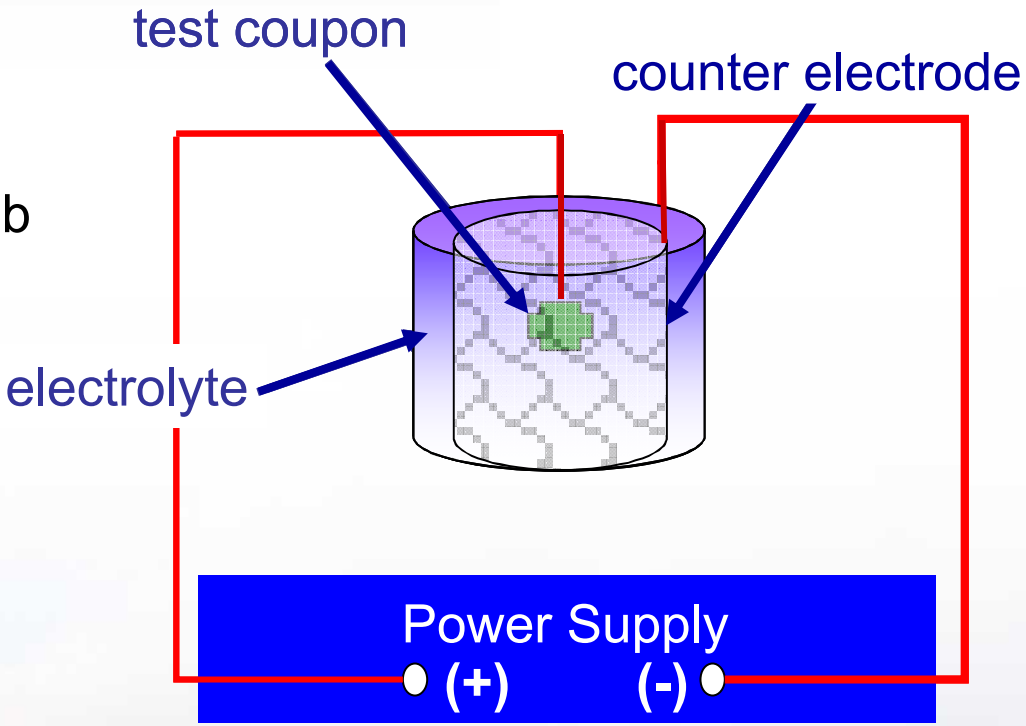






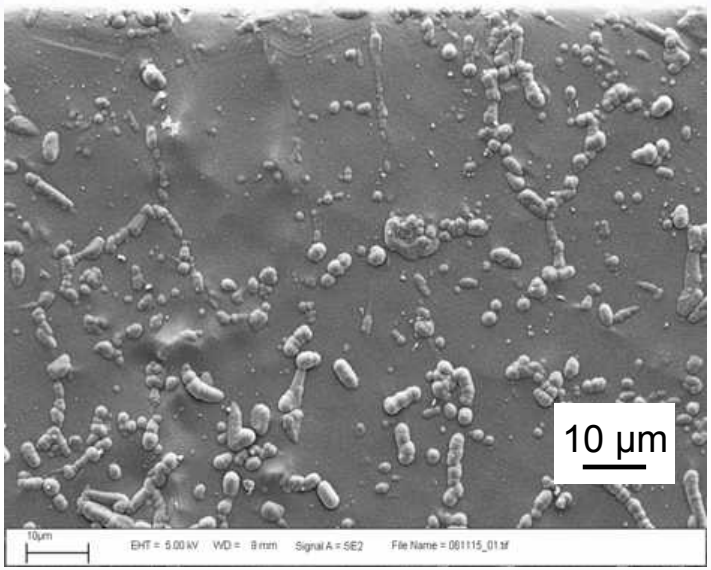
Electropolishing Experimental Details

- 80vol% H_3PO_4 + 20vol% n-butanol[1]
- BK Precision power supply
- Counter electrode – platinized Nb mesh
- Temperature - 70°C ± 5°C
- Current density –
- Immersion Time – 10 seconds



