2013 MPI Workshop

Numerical Modeling of Abrasive Fluid Jet (AFJ) Machining

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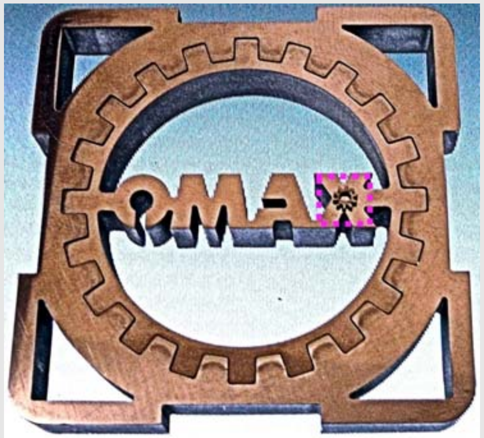
Outline of Presentation

- Introduction
- Objectives
- Brief History
- Fundamental
- Challenges
- Remedies/Novel Developments
- Samples
- Future Work

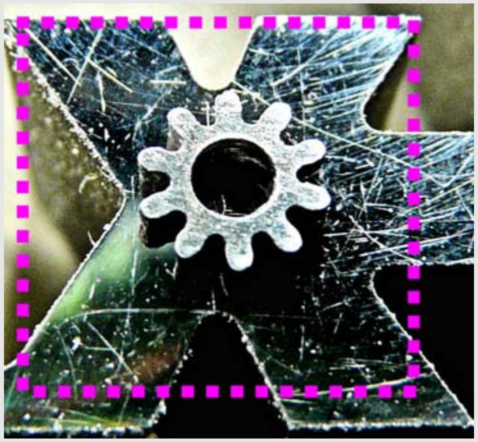
Introduction

- **Abrasive fluidjet (AFJ) technology is unique for its versatility that cannot be matched by most tools**
  - **Material and size independent - machining most materials from macro to micro scale (i.e., the 5M advantage)**
  - **A cold cutting tool that preserves material properties (structural, chemical, and thermal integrities)**

10-cm thick wind turbine gear



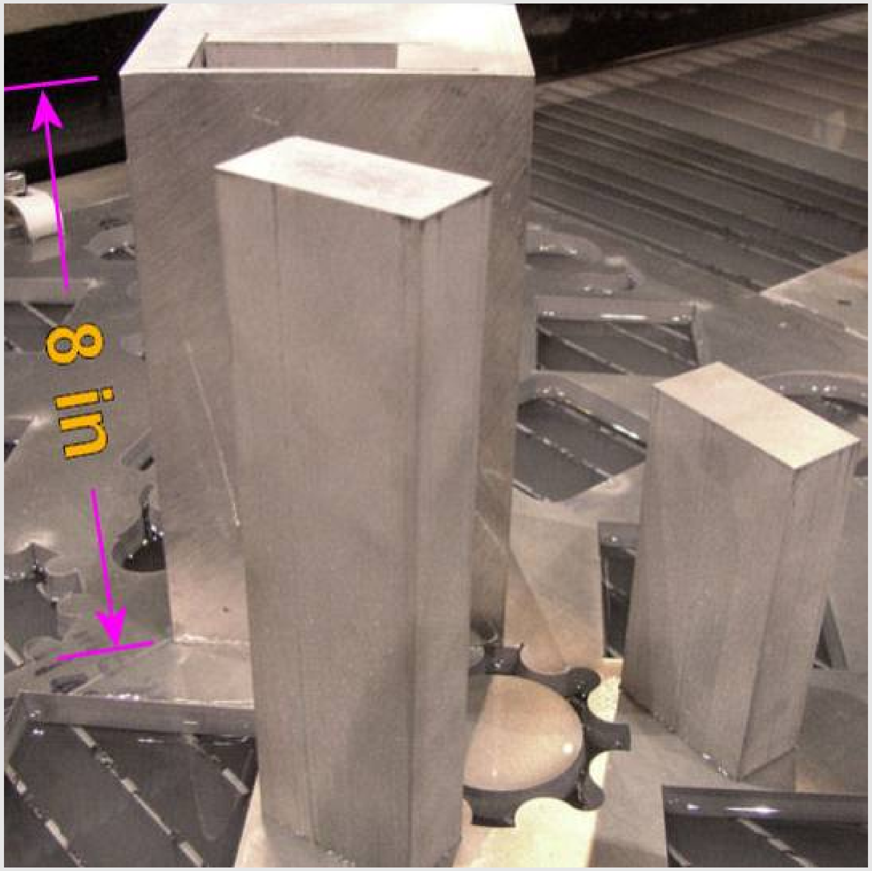
10 cm x 10 cm gear set



3.6 mm OD micro gears

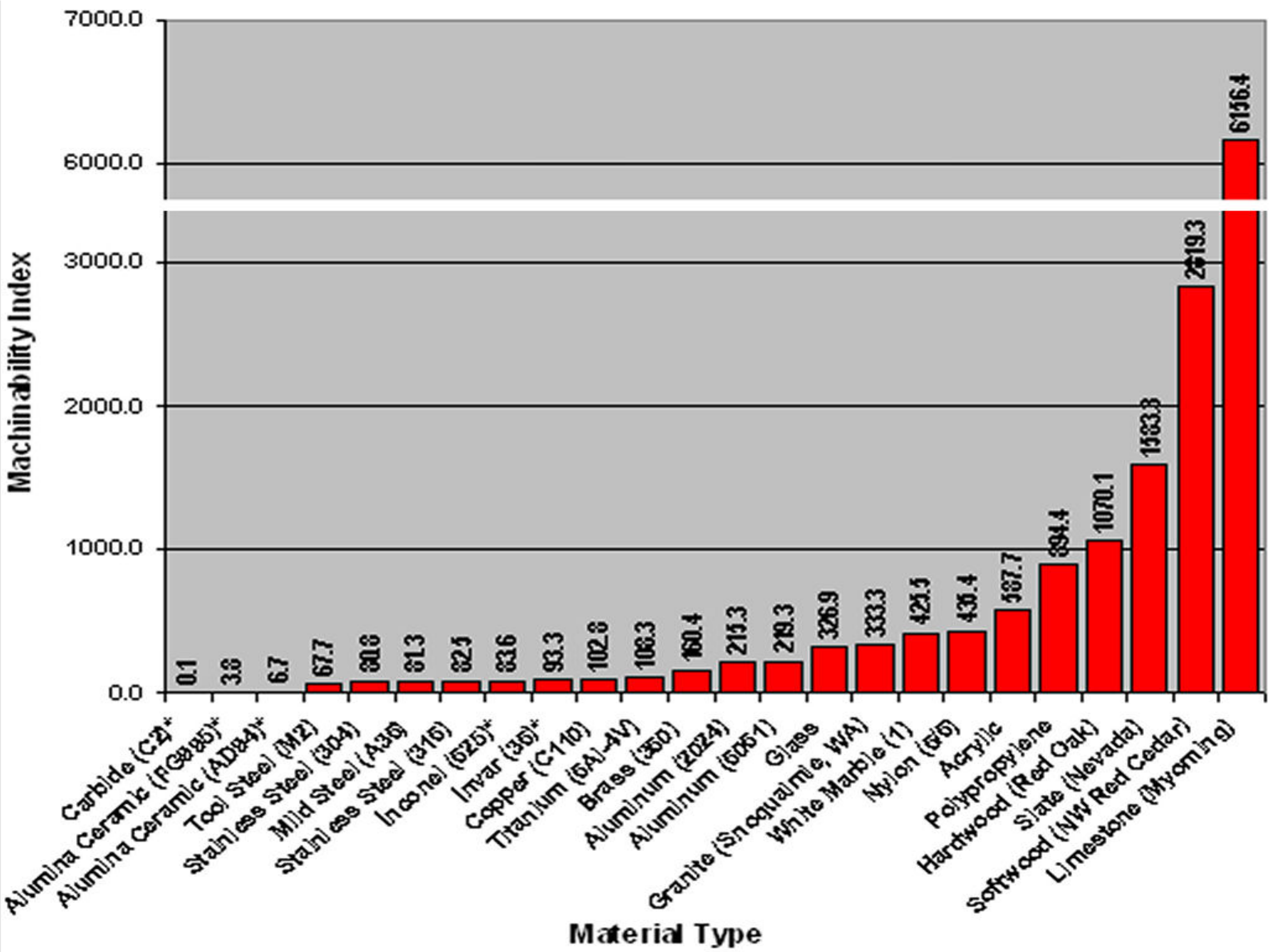
Introduction (cont'd)

