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Post Processing-Finishing

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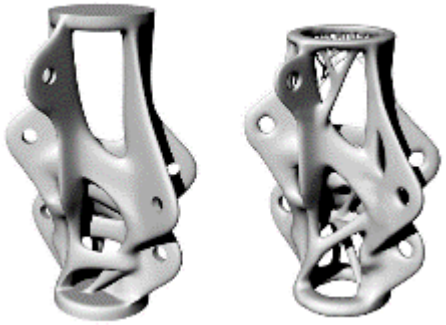
Benefits of AM as a Near Net Shape Process

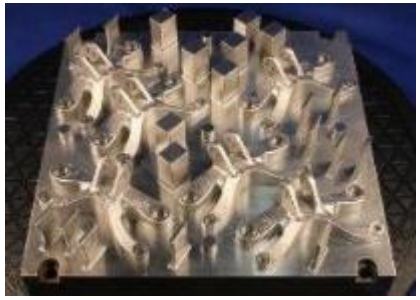


Topologically Optimized Parts

Rocket Thrust Chamber Printed from Functionally Graded Metal

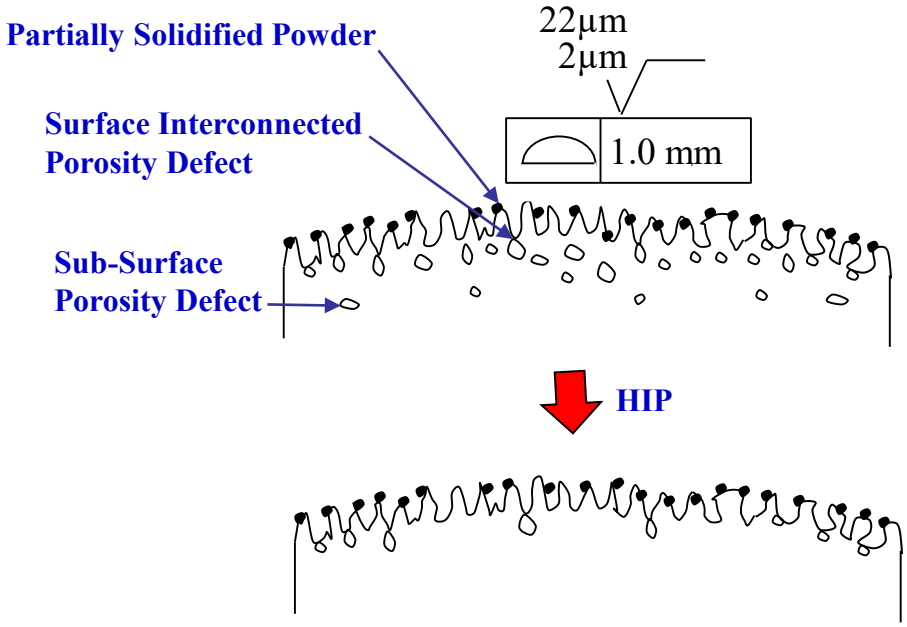
- Time Compression
- Complex Geometry
- Functionally Graded Material

Printed Metal Parts



Laser Powder Bed Fusion Build

L-PBF Part with Supports after Separation from the Build Plate



- Characteristics
  - Excess metal: supports
  - Geometric errors comparable to investment castings
  - Non-uniform surface texture comparable to sand castings
  - Higher concentration of near-surface porosity defects
  - Lower concentration of bulk volume porosity defects
  - Requires HIP to remove bulk porosity defects
  - Require subtractive processing to finish