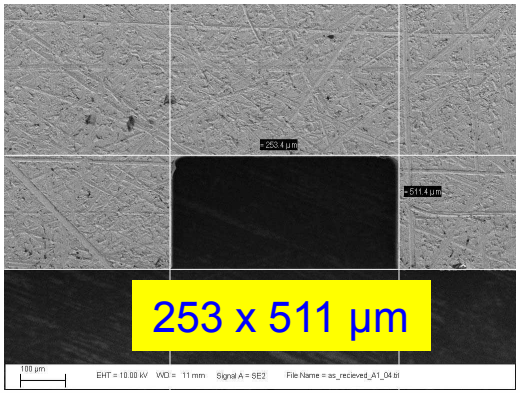
DLN Experimental Details

- Bekaert Advanced Coating Technologies
- Nominal thickness ~1 μm
- Single batch (Disc A and Disc B coupons)
- Deposited using plasma-enhanced chemical vapor deposition (PECVD)
- Substrate is negatively rf biased from −300 to −500 V
- Coupons not pre-heated

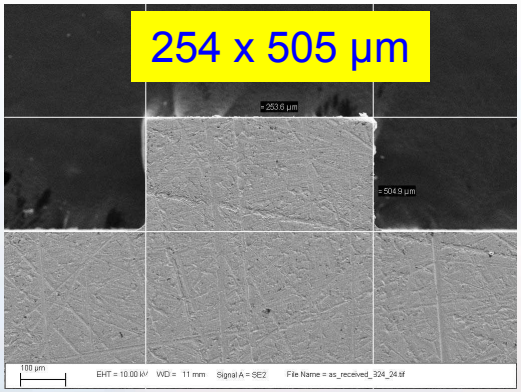


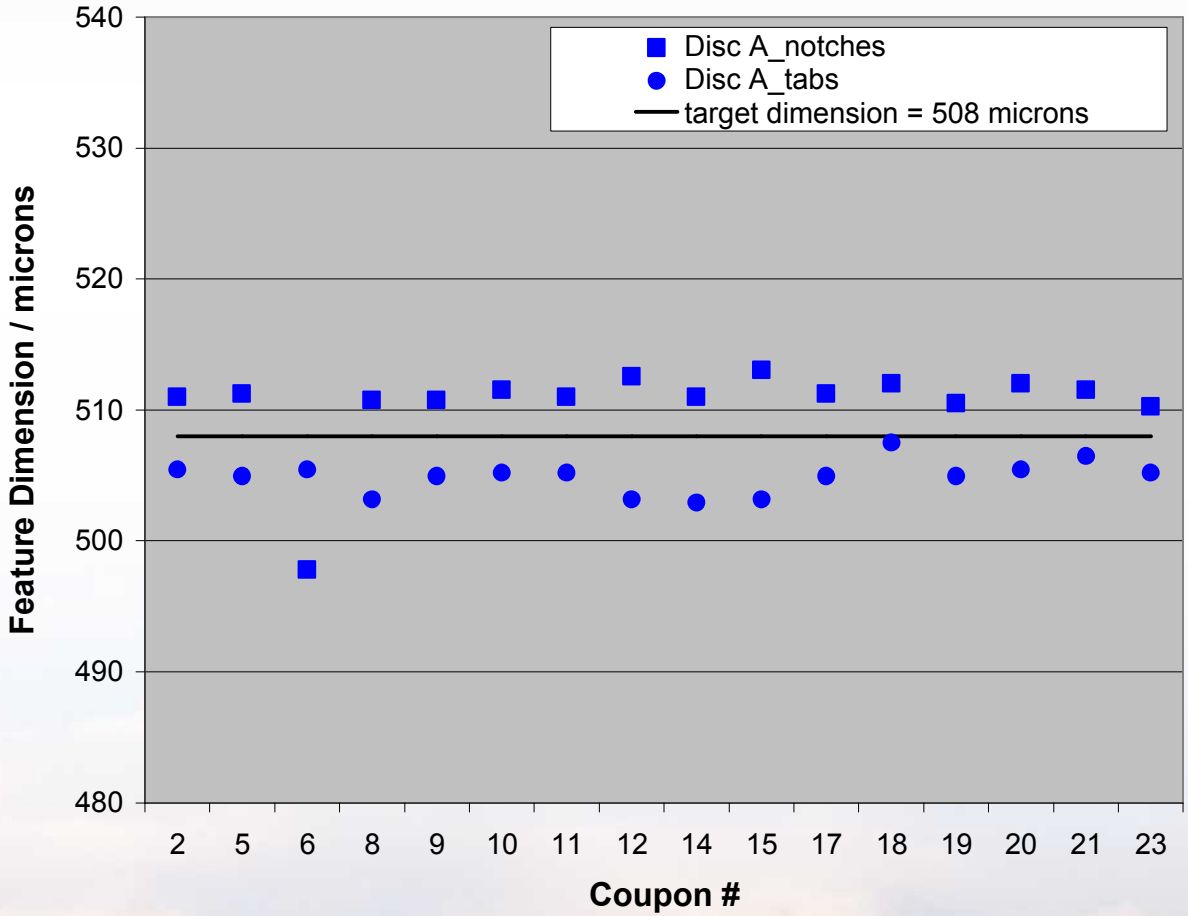
Calculated measurements for Disc A features

