FARADAY TECHNOLOGY, INC.

Electrochemical Surface Finishing of Additively Manufactured Parts

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Technical Meeting and Exhibition

MS&T17

MATERIALS SCIENCE & TECHNOLOGY

OCTOBER 8 – 12, 2017

DAVID L. LAWRENCE CONVENTION CENTER

PITTSBURGH, PENNSYLVANIA, USA

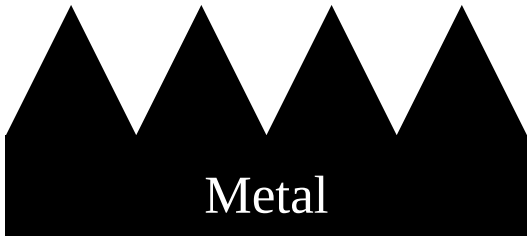
Problem/Opportunity

- **Problem**: Surface finishing is a major requirement of most manufactured materials
  - Medical – Aerospace – Automotive - Semiconductor Industries:
    - ✓ Defect and impurity free/Surface roughness as low as ≤ 0.05 µm Ra
  - Emerging Additive Manufacturing (AM) Applications
    - ✓ Ra/Rz reduction to achieve desired finish/removal surface voids
  - Conventional ElectroChemical Surface Finishing:
    - ✓Concentrated/Viscous Acids with (HF) ➔ process control & safety hazard!
    - ✓ Electrochemical cell designs are overly complicated at best
- **Need/Opportunity**: Electrochemical Surface Finishing
  - Produce the desired finish/Remove all surface particulate contaminants
  - Scalable/HF-free water based electrolytes ➔ Safe/Robust process
  - Selective material removal

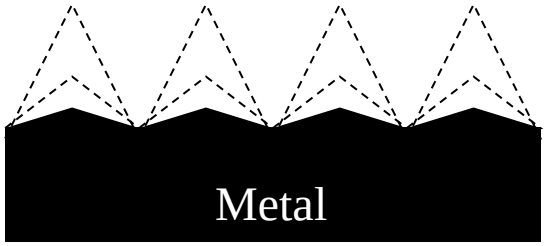
Conventional Electrochemical Surface Finishing

On some scale - All surfaces are rough:

1. $M^0 \rightarrow M^+ + e^-$
2. $xM + yH_2O \rightarrow M_xO_y + 2yH^+ + 2ye^-$



➔ preferential removal of asperities ➔



Traditional ElectroFinishing:

1. **Smooth, bright surface finish achieved under diffusion limited conditions†**

   ➔ **Viscous/concentrated acid electrolytes**

2. **For passive materials, electrolytes designed to mitigate oxide formation**

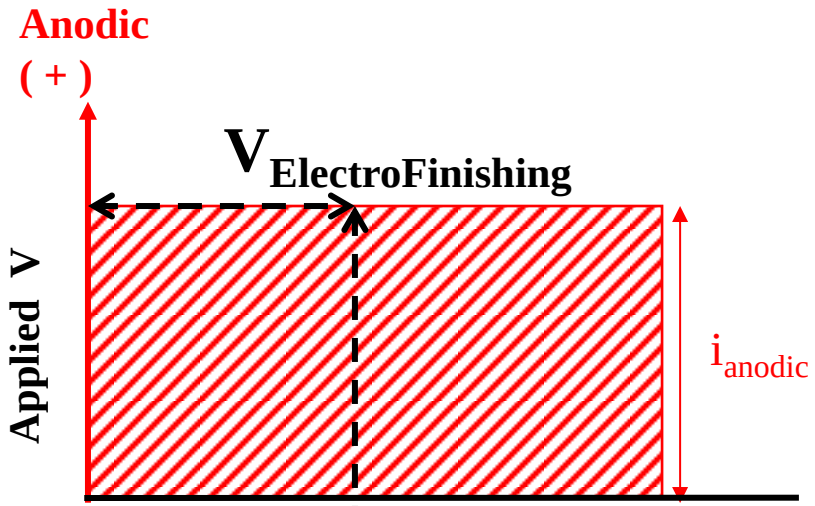
   ➔ **Oxide removal with fluoride or hydrofluoric acid (HF)**

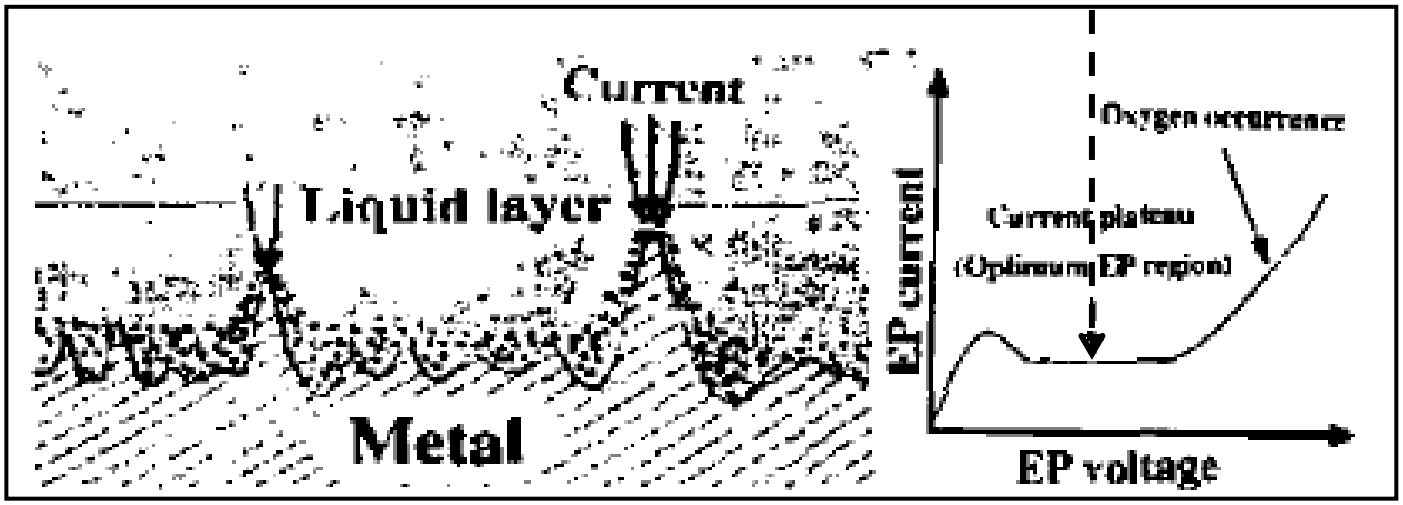
   ➔ **Non-aqueous to prevent oxide formation – not industrially practical**

† *P.A. Jacquet, Trans. Electrochem. Soc.,* ***69*** *629 (1936).*

ElectroFinishing – Direct Current (DC)

- Rectification:
  - DC - Constant voltage
  - Viscous salt film per Jacquet
  - Passive (oxide) film formation
- Electrolyte:
  - Concentrated/viscous acid
  - Chilled to increase viscosity
  - HF add to remove oxide