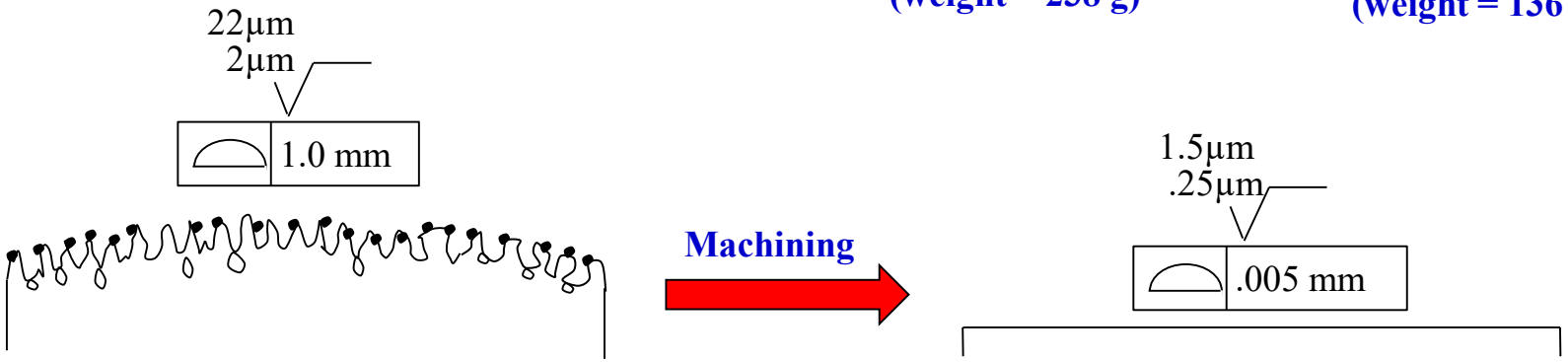
Required: Hard Tool Machining

Machining

Grinding

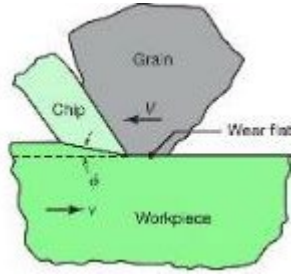
Bracket with Supports
(weight = 238 g)

Completed Bracket
(weight = 136 g)

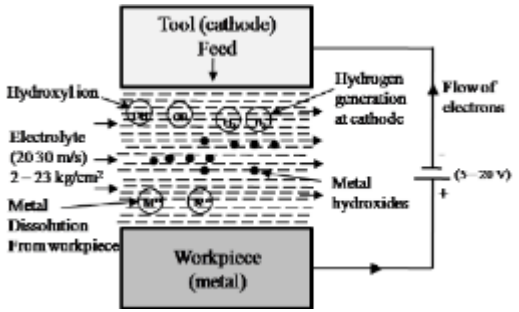


- Needed to remove supports and create surfaces with refined geometry and texture while also removing sub-surface defects
- Main Processes: Machining and Grinding
- Requires dedicated fixturing

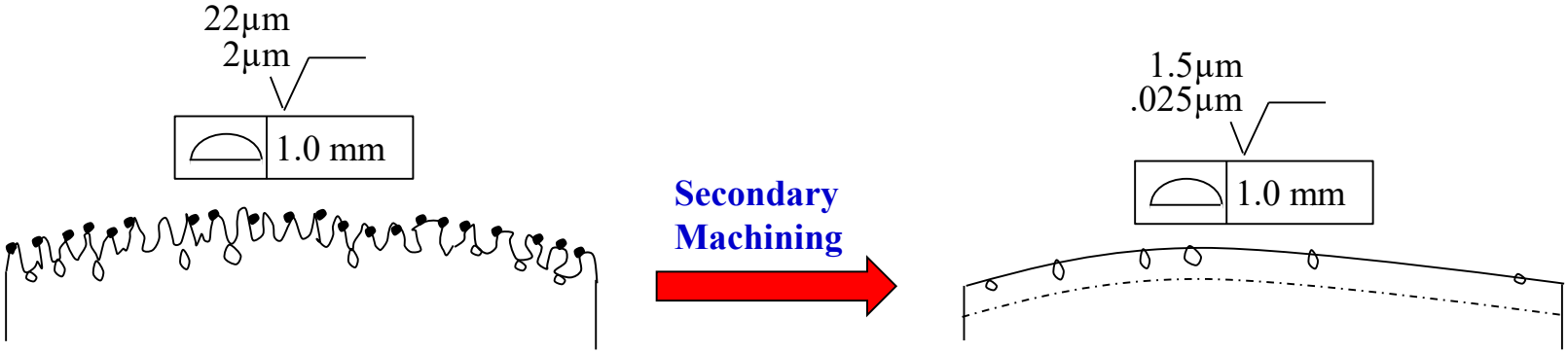
Optional: Secondary Machining



Abrasive Machining (Kalpakjian)



Electro-Chemical Machining



- Used to create refined surfaces with controlled texture
- Additional processing can eliminate sub-surface defects
- Main processes: Abrasive and Electro-Chemical Machining