- Notches are oversized



- Tabs are undersized





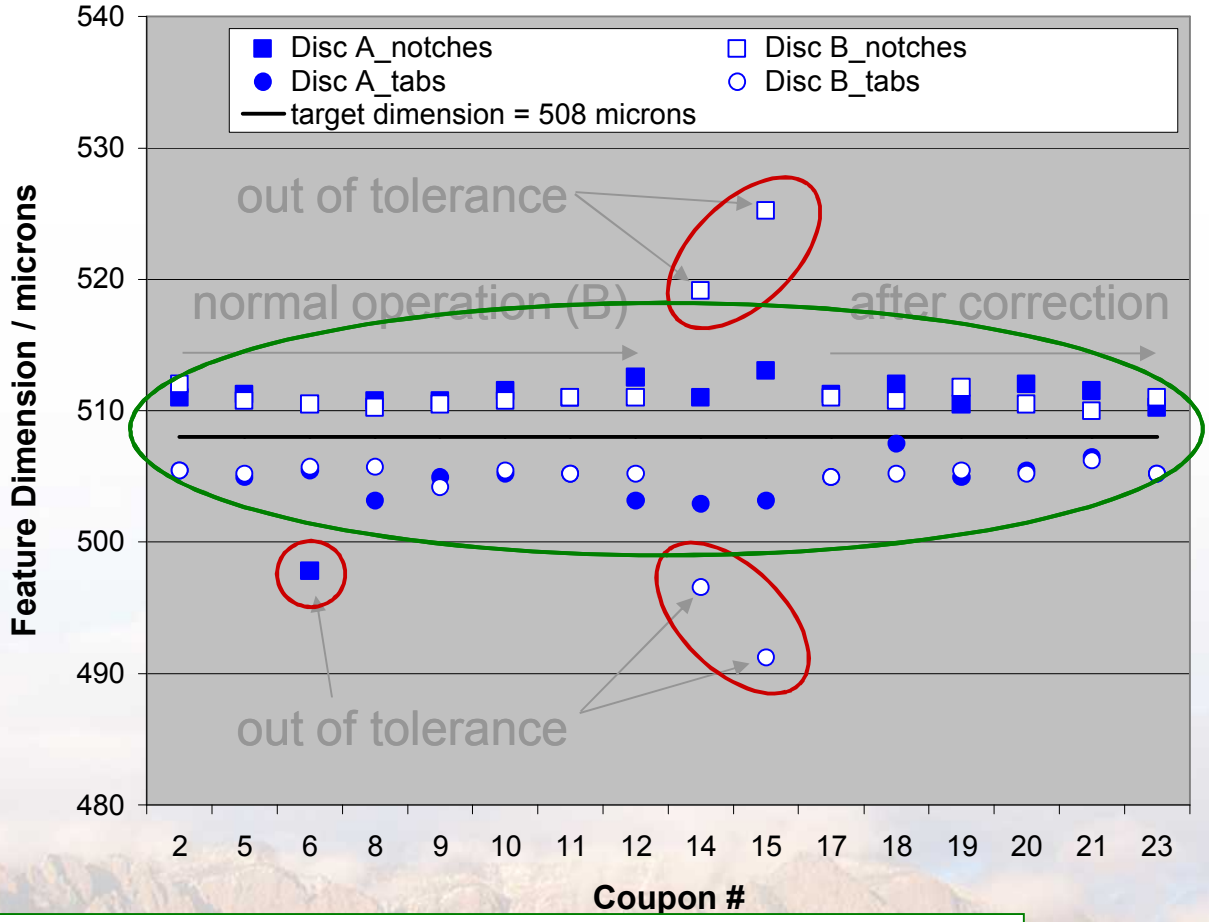
The target dimension of 508 microns was *almost* achieved.
Average results off target by ±0.6%.