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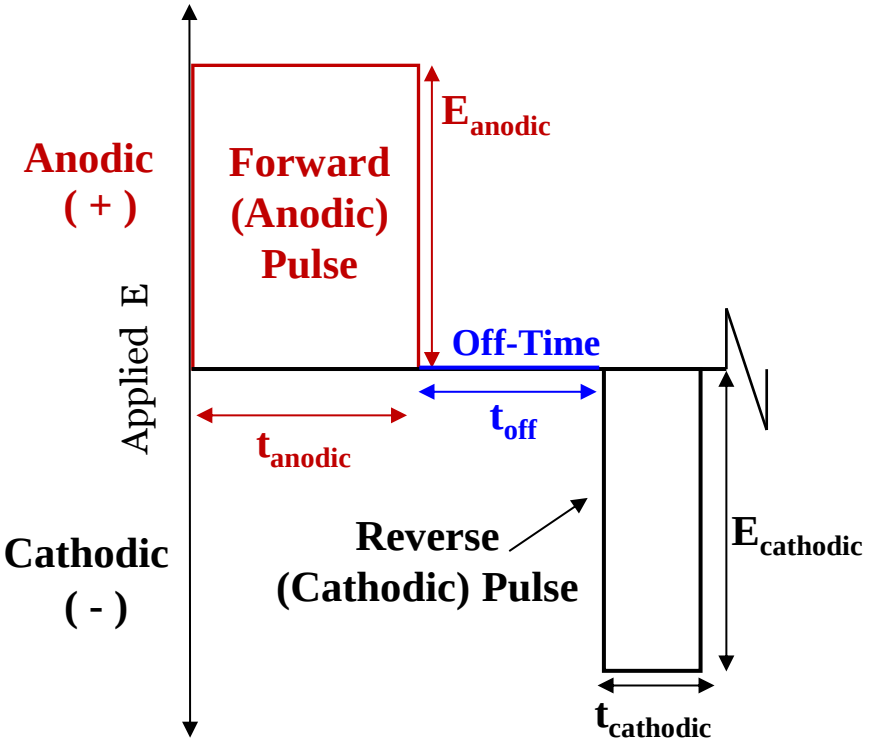
Pulse/Pulse Reverse (P/PR) ElectroFinishing



Anodic Pulse – focus the current distribution to smooth surface

➔ Eliminates need for viscous electrolyte

Cathodic Pulse – depassivates surface/ removal of surface oxide

➔ Eliminate need for HF and/or low water content electrolytes

Off-time – no applied voltage

➔ Dissipates heat – simplifies cell design

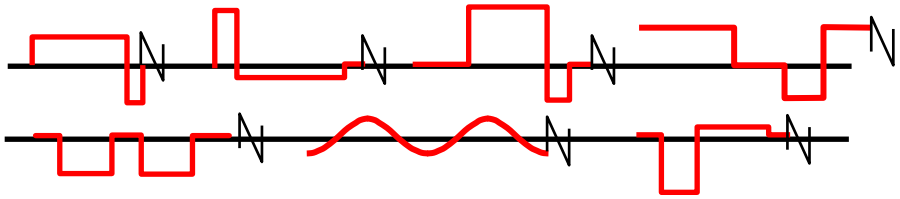
➔ Replenishment of reacting species

➔ Remove reaction products

P/PR ElectroFinishing shifts the paradigm ➔ enabling use of aqueous, non-viscous electrolytes free of F^- /HF acid

1. E.J. Taylor, M. Inman, *The Electrochemical Society Interface* 23(3), 57, Fall 2014
2. M. Inman, E.J. Taylor, T. Hall, *J. Electrochem Soc* 160(9), E94-E98, 2013
3. E.J. Taylor, M. Inman, T. Hall, B. Kagajwala, *ECS Trans* 45(8), 13-20, 2013

Pulse/Pulse Reverse ElectroFinishing: “Conventionally” Manufactured Materials Selective Material Removal Additively Manufactured (AM) Materials



Examples, Case Studies, & Current Developments

P/PR ElectroFinishing Demonstrations

- Titanium Alloys
  - Nitinol (Ni:Ti 50:50)
  - Ti-15Mo
  - Ti-6Al-7Nb
  - Ti-6Al-4V
  - CP Ti (Grade 2/4)
- Mo
  - Pure Molybdenum
  - Spherical Mo-Hf
  - 52.5Mo-47.5Re
- Co-Cr
- Nb
- SAE 4159 Steel
- Ta
- Ta 10W

- Stainless Steels
  - 316L
  - 301/304
  - 430
  - C450
- Ni Alloys
  - 718 Inconel
  - Hastelloy
  - Haynes 230
- Aluminum Alloys
  - 1010
  - 2024
  - 7075

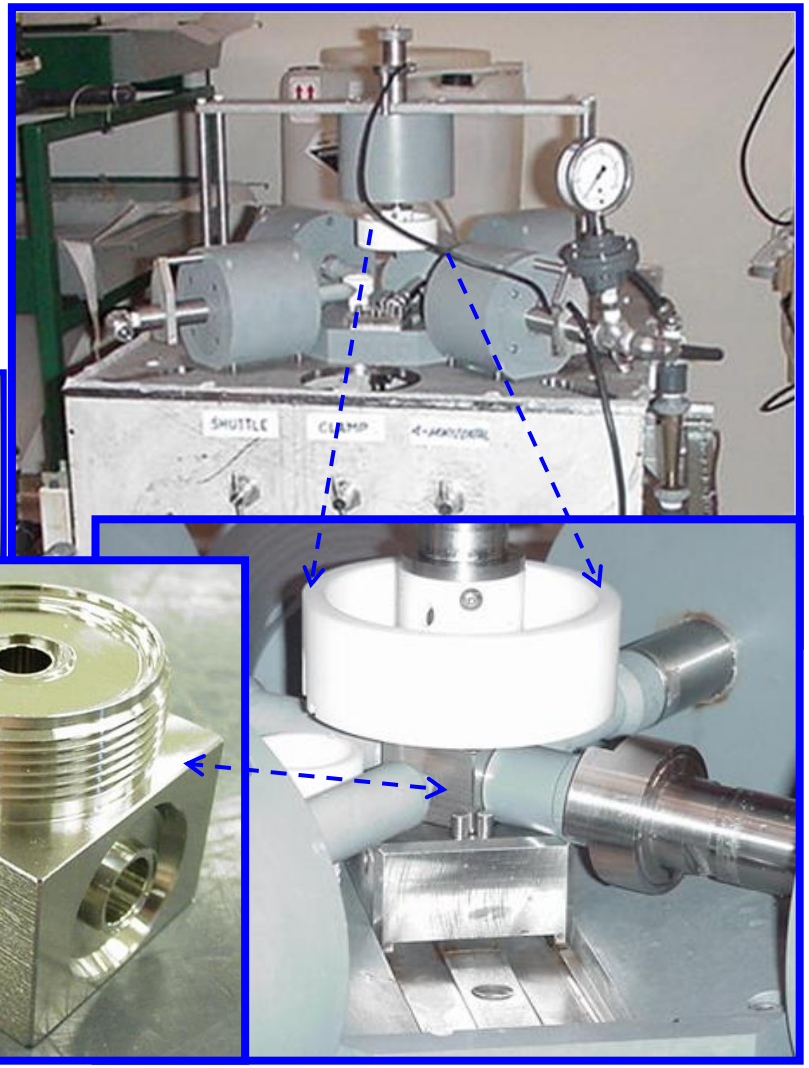
For P/PR (Generally);

V_{Anodic} /$V_{Cathodic}$ ➔ Material specific

t_{anodic} / $t_{cathodic}$ / t_{off} ➔ Part/Cell geometry specific

P/PR ElectroFinishing - SS Valve (Swagelok)