Abrasive Machining

Rigid Abrasive Carrier

Multi-Vibe Finishing

Visco-Elastic Fluid-Abrasive Carrier

Typical part geometry successfully machined

Centrifugal Disk Finishing

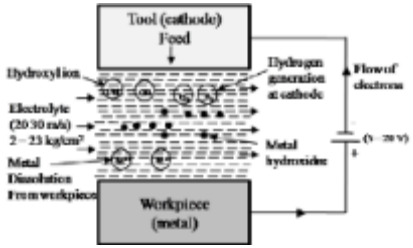
Typical part geometry successfully machined

Abrasive Flow Machining

Typical part geometry successfully machined

- Abrasive grit carrier is either rigid or visco-elastic fluid
- MRR and surface texture are influenced by pressure, flow rate, and grit size, rigid carrier shape and size, and viscosity (AFM)
- Maybe assisted with ultra-sonics or weak acids
- Most processes require dedicated fixturing/tooling

Electro-Chemical Machining



Anodic dissolution of workpiece surface asperities

Cathode surrounding printed nozzle

ECM Machine

Typical part geometry successfully machined

- Energy supplied by electric field between tool (cathode) and part (anode)
- Metal from the anode (part) is removed via anodic dissolution
- MRR and surface texture are influenced by electrolyte, surface current density, and electrolyte flow rate
- Dedicated cathodes are required

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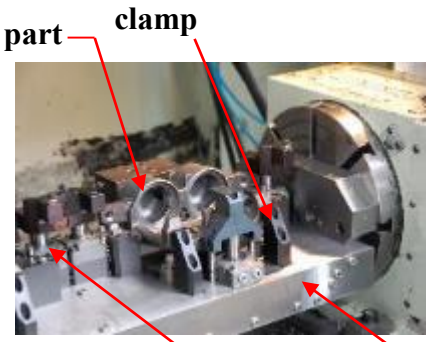
Technical Challenges to Finishing AM Parts

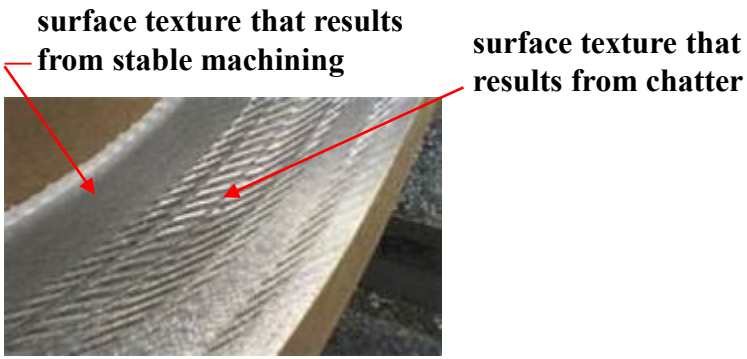
- Hard Tool Machining
- Secondary Machining

Challenges to Hard Tool Machining T.O. Parts

Topology optimized Motor Bracket for Lunar Lion Satellite Module



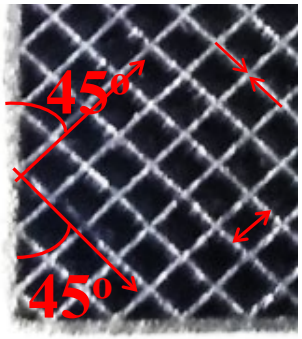
Conventional Machining Fixture with Hard Contact Locators and Mechanical Clamps



Machined Surface Destroyed by Unstable Machining Vibration (Chatter)

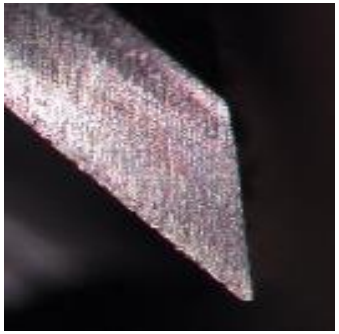
- Topology optimized parts are difficult to hold with conventional fixtures and successfully machine
  - Light-weighted shapes are geometrically complex and compliant
  - Difficult to clamp, stiffen, and machine without distortion or chatter
  - Easy to fail and expensive to scrap or rework