From Macro to Micro



Introduction (cont'd)

Machinability



Introduction (cont'd)

- Other Advantages
  - Cut hardened steel nearly as fast as annealed steel and cut titanium 34% faster than stainless steel
  - A single tool with interchangeable nozzles for multimode machining – cutting, turning, drilling, milling, slotting, ….
  - Low force on workpiece - requires only simple fixturing
  - PC-based CAD/CAM for 2D/3D machining –user friendly without steep learning curves
  - Cost effective and fast turnaround for small and large lots
  - Environmental friendly
    - Dustless and quiet (when cutting submerged)
    - Wastes are acceptable for landfill

Introduction (cont'd)

- Significant progress was made since commercialized in the mid 1980s'
  - Elevated from a rough cutting tool to a precision tool - in equal footing with laser, EDM, chem etching, and others
  - Most advancements were through physical experiments
  - Very limited numerical modeling has been conducted
- AFJ is a complex flow phenomenon
  - Ultrahigh pressure, multi-fluid, multi-phase (phase changing), and multi-scale flows at supersonic speeds
  - It involves fluid-fluid, fluid-solid, and solid-solid interaction in rapid changing spatial environment
  - It consists of segments of free and confined jets

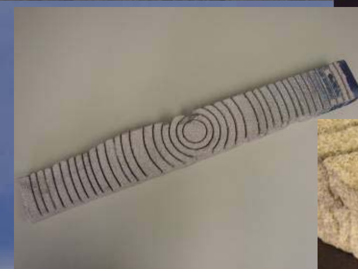
Introduction (cont'd)

- Recent advent in numerical modeling would facilitate simulation of AFJ processes realistically
  - Results would help understand the physics of AFJ and the associated components/processes
  - Such understanding would accelerate the advancement of precision AWJ machining/ micromachining

Objectives

- Present the emerging AFJ machining process as a challenging industrial problem
  - Kinematics and dynamics of AFJ
    - Gravity and capillary dominated flows for different working fluids
    - Optimum nozzle geometries for different forms of AFJ
  - AFJ machining process
  - Feeding of fine abrasives
  - AFJ wear on nozzle components
- Invite participants to take on the challenge

History of Waterjet Technology



- **1970's – High Pressure waterjet cutting was introduced commercially at Flow Industries, Inc.**
- **1980's – Abrasive jet cutting was introduced commercially**
  - **Flow International was spun off from Flow Industries**
- **1990's – Advanced PC-based controllers (OMAX was established)**
  - **Ease of use (OMAX patent on "Compute first, move later")**

History of Waterjet Technology

- 1990's (cont'd)
  - **Improved precision**
  - **Process automation**
  - **Faster cutting**
- 2000's – Performance improvement
  - **Reliability and 2+D capability**
  - **Material independent machining**
- 2010's - Performance improvement
  - **Micromachining**
  - **Multi-mode machining**
  - **Mobile machining**

Then and Now

Tool of Last Resort vs. Tool of Choice

1980s’

Today

Fundamentals

- High-pressure fluid jet - force pressurized working fluid up to 600 MPa through an orifice
- Pumps: intensifier or direct-drive pumps
- Forms of AFJ
  - Abrasive-waterjet (AWJ) –abrasives entrained via the jet pump (Venturi) effect are accelerated by the waterjet through a mixing tube
  - Abrasive Cryogenic Jet (ACJ)/Flash AWJ (FAWJ)§ – Liquefied N_2/Super-heated water as working fluid
  - Abrasive Slurry Jet (ASJ) –pump slurry directly through the orifice

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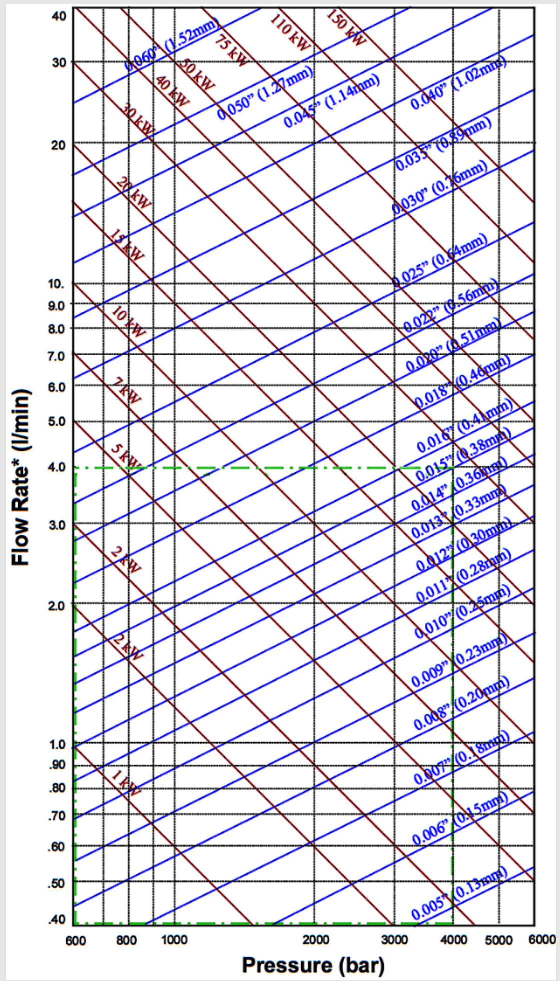
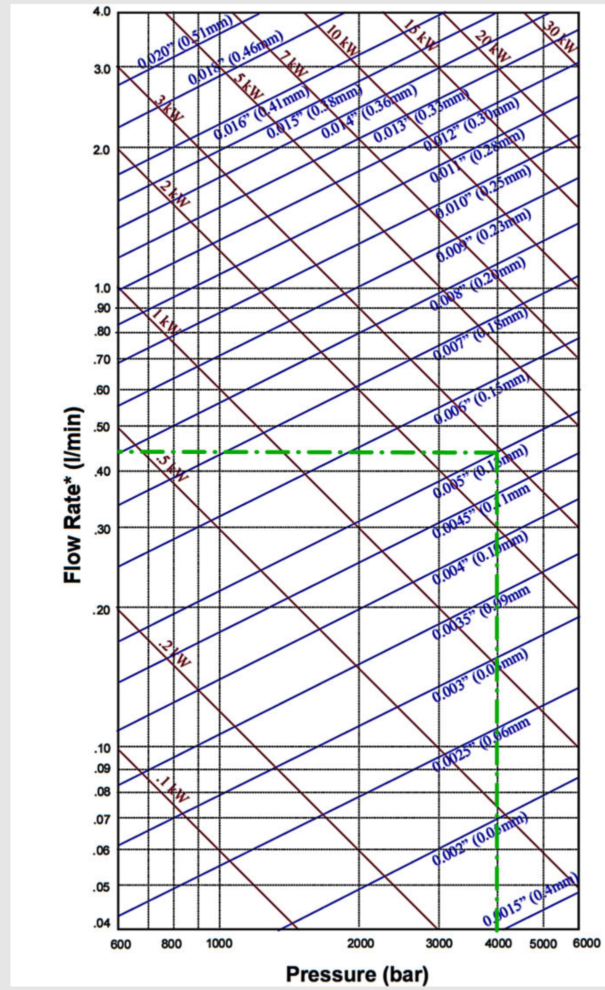
§**US Patent** No. 7,815,490

Fundamentals – Normalgrams

Parameters:

1. Pressure
2. Flow rate
3. Power
4. Orifice ID





Nozzles

FJ/AFJ Nozzles

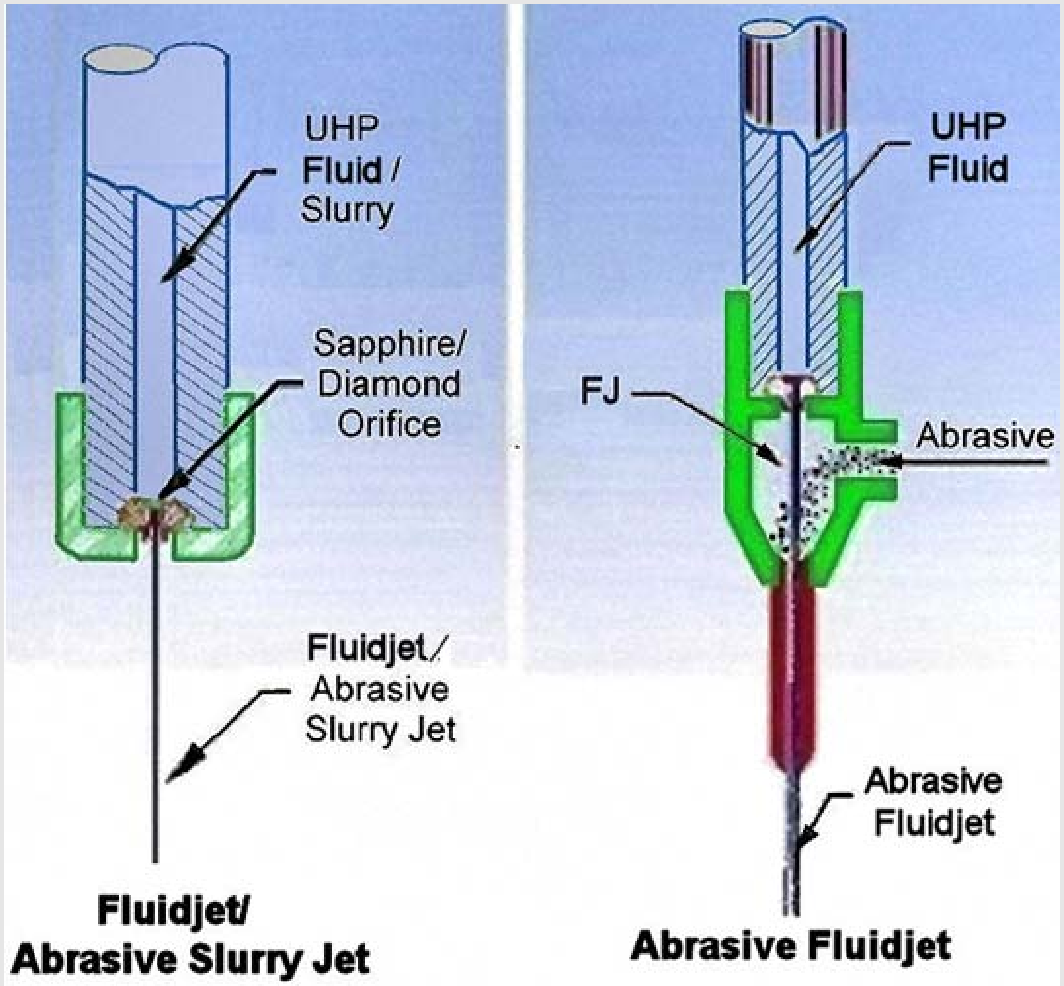
Working Fluids:

Water (w/wo additive)