Feature dimensions for A and B manufacturing runs are very similar

- Both runs exhibited fabrication errors
  - Cause(s) of errors is not known
- Agiejogger has automatic correction feature
- If out of tolerance features are detected, Agie adjusts to bring features back into tolerance
- Abnormal events are beyond scope of this study

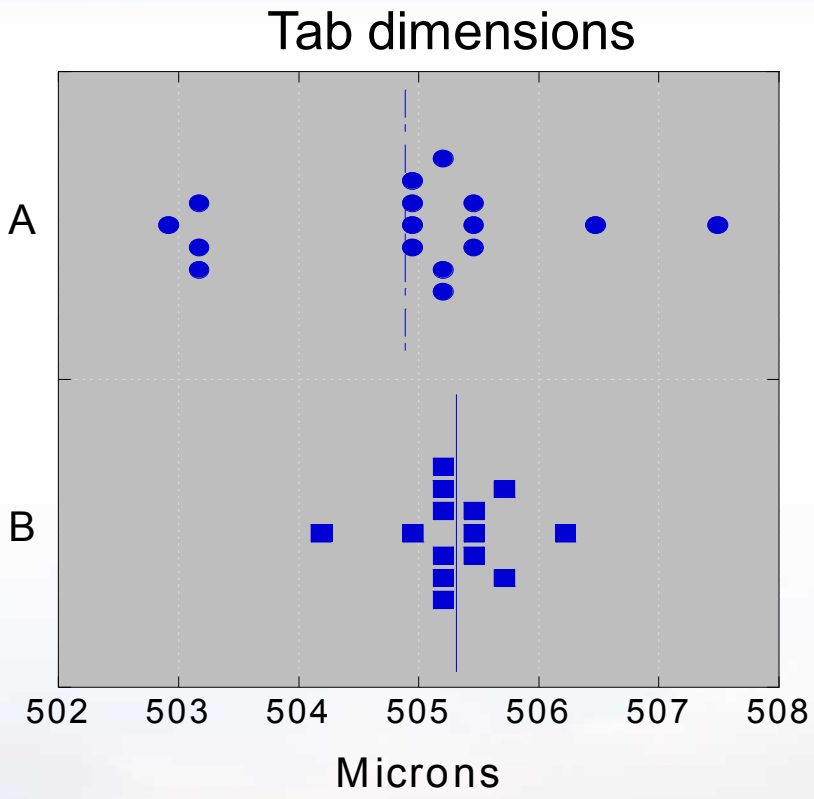
  Outliers: A6, B14, B15

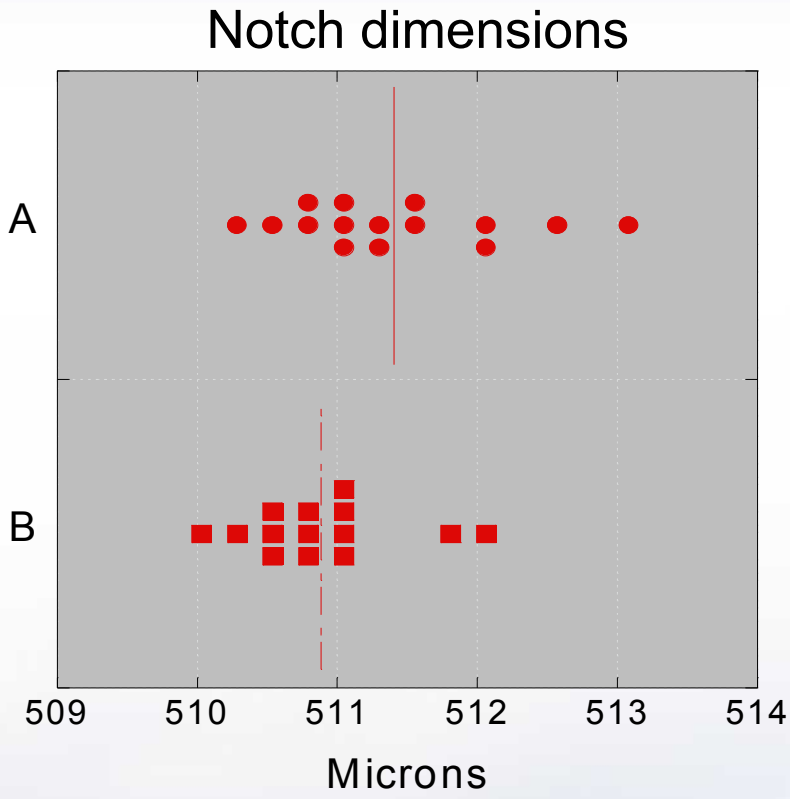
  (5 datapoints)