Challenges to Hard Tool Machining Printed Supports

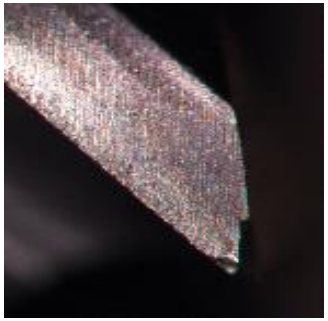


Support Lattice


End Milling Support Lattice

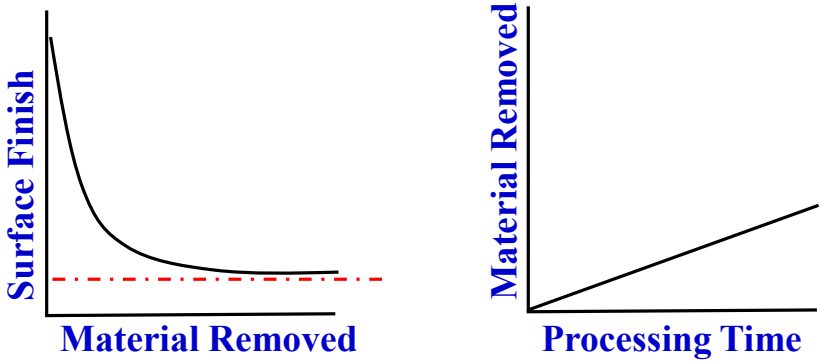

New Cutting Edge


Edge after milling fully dense metal for 5.67 min


Edge after milling block support for 1 min

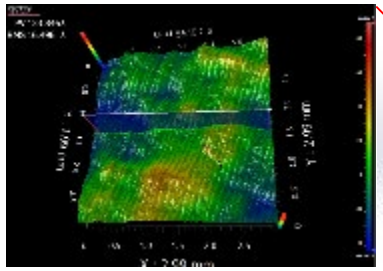
- Milling printed metal: Nothing special!
- Milling printed metal supports: Interesting!
  - Specific cutting energy is less than 10% of that of solid metal
  - Tool wear is greatly accelerated
  - Reasons why are not fully understood

Challenges to Secondary Machining Processes

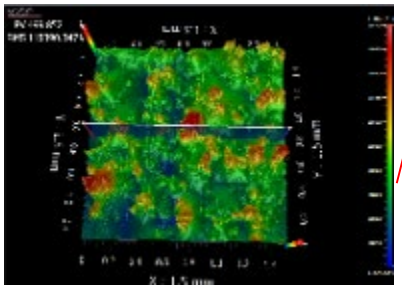


- In practice, it is difficult to maintain uniform process conditions across all part surfaces leading to uneven wear and surface texture
- Even more difficult to predict
- Current process development practice is to build, test, measure, and repeat until a feasible solution is derived

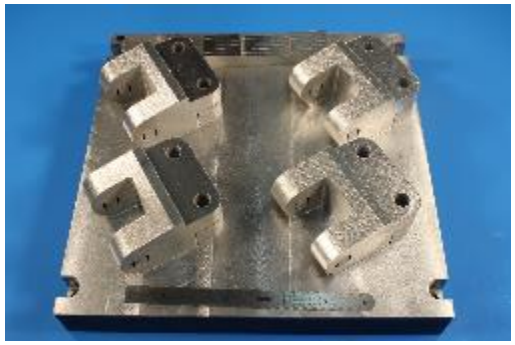
Challenges to Secondary Machining AM Parts



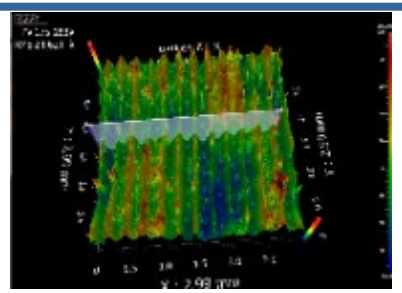
R_a = 1.9 µm



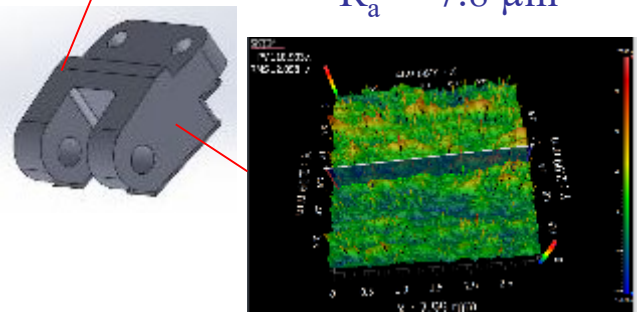
R_a = 22.8 µm



Inconel 718 L-PBF Bracket



R_a = 7.8 µm



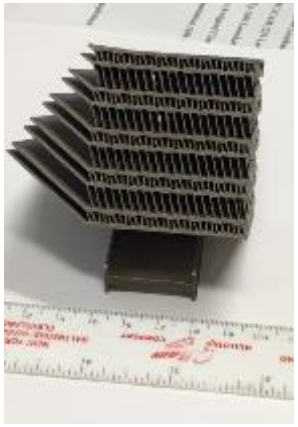
R_a = 3.7 µm

- Nonuniform AM surface texture complicates process planning
- Functionally graded materials exacerbate the problem further