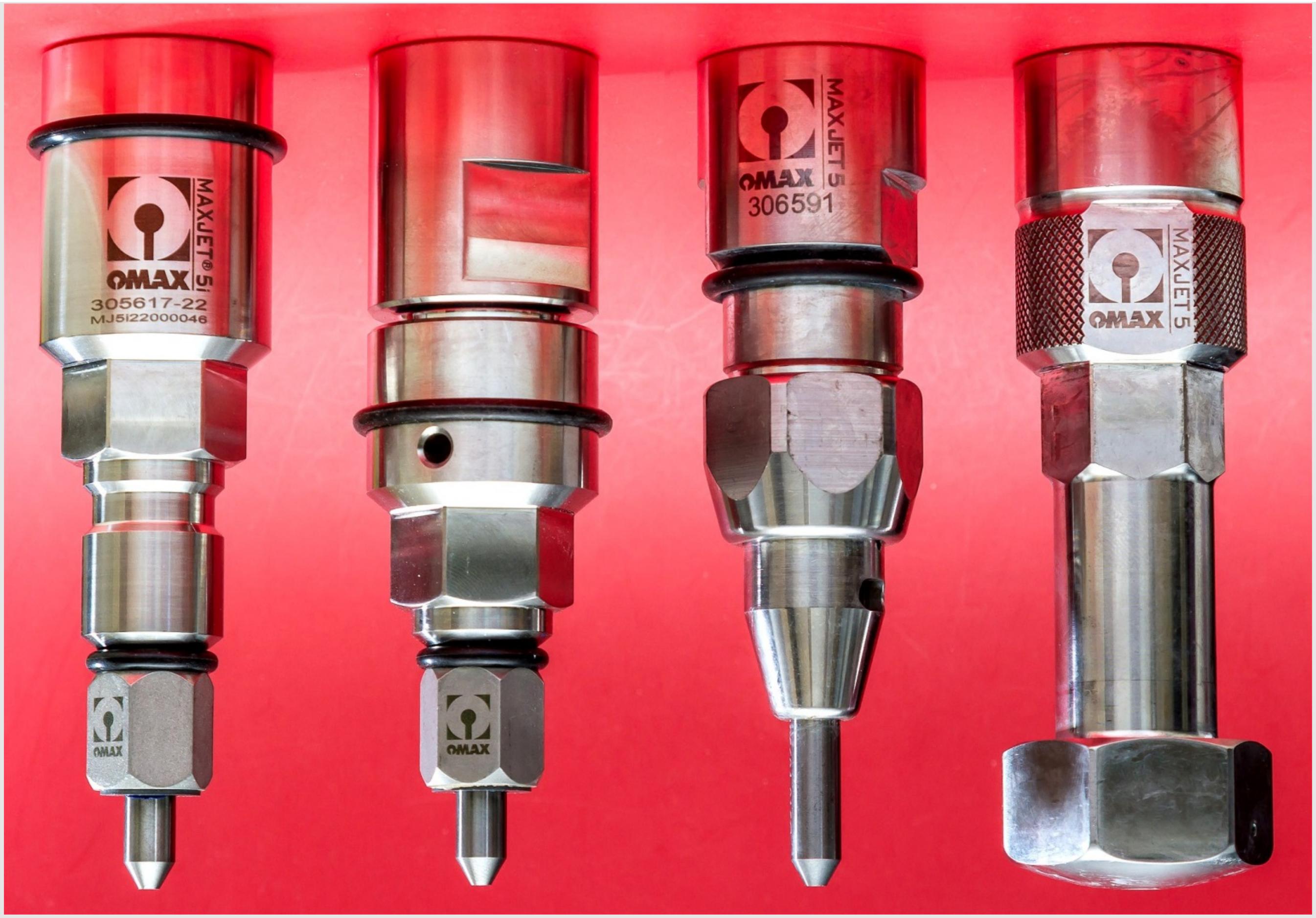
Liquefied Nitrogen

Superheated water

Others



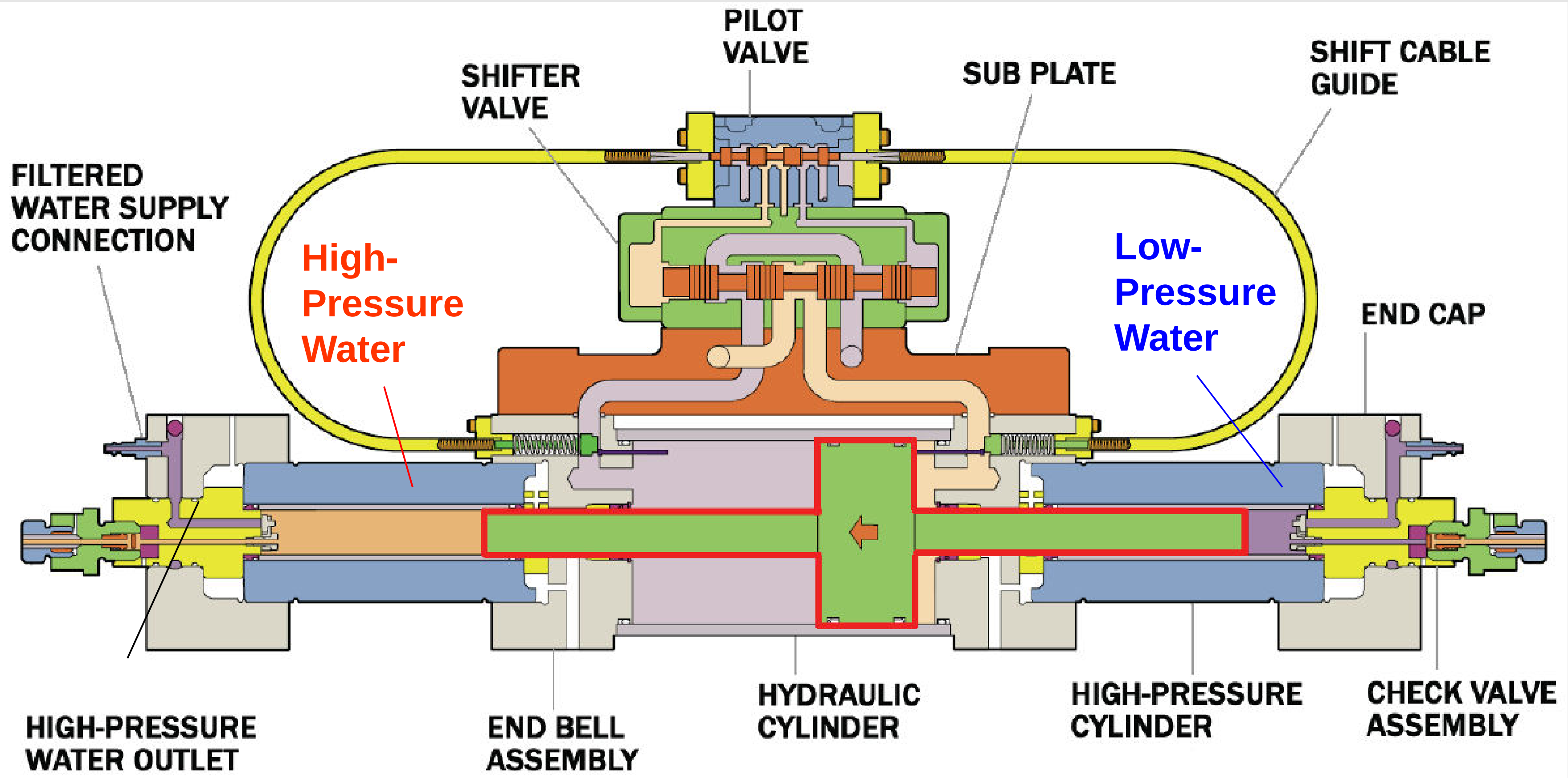
Production Nozzles



14/30 | 10/21 | 7/15 | Water Only

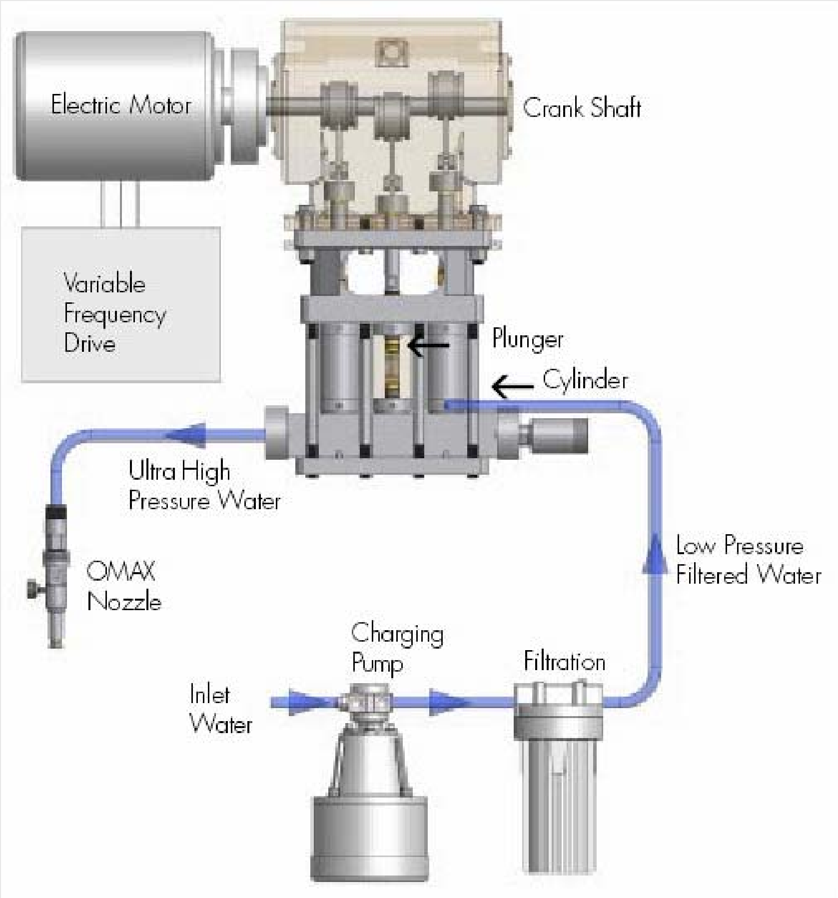
Type of Pumps

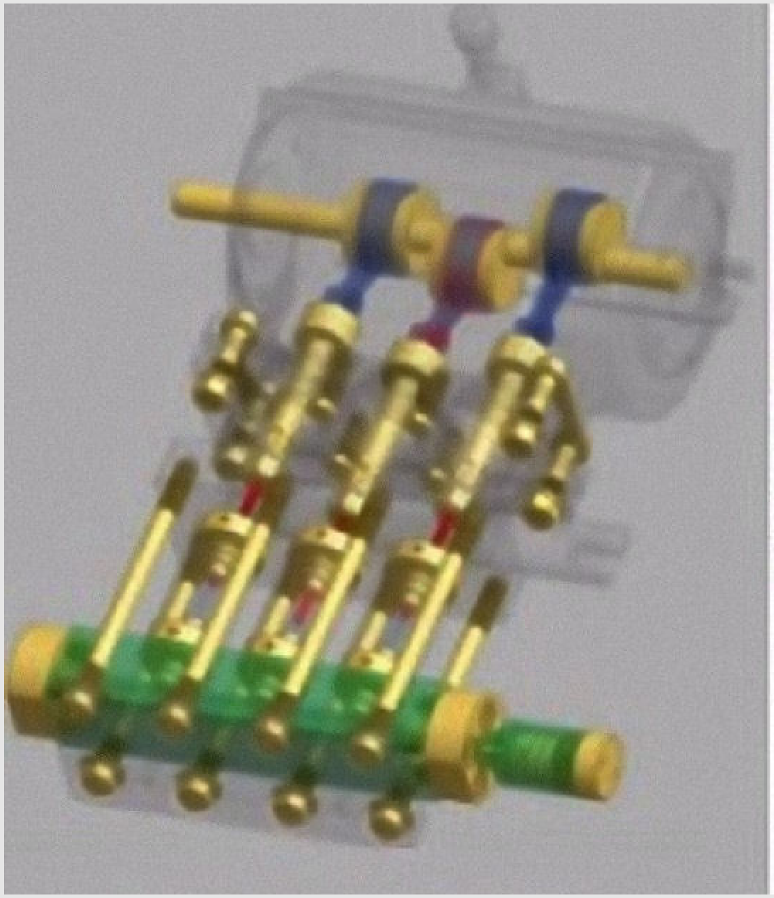
UHP Intensifier Pump



Type of Pumps (cont'd)