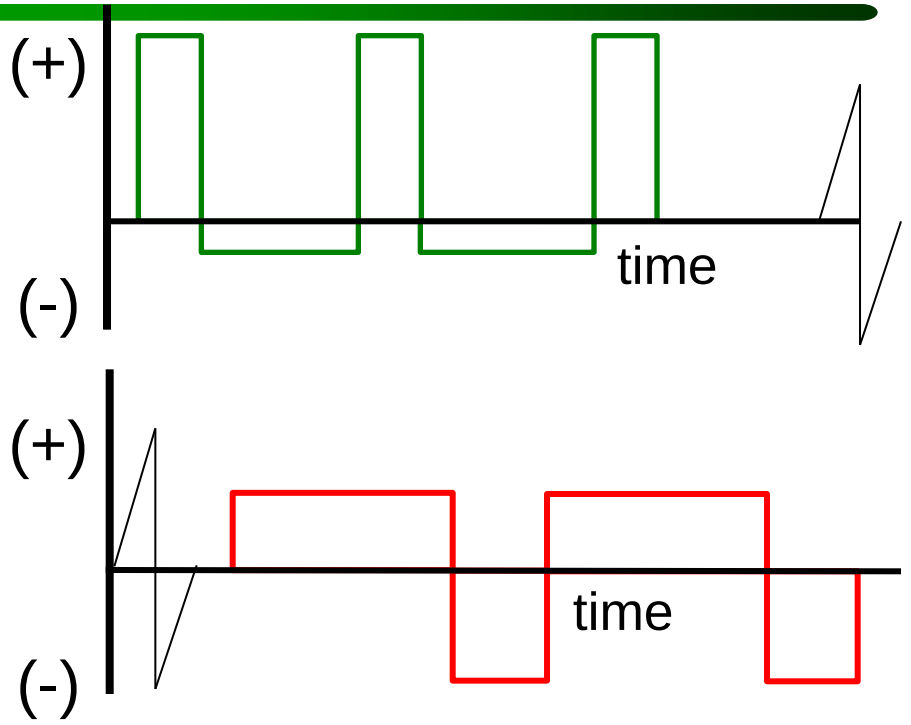
- **Challenge:** Replace two step process
  1. Abrasive Flow Media (Tool Lines)
  2. Conventional polishing (**160 sec**)
- **Replace:**
  - More robust process
  - Eliminate expensive consumables
  - Simple water based solution



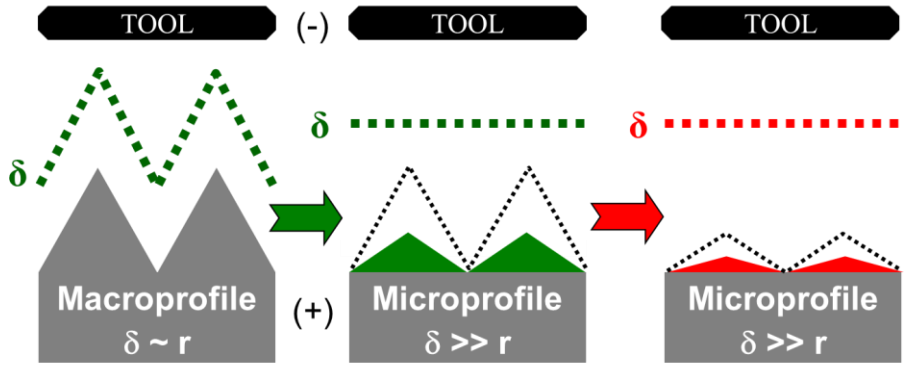
P/PR ElectroFinishing – Waveform Sequencing†

- To achieve the final surface finish required by Swagelok
  - ➔ Waveform Sequencing

- Pulse/Pulse Reverse Sequence
  - Initial R_a ~ 1µm
  - Waveform 1
    - After 30 sec R_a ~ 0.2µm
  - Waveform 2
    - After 15 sec R_a ~ 0.05µm



➔ 45 sec single-step process compared to 160 sec + Abrasive Flow Media time ➔

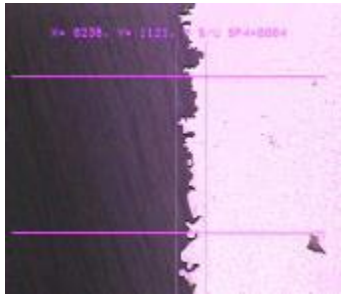


†E.J. Taylor "Sequential Electromachining and Electropolishing of Metals and the Like Using Modulated Electric Fields" US Patent No. 6,558,231; 5-6-2003.

P/PR ElectroFinishing - AM Materials

- Ti-64: Target finish Ra: ≤ 6 µm (236 µinches)

Initial Ra/Rz ~ 20 / 80 µm (787/ 3200 µinches);



5 w/w% H_2SO_4
+ 150 g/L Na_2SO_4
+ PRC

Final Ra/Rz ~ 4 / 18 µm (157/ 700 µinches);

- Hast-X: Target finish Ra: ≤ 2 µm (80 µinches)

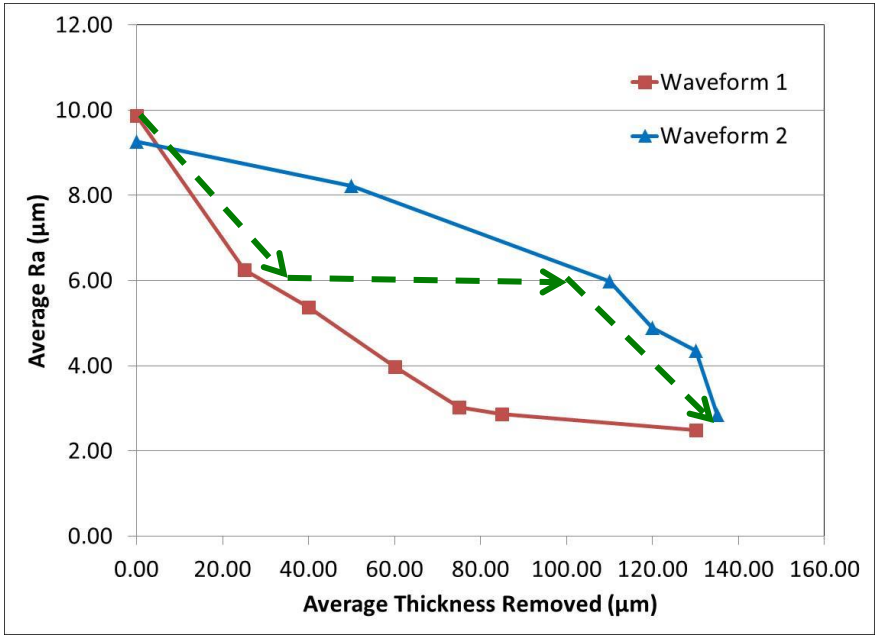
Initial Ra/Rz ~ 13 / 30 µm (500/ 1200 µinches);

150 g/L Na_2SO_4
+ PRC

Final Ra/Rz ~ 1.4 / 6 µm (55/ 236 µinches);

P/PR Waveform Sequencing – SLM HAST-X

- **CHALLENGE:** improve Ra to 2 µm while minimizing material removal
  - ***Waveform 1:***
    - Initial rapid ΔRa/Δmaterial removed until ~6 µm Ra reached
    - Decrease in ΔRa/Δmaterial removed after ~6 µm Ra reached
  - ***Waveform 2:***
    - Initially slow ΔRa/Δmaterial removed until ~6 µm Ra reached
    - Increase in ΔRa/Δmaterial removed after Ra < 6 µm

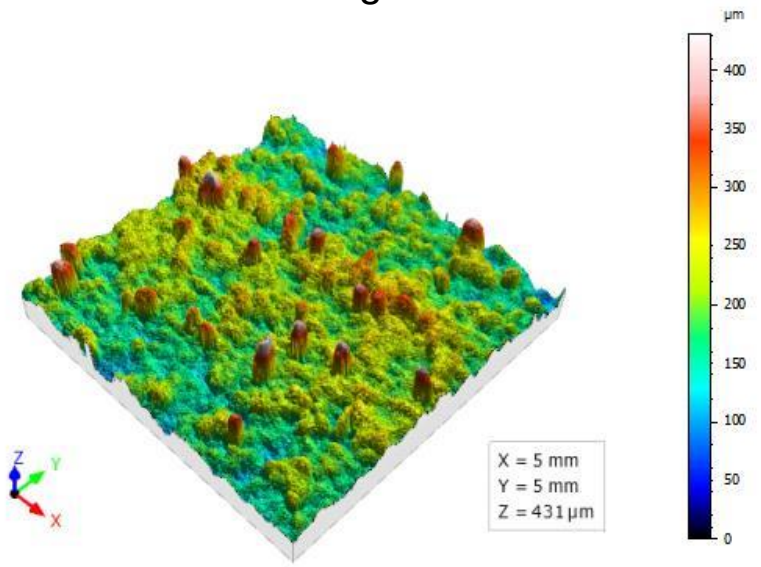


➔ Tune process by waveform sequencing in order to achieve desired surface finish while minimizing material removal ←