Challenges to Secondary Machining AM Parts

Open Geometry: Easy

Printed Lattice: Hard



Printed Cross Flow
Heat Exchanger: Hard

- Machining open geometry is easy

- Machining small nooks, crevices, and discontinuities is not
  - complex lattices
  - small blind cavities and recesses
  - serpentine interior passageways of varying cross section
  - intersecting interior passageways

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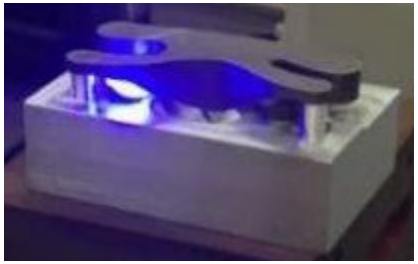
Needed Future Research

- Hard Tool Machining
- Secondary Machining

Future Research: Hard Tool Machining AM Parts



Bracket Bonded to PAAW Fixture for 2nd Op

2nd Op Machining Completed

Hybrid PAAW for AM Application (Renishaw)

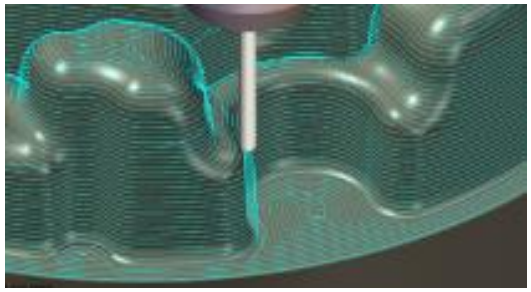
Bracket Support Bonded to PAAW Fixture for 1st Op

1st Op Machining

- Topology Optimized Parts
  - Develop advanced workholding technologies such as PAAW to:
    - maximize access and holding stiffness
    - minimize holding distortion
    - accommodate stress relaxation distortion and maintain free state geometry

  - Printed supports as work holding agents and stiffeners
  - New topology optimization algorithms to accommodate “design for machining logic”
  - New tool path planners to account for machining dynamics