Crank Shaft Pump





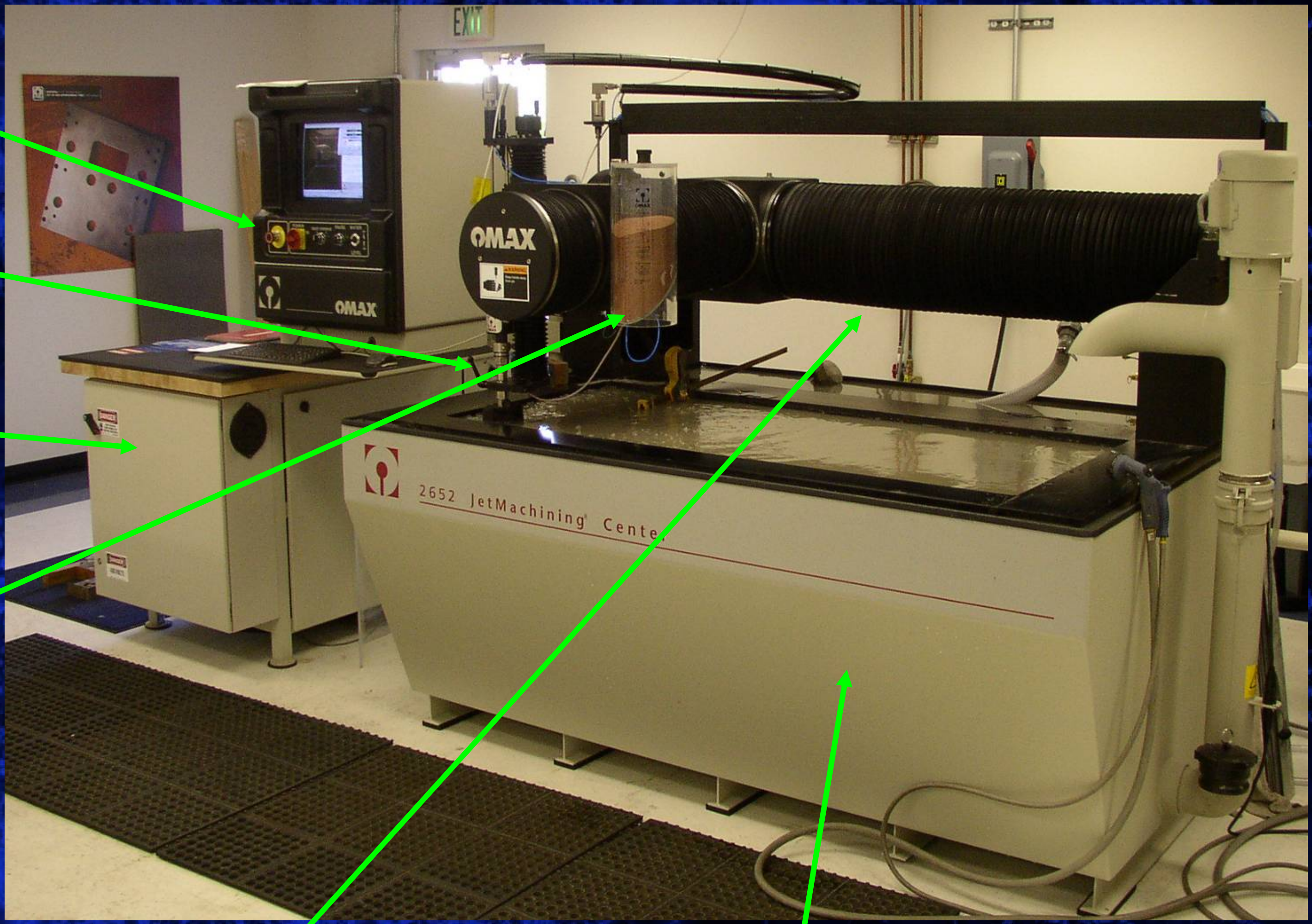
Typical JetMachining® Center (JMC) : 2652

PC-based Controller

Nozzle

Pump (Direct Drive)

Abrasive Delivery System

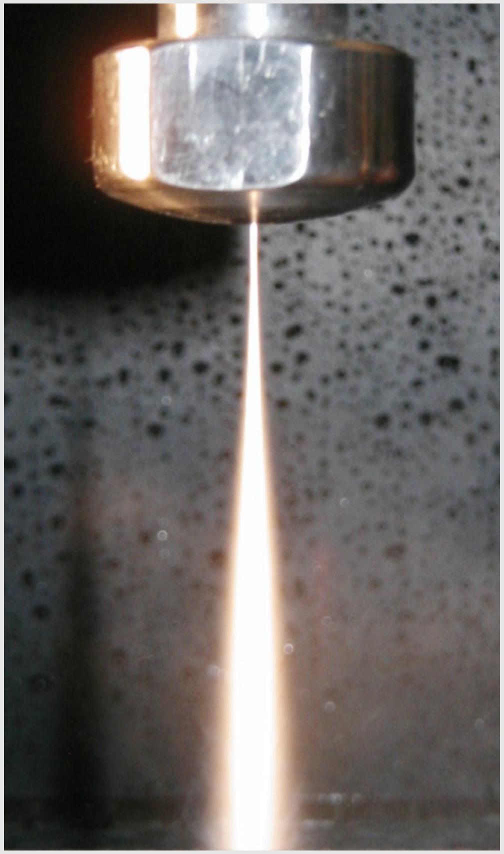


Motion System

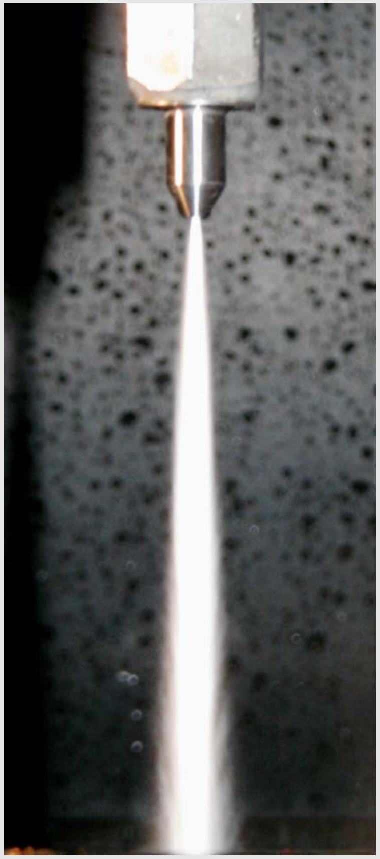
Catcher Tank

Not Shown: (Accessories)

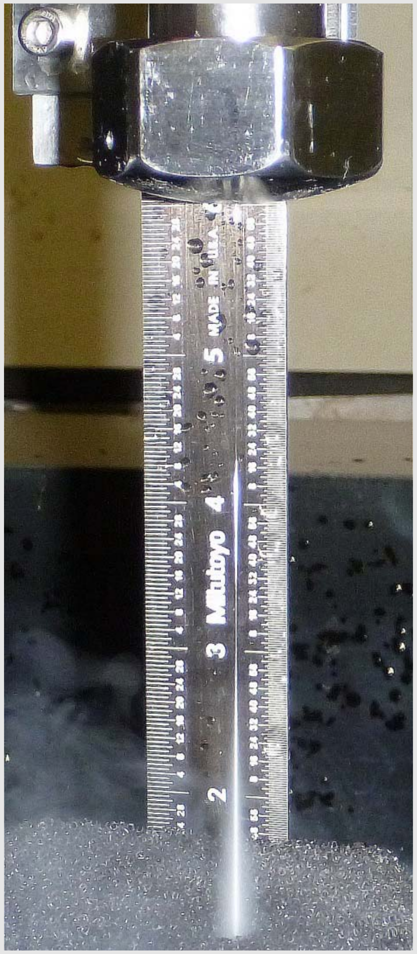
Geometry of WJ and AWJ



Typical WJ



Typical AWJ



Highly Collimated WJ

AWJs for Precision Machining

- Patented PC-based motion control: “Compute first, move later” with up to 8000/in (316/mm) resolution
- Position accuracy
  - ±0.003” (±75 μm) to ±0.0004” (±10 μm)
- PC-based Intelli-MAX™ software - make parts with high tolerance fast
- Intuitive CAD/CAM for automation
- Edge quality is governed by size of abrasives and cutting speeds
- AWJ nozzle is being downsized for meso-micro machining