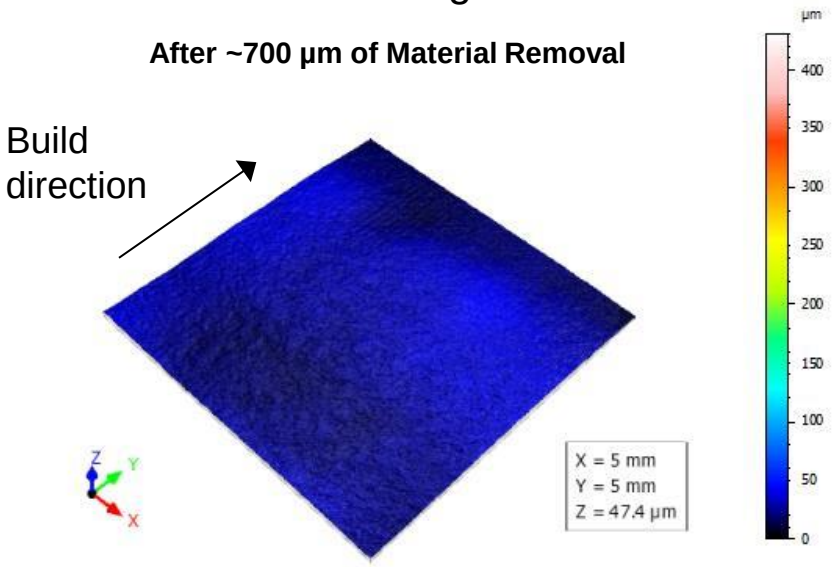
- **SOLUTION:** Initiate process with Waveform 1(4 min) until Ra ~6 µm then switch to Waveform 2(1 min) until next critical Ra ~1.8 with 80 µm removed.

P/PR ElectroFinishing Coupon Studies: Concept-HIP-IN718

Concept HIP B320_1_30 Bottom Face
Before Surface Finishing
3D Image



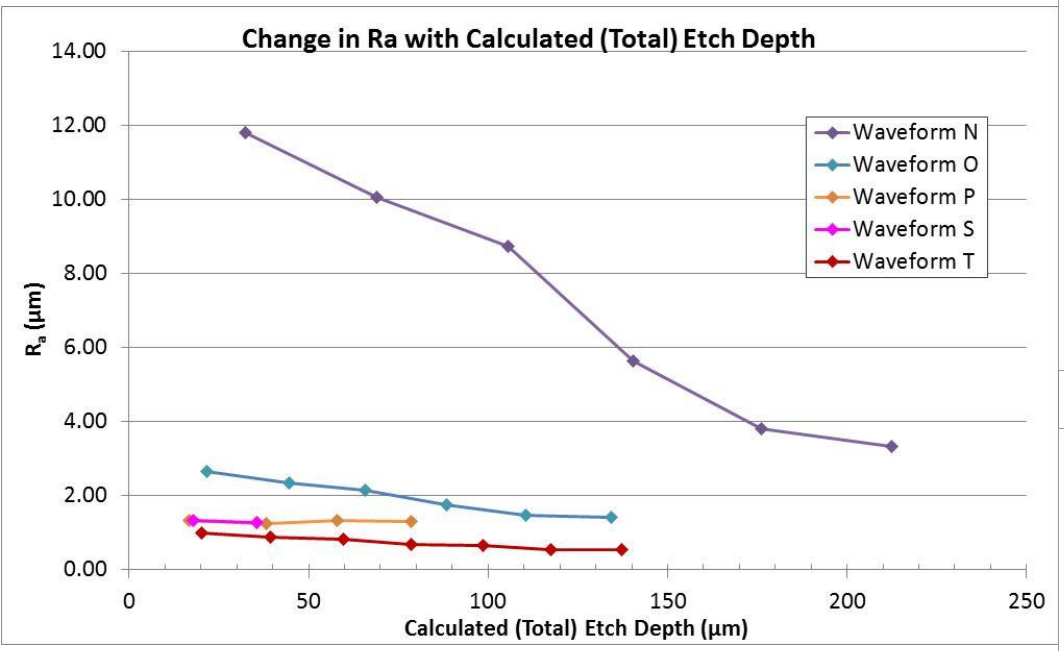
Concept HIP B320_1_30 Bottom Face
After Surface Finishing
3D Image



	R_a (µm, µin)		R_z (µm, µin)		S_a (µm, µin)	S_z (µm, µin)
	X-axis	Y-axis	X-axis	Y-axis		
B315_1_60 Initial	15.2 (598)	15.6 (614)	75.8 (2984)	74.8 (2944)	18.7 (736)	309 (12165)
B315_1_60 Final	0.71 (28)	0.78 (31)	4.6 (181)	4.9 (193)	0.94 (37)	17.3 (681)

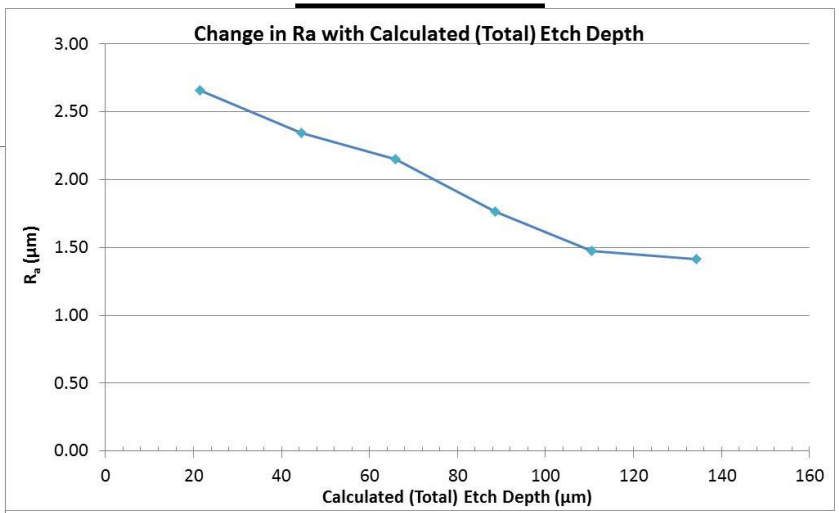
P/PR ElectroFinishing Coupon Studies: EBM-HIP-IN718