Statistical study will focus on “normal” fabrication variations

EDM condition: No significant differences were observed across days

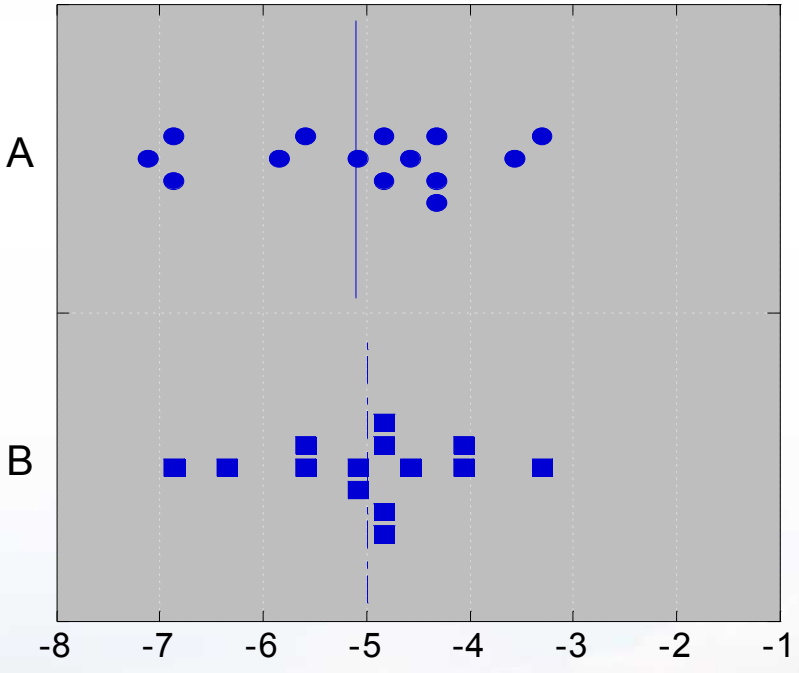




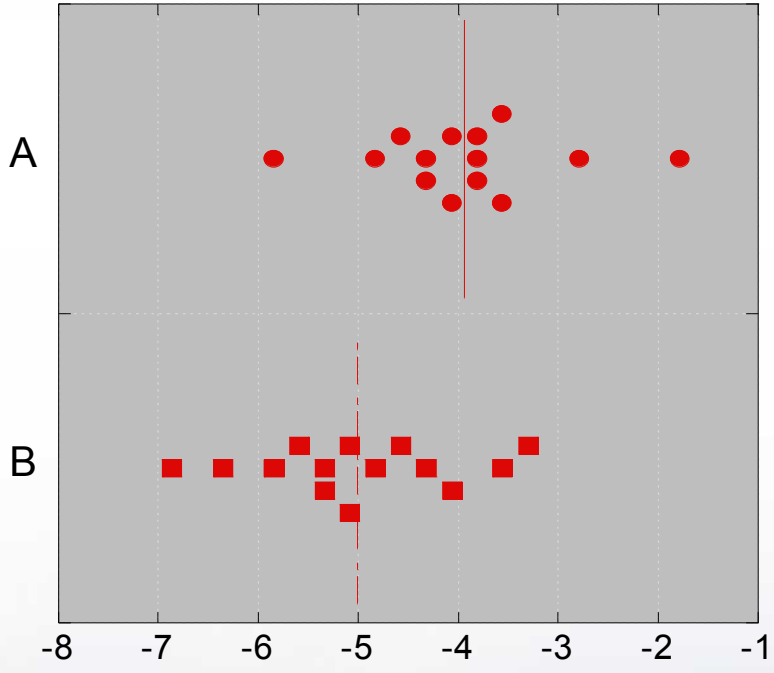
	Mean	Standard Deviation
Tabs (A+B)	505.1	1.00
Notches (A+B)	511.1	0.68

The EP process seems to be different across days for notches only – reason unknown

Tab dimensions (EDM-EP)



Notch dimensions (EP-EDM)