Effect of Speed vs Edge Quality

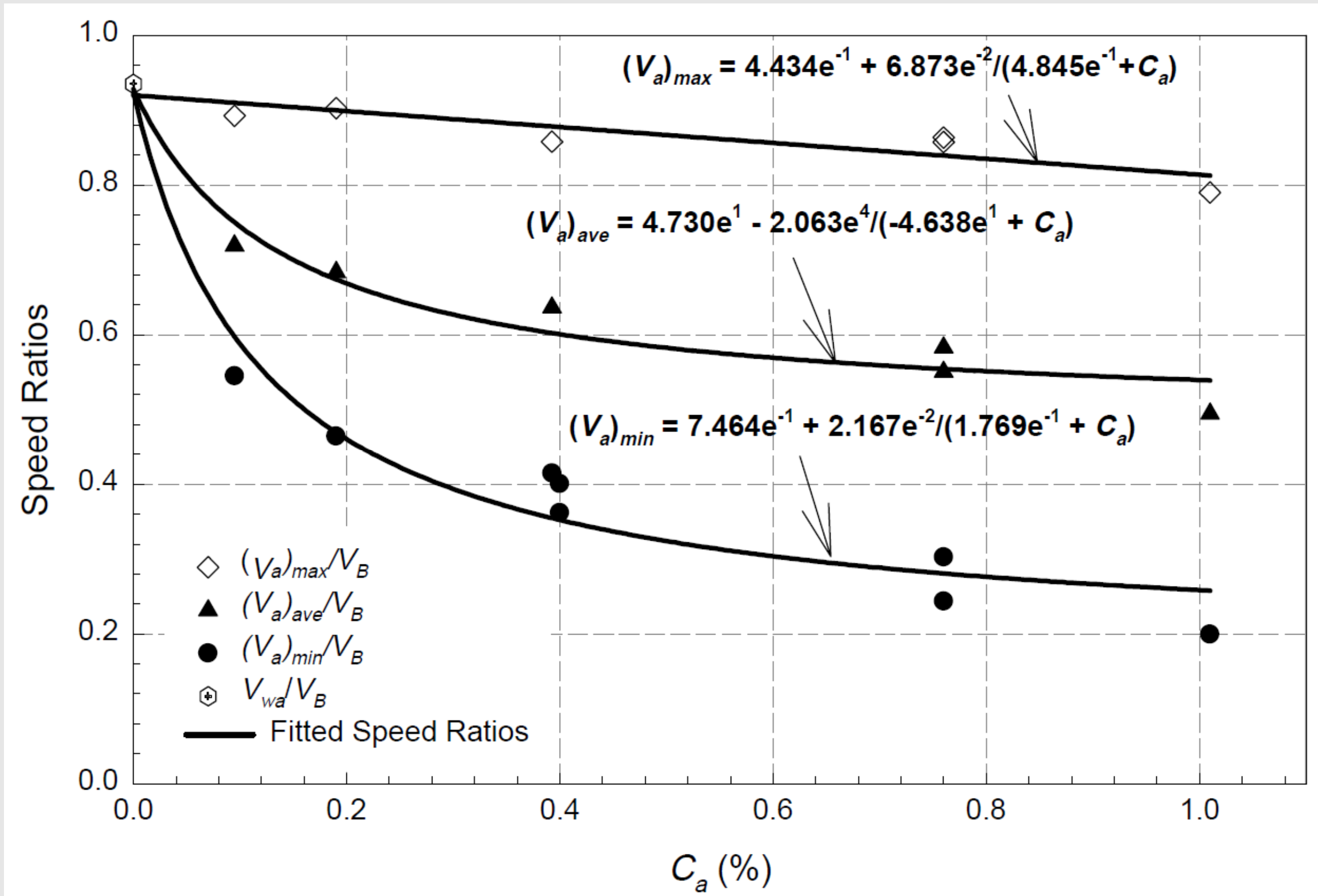
Five Finger Part

Length of finger ~ cutting speed

Kinematics - Measured Speeds

Abrasive (220 mesh garnet)

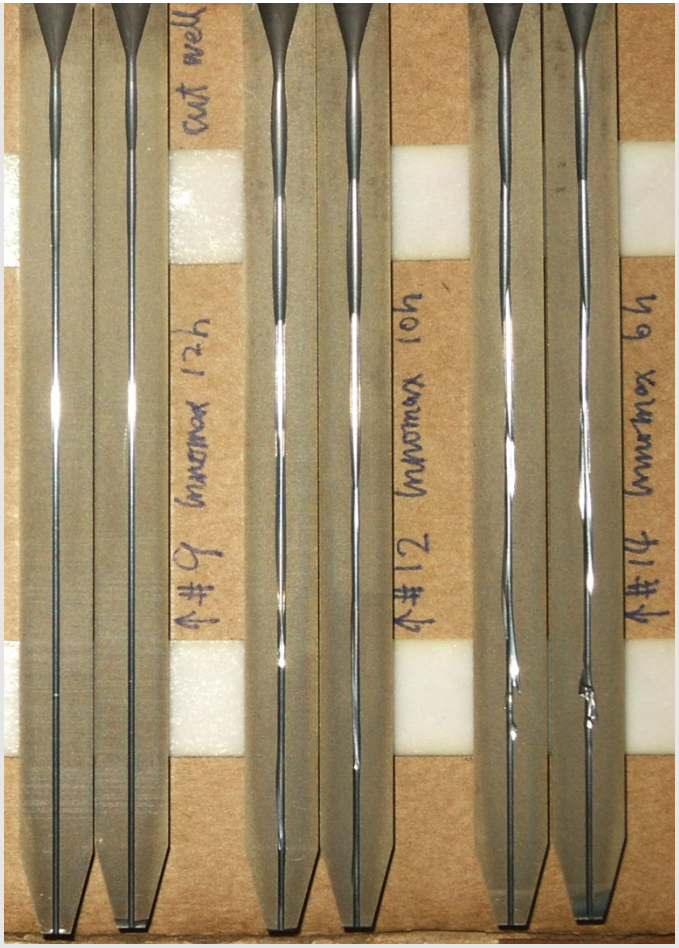
p = 345 MPa and d_o/d_m = 0.18/0.51

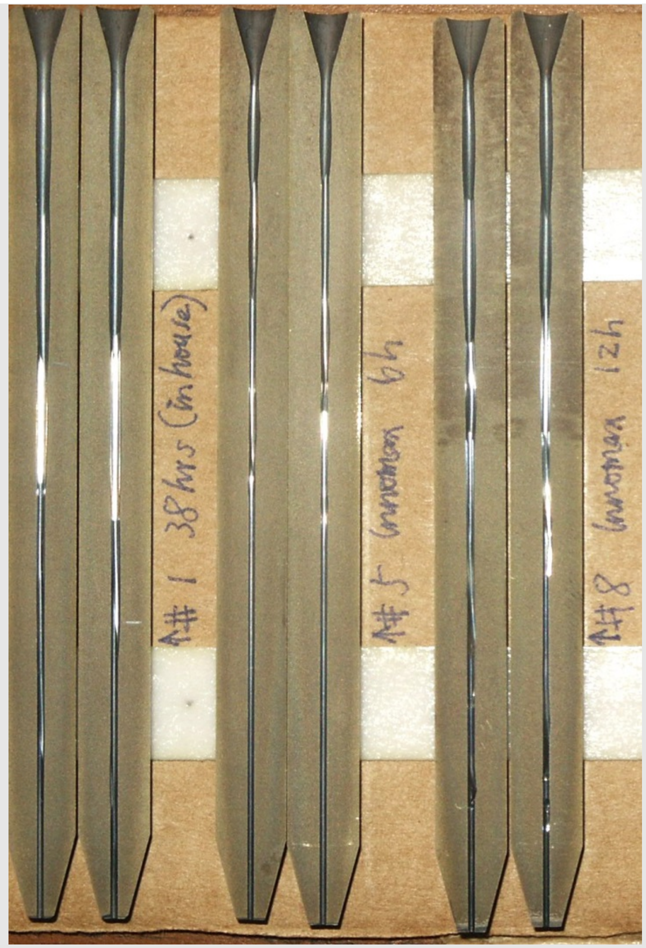


Factors Affecting Precision

- Nozzle wear
- Machine positioning errors
  - Dependent on construction
  - Repeatable errors can be mapped
  - Random errors
  - Temperature effects
- Jet shape errors
- Other
  - Clamping
  - Stress relief
  - Cutting inside before outside features