60° Build Bottom Face

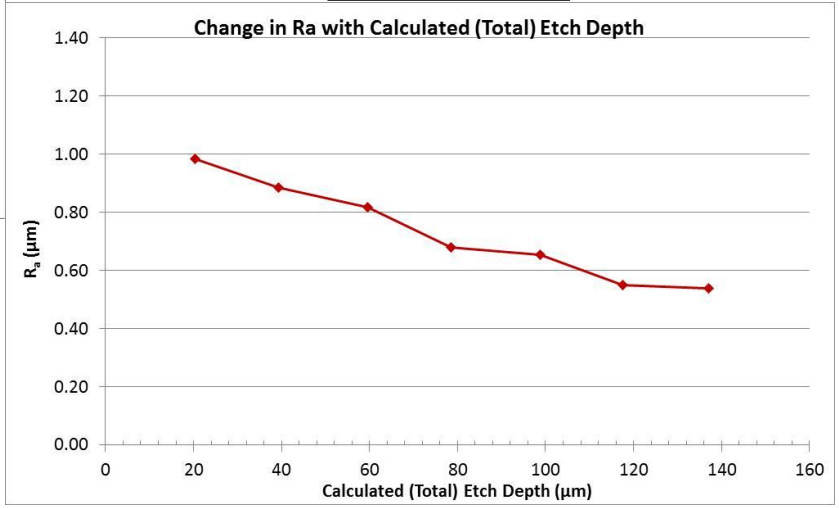


Removing 1159 µm of Material Removal

Waveform O



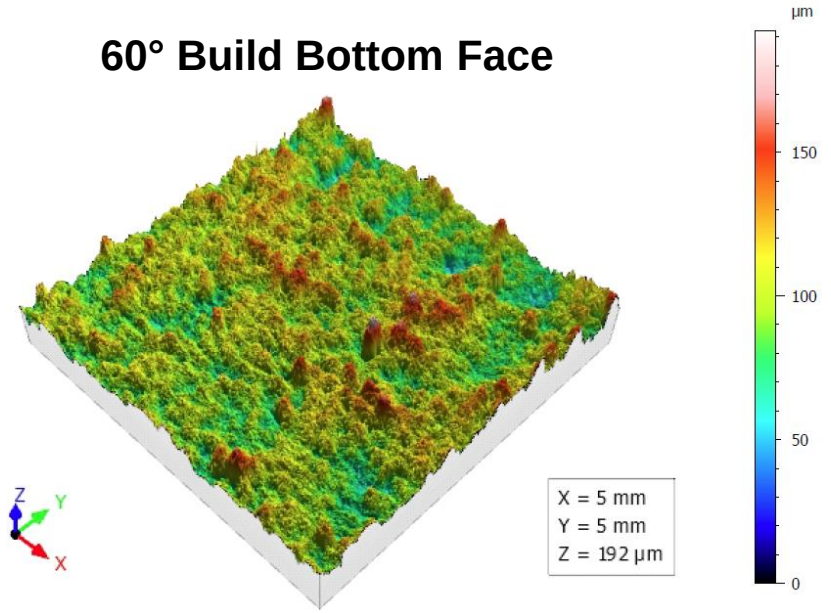
Waveform T

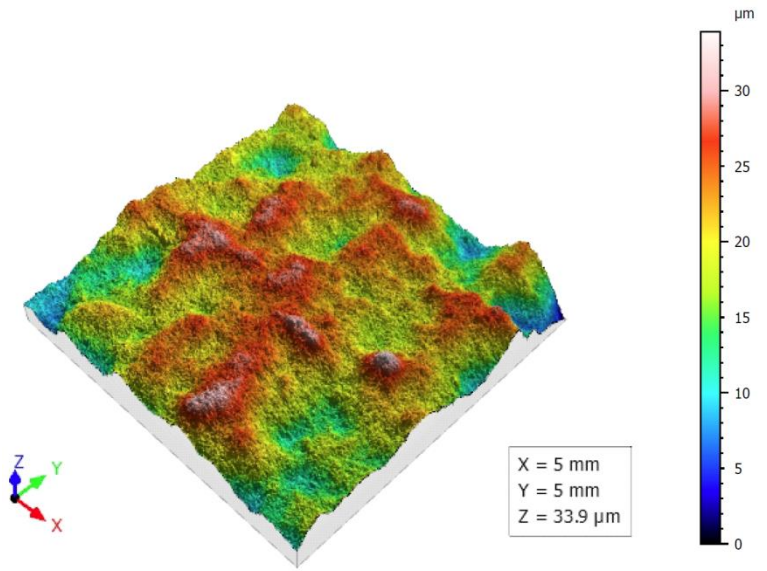


P/PR Waveform Sequencing Coupon Studies: SLM-HIP-IN718

With sequencing optimization 380 µm of material removed (Surface pore depth ~290 µm)

60° Build Bottom Face





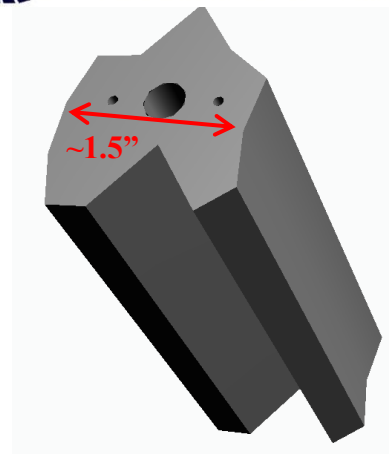
	R_a (µm, µin)		R_z (µm, µin)		S_a (µm, µin)	S_z (µm, µin)
	X-axis	Y-axis	X-axis	Y-axis		
B315_1_60 Initial	8.85 (348)	8.88 (350)	46.2 (1819)	42.8 (1685)	8.12 (320)	123 (4842)
B315_1_60 Final	0.58 (22.8)	2.98 (117)	0.68 (27)	3.9 (153)	0.97 (38.2)	14.2 (560)

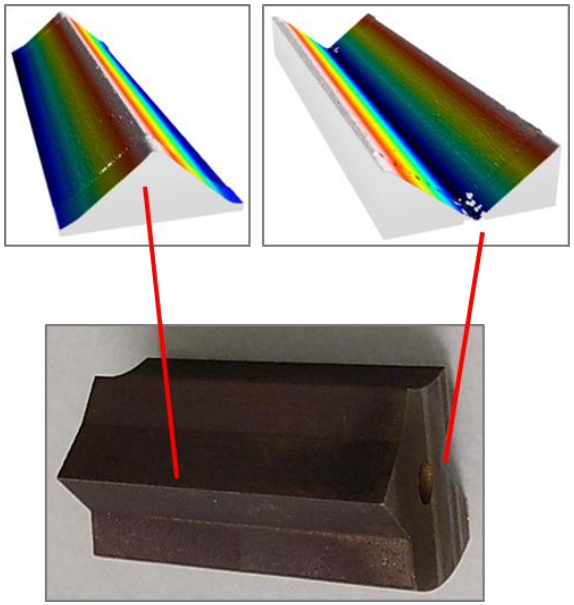
Concept Laser-IN718 ElectroFinishing – Scale-up to Complex Component Finish

- Prototype part should address many of the challenges of building and finishing parts like:
  - ~2” long (tall)
  - Making sharp corners (75°)
  - Finishing deep notches (75°)
  - Processing concave/convex profiles
    - Radii: 1 ¼”

Simple Tool

CalRAM
A Division of Precision Holdings





GOAL: Gain the necessary knowledge to understand the limitation of various build and finishing processes on specific shapes in order to initiate the design of a Manufacturing Decision Tree Model (MDTM) that can accelerate decision time and reduce cost and error.