Future Research: Hard Tool Machining-AM



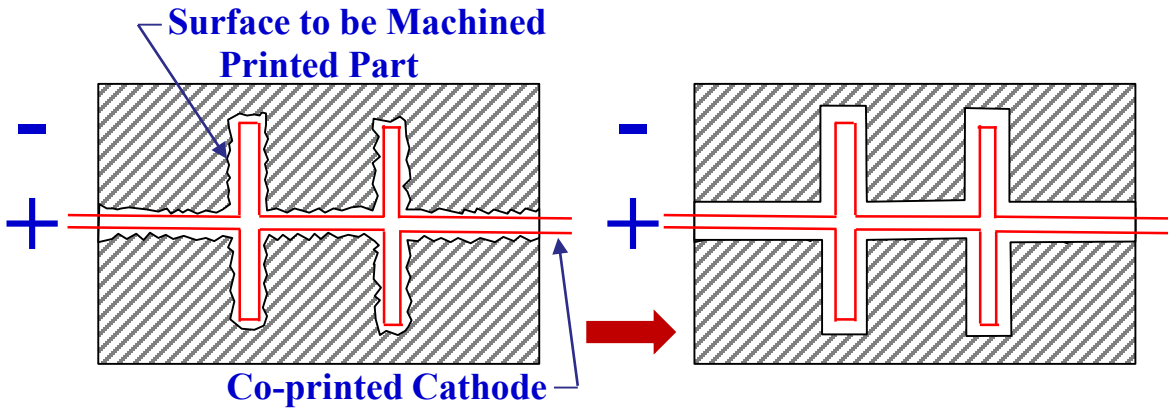
MasterCAM

Prototype PAAW Fixtures Printed from Carbon Fiber Reinforced Nylon

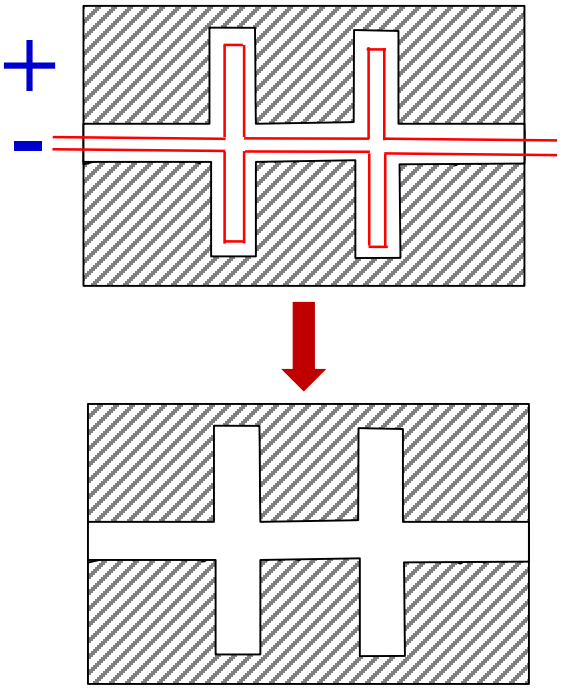
DMG Mori Lastertec 65

- Time Compression
  - Computer Aided Process Planning
  - Automated Fixture Design and 3D Printing
- Hybrid AM-Machining
  - Technology development including environment control
  - Computer Aided Process Planning

Future Research: Secondary Machining AM Parts



Forward Bias: Machine the Part



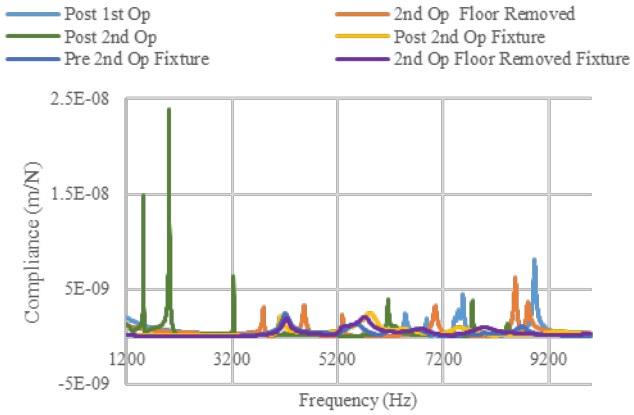
Reverse Bias: Machine the Cathode

- Basic Science
- CAM/CAE Tools
- New Processes
- Time Compression
- Co-Printing/Co-Machining

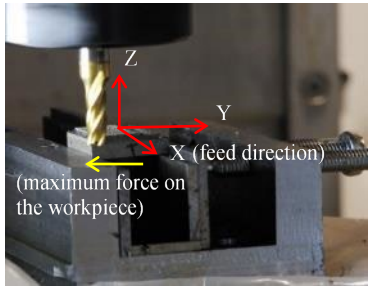
Penn State Initiatives in AM Part Finishing

Hard Tool Machining

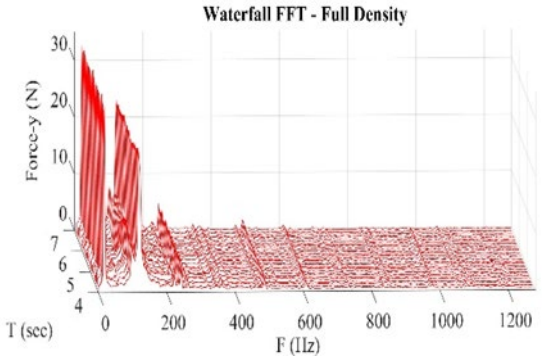
Five Axis Machining of GE Aviation Bracket using Modular PAAW Fixture



Dynamic Response of GE Aviation Bracket with and without Supports or PAAW Fixture



End Milling of Block Supports



Water Fall Plot of Milling Force Spectrum

Secondary Machining

ExtrudeHone 150 Abrasive Flow Machine

ExtrudeHone CoolPulse 1000 ECM Machine

Walther Trowal MV-21 Multi-vibe Vibratory Bowl Machine

Walther Trowal TT-45 Centrifugal Disk Finishing Machine