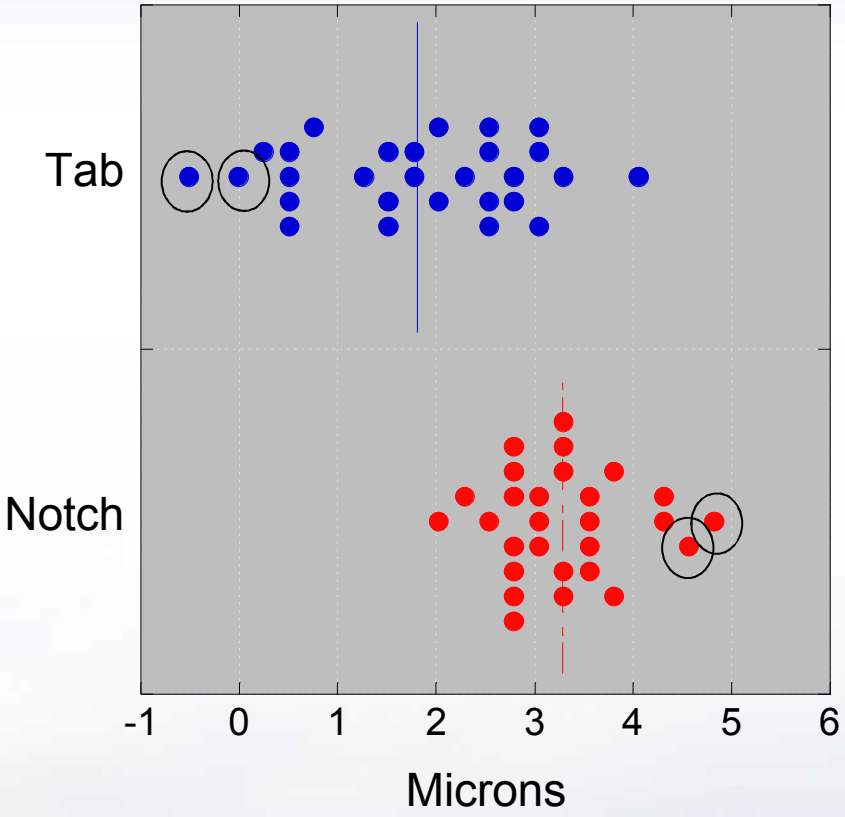


	Mean	Standard Deviation
Tabs (A+B)	-5.0	1.05
Notches (A+B)	-4.5	1.10

DLN deposition seems to be greater in notches compared to tabs

- Based on OGP data, DLN coating appears to be thicker in notches compared to tabs.

- ◯ samples selected for FIB sectioning



	Mean	Standard Deviation
Tabs (A+B)	1.8	1.15
Notches (A+B)	3.3	0.67

FIB cuts and metallography of DLN coated samples

Statistical analyses was based on post-DLN measurements – i.e. the final product.

n = 27; (32 total data points – 5 outliers)

Tabs

- Mean ($\hat{\mu}$) = 501.8 microns
- Standard deviation ($\hat{\sigma}$) = 1.27 microns
- 26 degrees of freedom
- No significant lot-to-lot (A vs. B) variation
- Assuming no error in parameter estimates; $\hat{\mu} = \mu$ and $\hat{\sigma} = \sigma$
- 90% confidence interval for 95% of production yield is given by:

$$Lower\ Tolerance\ Limit = \hat{\mu} - 2.48 \cdot \hat{\sigma} = 499 \text{ microns}$$

$$Upper\ Tolerance\ Limit = \hat{\mu} + 2.48 \cdot \hat{\sigma} = 505 \text{ microns}$$

Statistical analyses was based on post-DLN measurements – i.e. the final product.

n = 27; (32 total data points – 5 outliers)

Notches

- Mean ($\hat{\mu}$) = 512.3 microns
- $\hat{\sigma}_{between-lots}$ = 0.61 microns (1 degree of freedom)
- $\hat{\sigma}_{within-lots}$ = 0.74 microns (25 degrees of freedom)
- $\hat{\sigma} = \sqrt{\hat{\sigma}^2_{within-lots} + \hat{\sigma}^2_{between-lots}}$ = 0.96 microns