scikit learn

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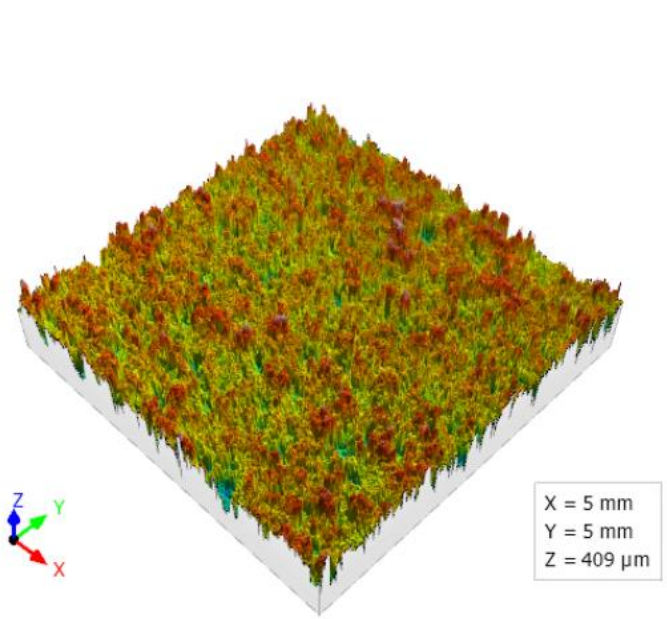
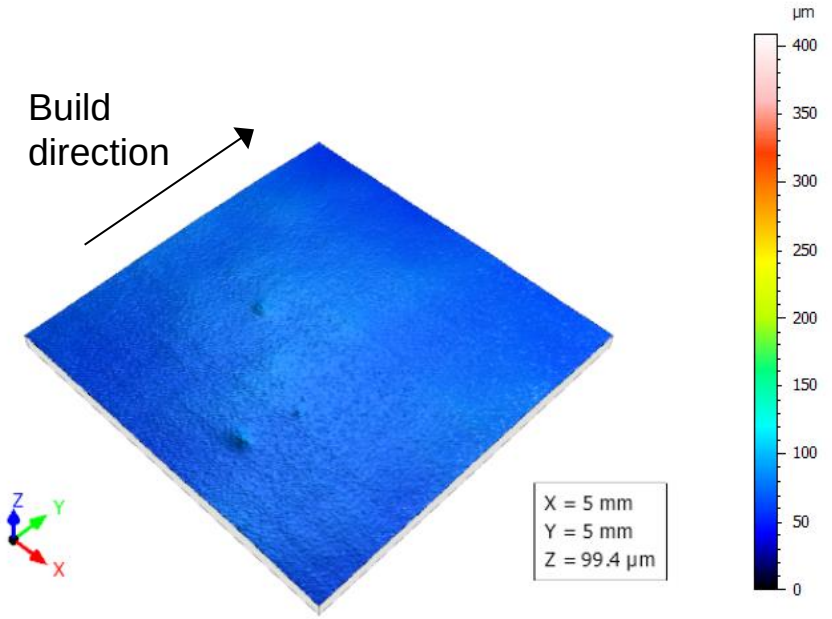
P/PR ElectroFinishing Coupon Studies: EBM-HIP-Ti64 (9-90)

90° Build: Tool Area 1 x 1 cm; Part Area 2 x 2 cm





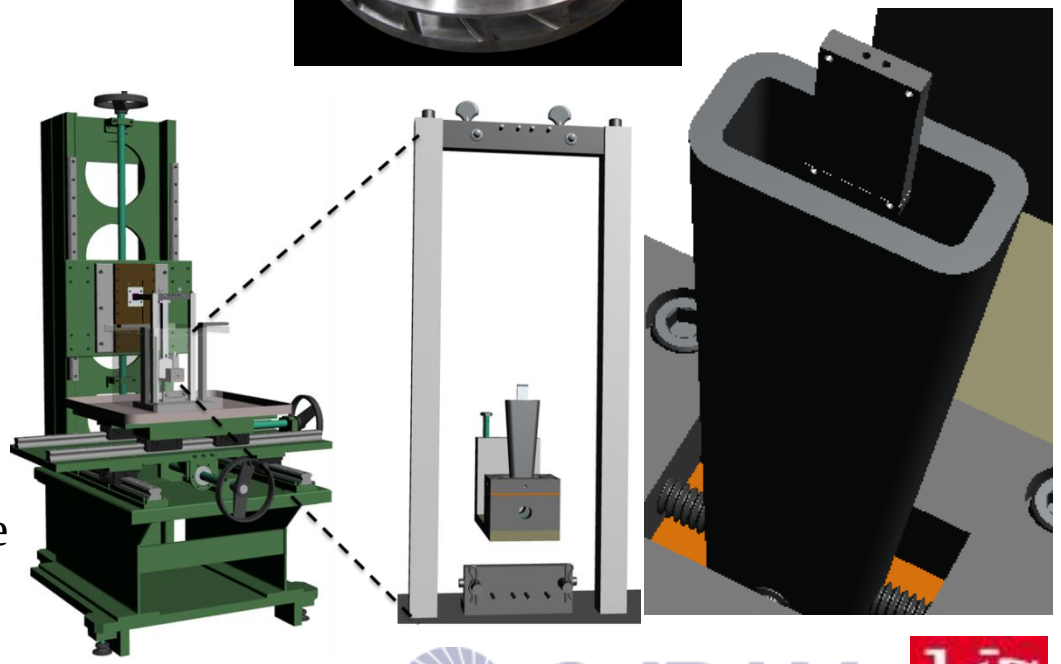
Average/Max Material Removal = 280 µm

	Ra (µm, µin)		Rz (µm, µin)		Sa (µm, µin)	Sz (µm, µin)
	X-axis	Y-axis	X-axis	Y-axis		
9-90 Initial	30.0 (1181)	35.4 (1394)	157 (6,181)	170 (6,693)	33.6 (1,323)	338 (13,307)
9-90 Finished	0.52 (20.5)	0.46 (18.1)	2.9 (114)	3.4 (134)	0.51 (20.1)	75 (2,953)

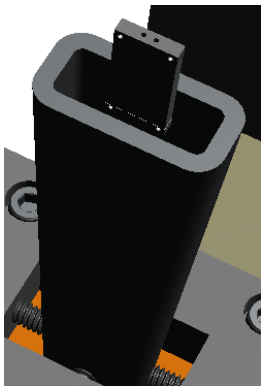
EBM-Ti64 ElectroFinishing Tooling – Step 1 Tooling Optimization

- Goal: Is to understand waveform conditions effect on the uniformity of the etch around a external part circumference
- Factors:
  - Tool Area: 9 x 19 x 2 mm
  - Electrolyte 30 w/w% H_2SO_4 + 150 g/L Na_2SO_4
  - Flow Rate 1 GPM; Max Temp 70°F
  - Tool Stationary ¼” from top of kazoo on large gap side
- All Kazoos built in standing direction (symmetric roughness throughout kazoo internal)
- Top and bottom of tool masked where electrical connection made

Target Shrouded Impeller Component



EBM-Ti64 ElectroFinishing Tooling – Etch Profile Analysis



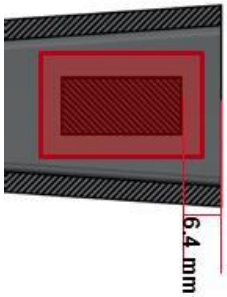
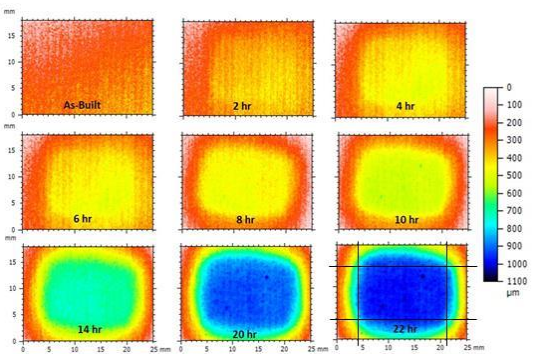