Mixing Tube Worn Pattern





Short to Medium Operating Times

Mixing Tube Worn Pattern (cont'd)

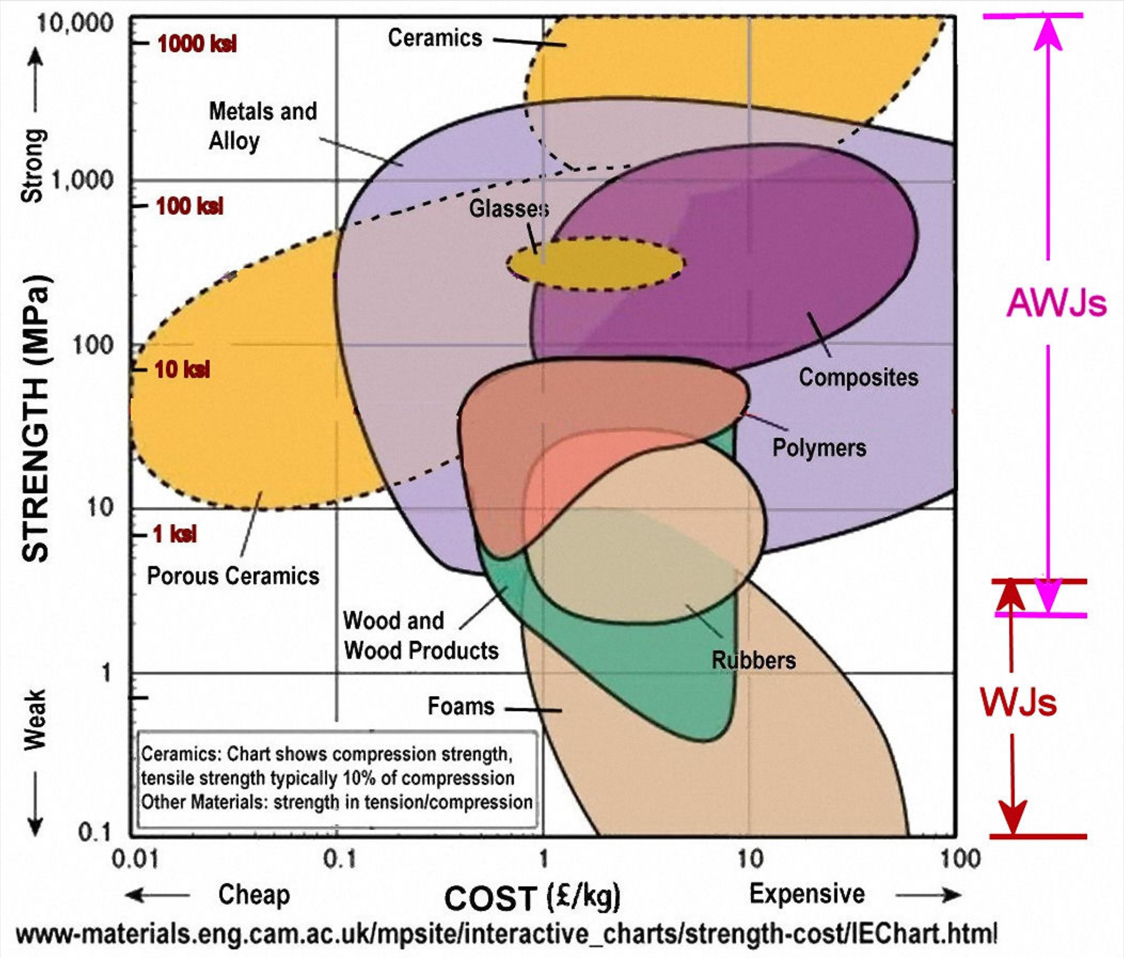
Medium to Long Operating Times

Mixing Tube Worn Pattern (cont'd)

a. Upstream half

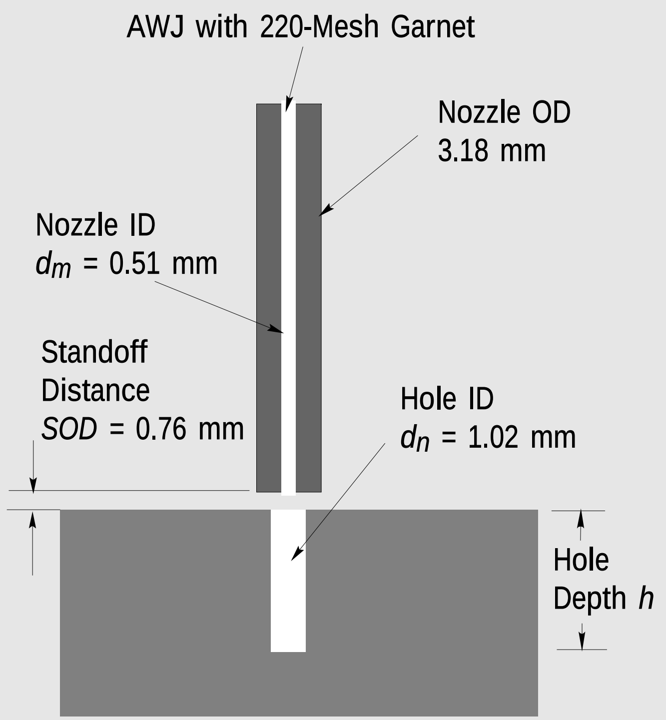
b. Downstream half

Material Cost vs Strength



CFD Simulation

- **CFD 2000 was used to simulate AWJ hole piercing**
  - **Incompressible code using k-ε turbulence model**
  - **Lagrangian or momentum tracking of particles**
  - **Hole diameter - 1 mm with 3 depths – 0, 1, and 2 mm**
  - **Density ratio of abrasive to water: 4 to 1**