- Assuming no error in parameter estimates; $\hat{\mu} = \mu$ and $\hat{\sigma} = \sigma$
- 90% confidence interval for 95% of production yield is given by:

$$Lower\ Tolerance\ Limit = \hat{\mu} - 3.39 \cdot \hat{\sigma} = 509 \text{ microns}$$

$$Upper\ Tolerance\ Limit = \hat{\mu} + 3.39 \cdot \hat{\sigma} = 516 \text{ microns}$$

Summary and Conclusions

- A 3-step manufacturing process for high-strength stainless steel precision parts was statistically characterized.
  - **μWEDM → electropolishing → DLN coat**
- μWEDM process showed no within process or between process variability (outliers removed).
- The target dimension was *almost* achieved; tabs slightly undersized, notches slightly oversized.
- On average, electropolishing appeared to remove 4 to 5 microns of material.
- The DLN coating did not appear to be uniform across feature geometry; more material was deposited in notches compared to tabs.

Summary and Conclusions cont.

- Assuming 90% confidence of 95% yield, the tolerance limits for the current process are:
  - Tabs - 499 to 505 microns
  - Notches - 509 to 516 microns
- A geometry dependent offset may compensate for
  1) the apparent offset inherent in the μWEDM process and
  2) the nominal losses and gains in material due to electropolishing and DLN coating.

Q & A

QUESTIONS????

Acknowledgements

Michael Rye and Gary Bryant for FIB work;
Alice Kilgo for metollagraphy