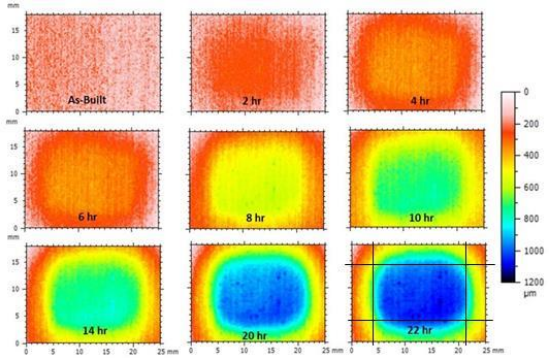
Image Area:
18 mm x 25 mm

Tool Area:
9 mm x 19 mm

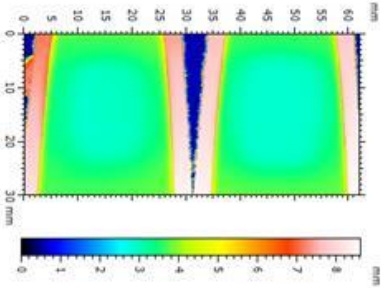
TOP



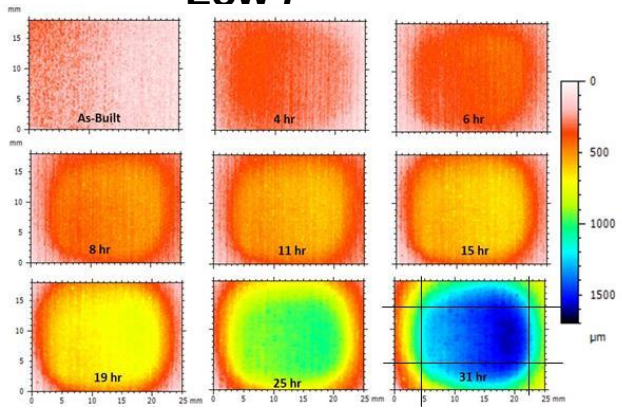
BOTTOM



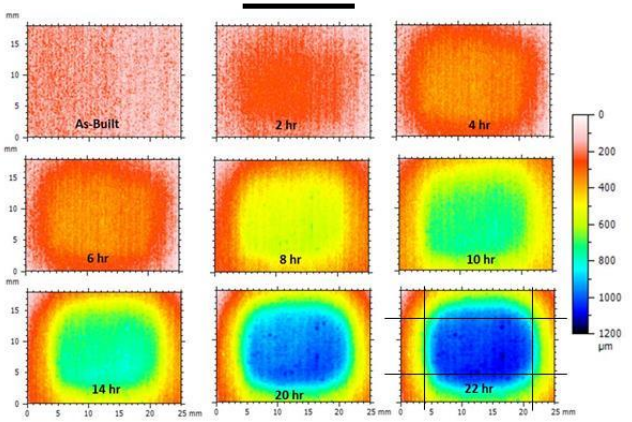
Nanovea Analysis Area



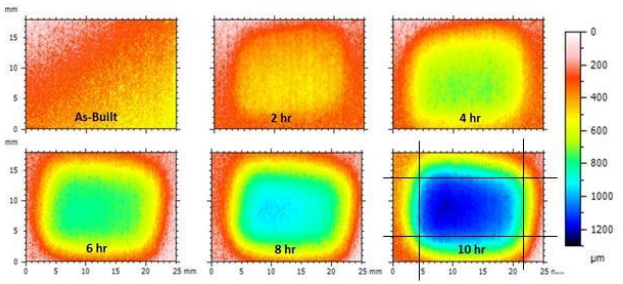
Low *f*



Mid *f*

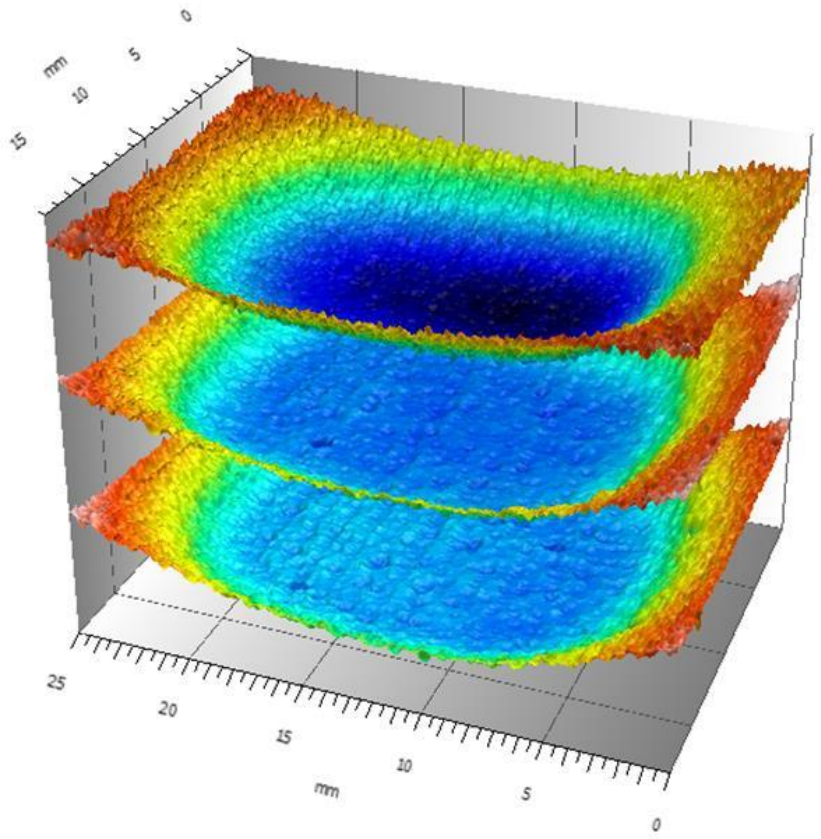


High *f*



EBM-Ti64 ElectroFinishing Tooling – Etch Profile Process Comparison

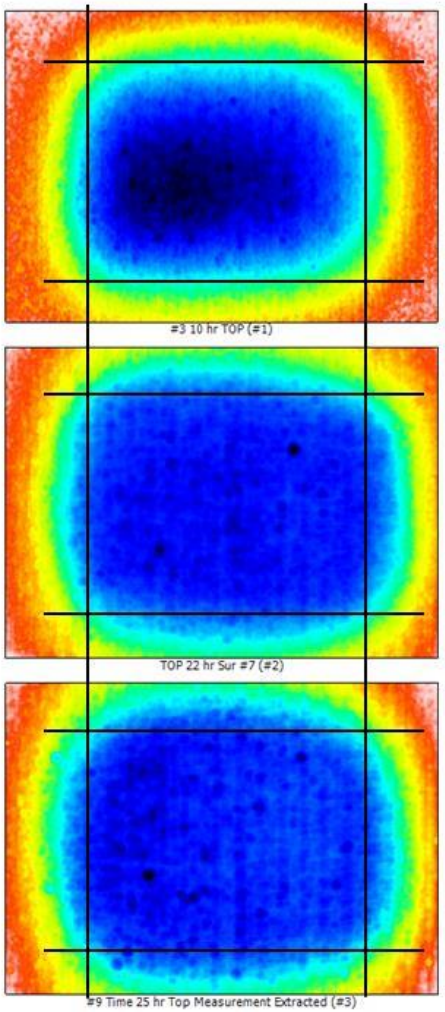
- Higher the frequency higher the lower the throw



HIGH *f*
754 µm
75.4 µm/hr

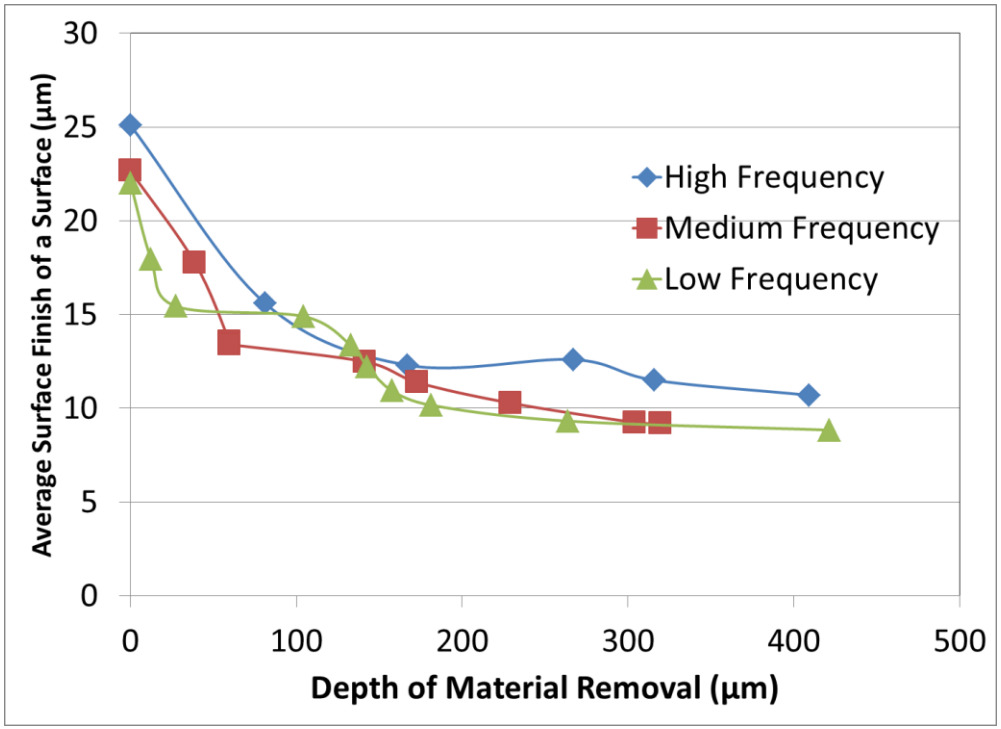
MID *f*
672 µm
30.5 µm/hr

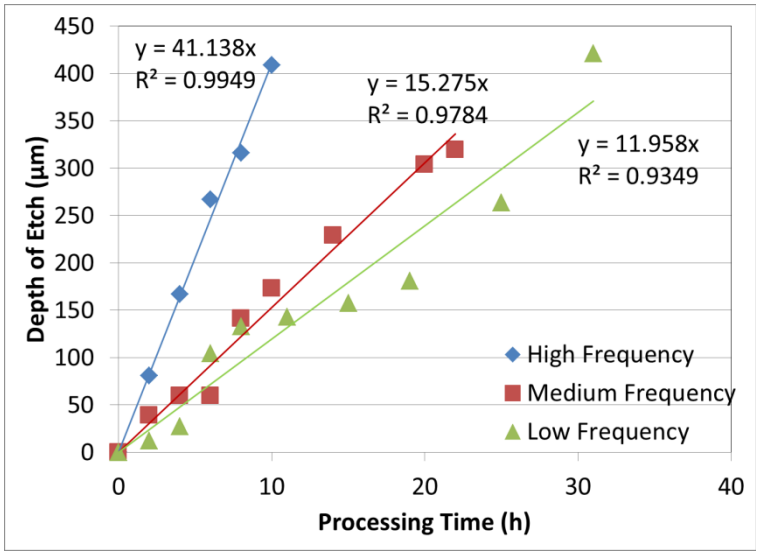
LOW *f*
798 µm
25.7 µm/hr

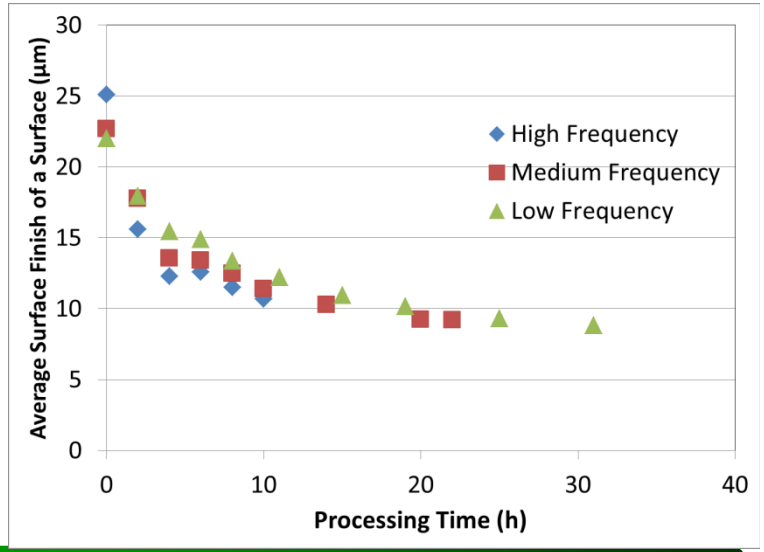


EBM-Ti64 ElectroFinishing Tooling – Kazoo Polishing Analysis

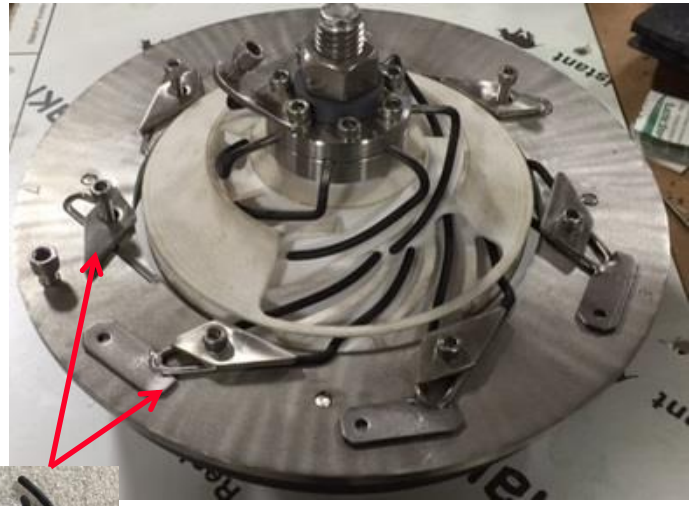
- Higher the frequency higher the etch rate
- With given overpotential same finish achievable
- Rate of finish achieved is a function of frequency

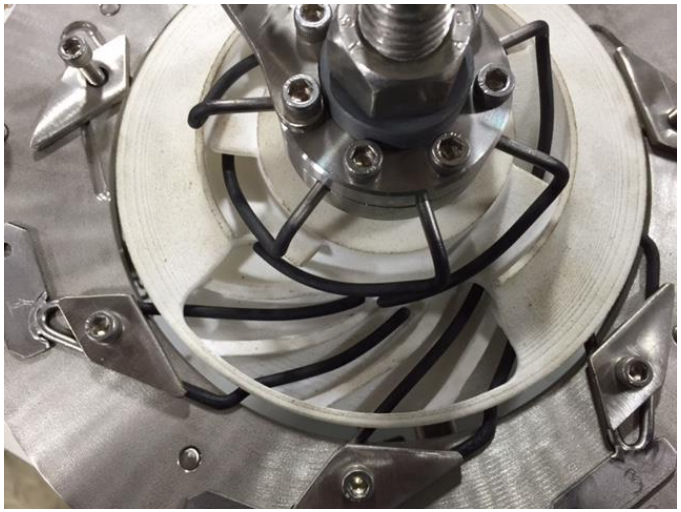






EBM-Ti64 ElectroFinishing Tooling – Step 2 Shrouded Impeller Tooling





Summary

- Demonstrated potential to use P/PR ElectroFinishing techniques to finish various Conventionally Manufactured and Additively Manufactured materials in water based HF-free electrolytes
  - Ti64, Hast-X, IN 718, etc…
- Demonstrated potential to selectively remove dissimilar materials from surface feature
- Demonstrated the potential of electrically controlled electrochemical processes and sequencing to produce the desired finish while limiting material removal
- **Applications:**
  - Medical, Automotive, Aerospace, Energy Markets, Even Superconducting Nb structures

Acknowledgements

THANK YOU FOR YOUR ATTENTION!
QUESTIONS?

Financial support: USAF RIF, USAF, Client Confidential

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