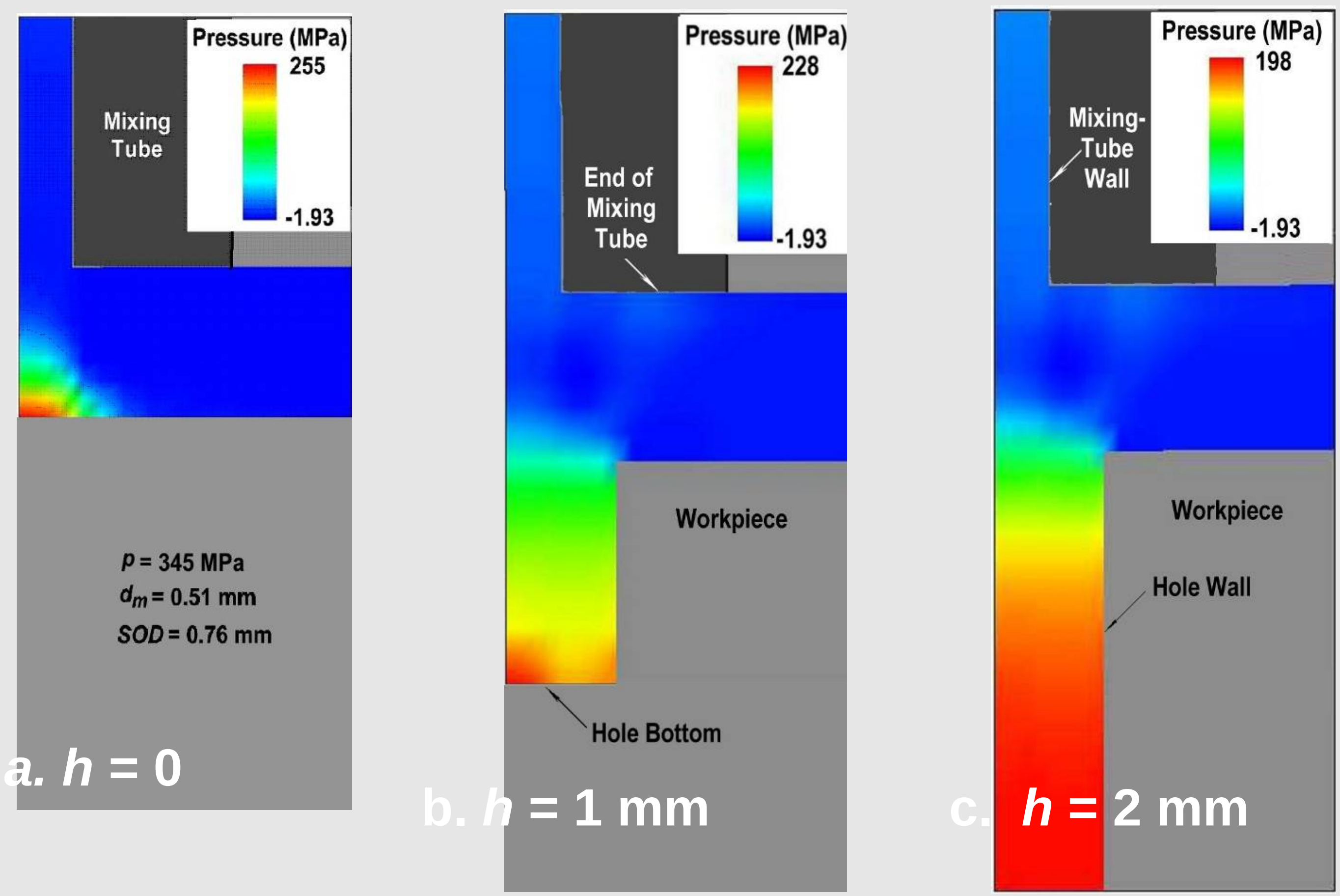


Configurations for CFD modeling of hole drilling
(v_w = 368 m/s, v_a = 184 m/s).

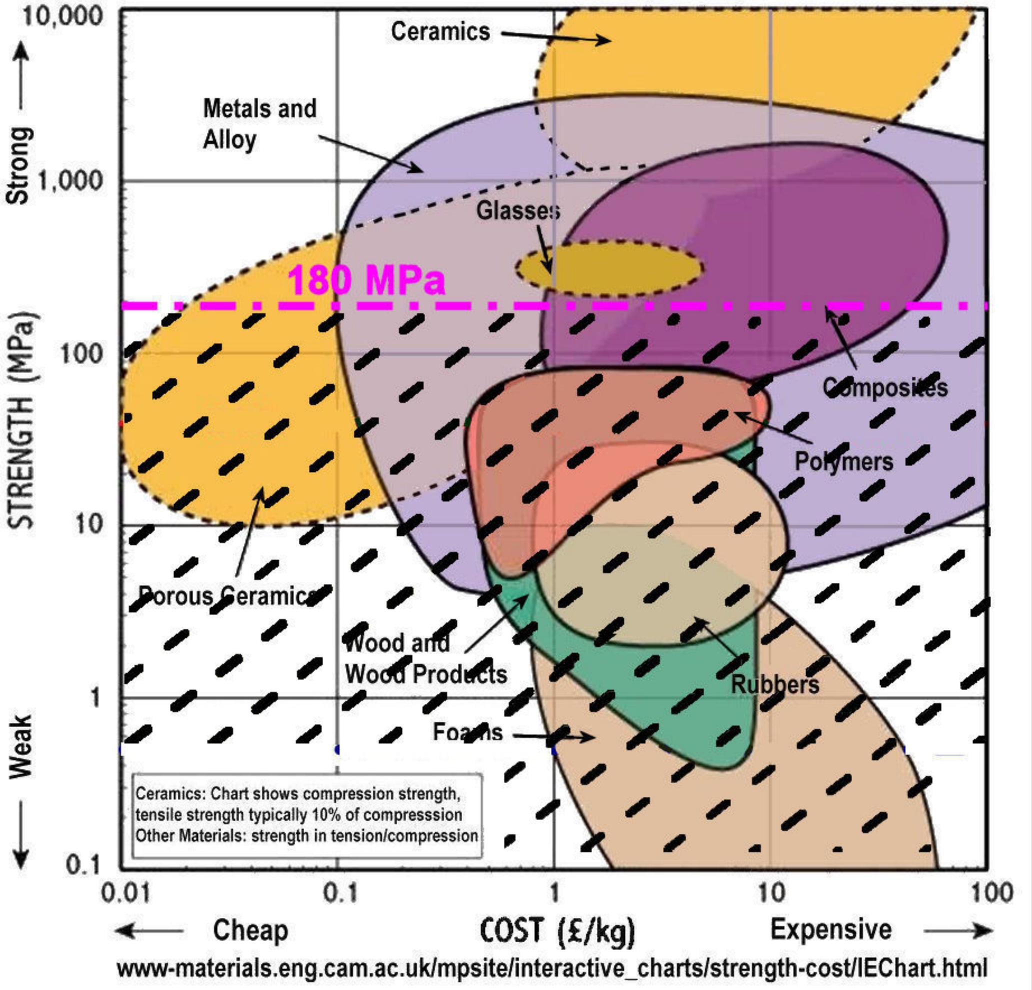
CFD Study (cont'd)

p = 345 MPa, d_m = 0.51 mm., d_n = 1.02 mm, h = 2.03 mm, SOD = 0.76 mm, S = 4, d_a = 0.07 mm

CFD results of static pressure in blind holes (Liu et al., 1998)



Piercing Damage to Materials



Remedies

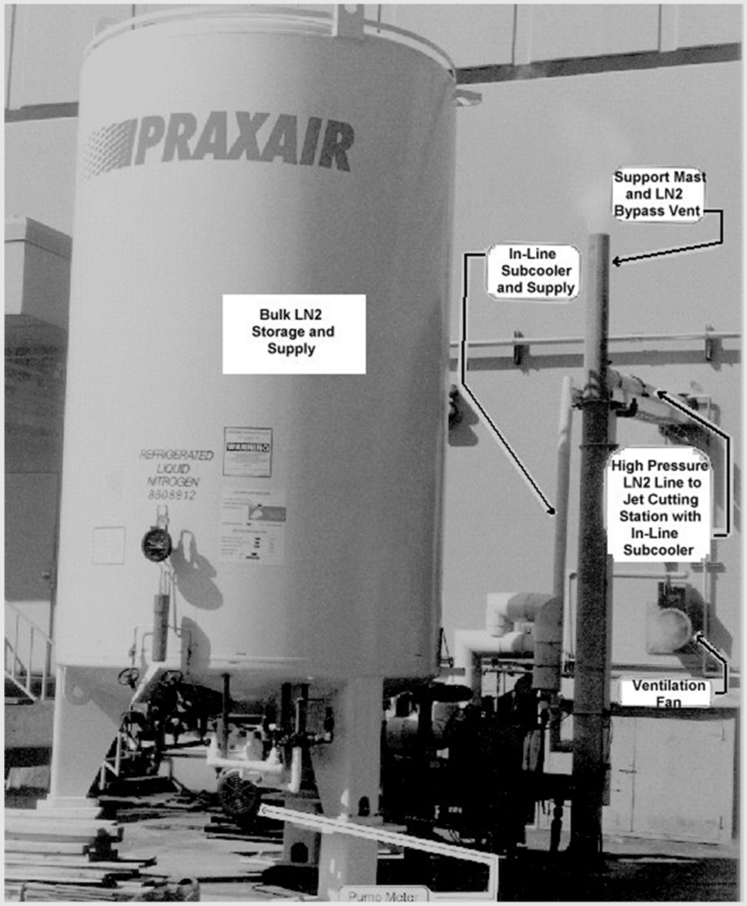
- Current Practices
  - Mechanical pre-drilling
  - Pressure ramping
    - Helps deliver abrasives to nozzle at pressures below threshold values
    - Ramping depends on material properties
    - Vacuum assist/water flushing
      - Increases vacuum improves abrasive delivery
      - Water flushing removes wet abrasives

Remedies (cont'd)

- New Development
  - ACJ - Phase change of LN_2 upon exiting ACJ nozzle minimizes piercing damage
  - ACJs are however not a viable machine tool (too costly and bulky)
  - An FAWJ has been successfully developed to emulate the phase change of ACJ*

Disadvantages of ACJs

- Too complex and bulky
- Cost ineffective
- Difficult to maintain and operate
- Short life for key components operating at cryogenic temperature
- Potentially hazardous environment



Flash Abrasive-Waterjets (FAWJs)

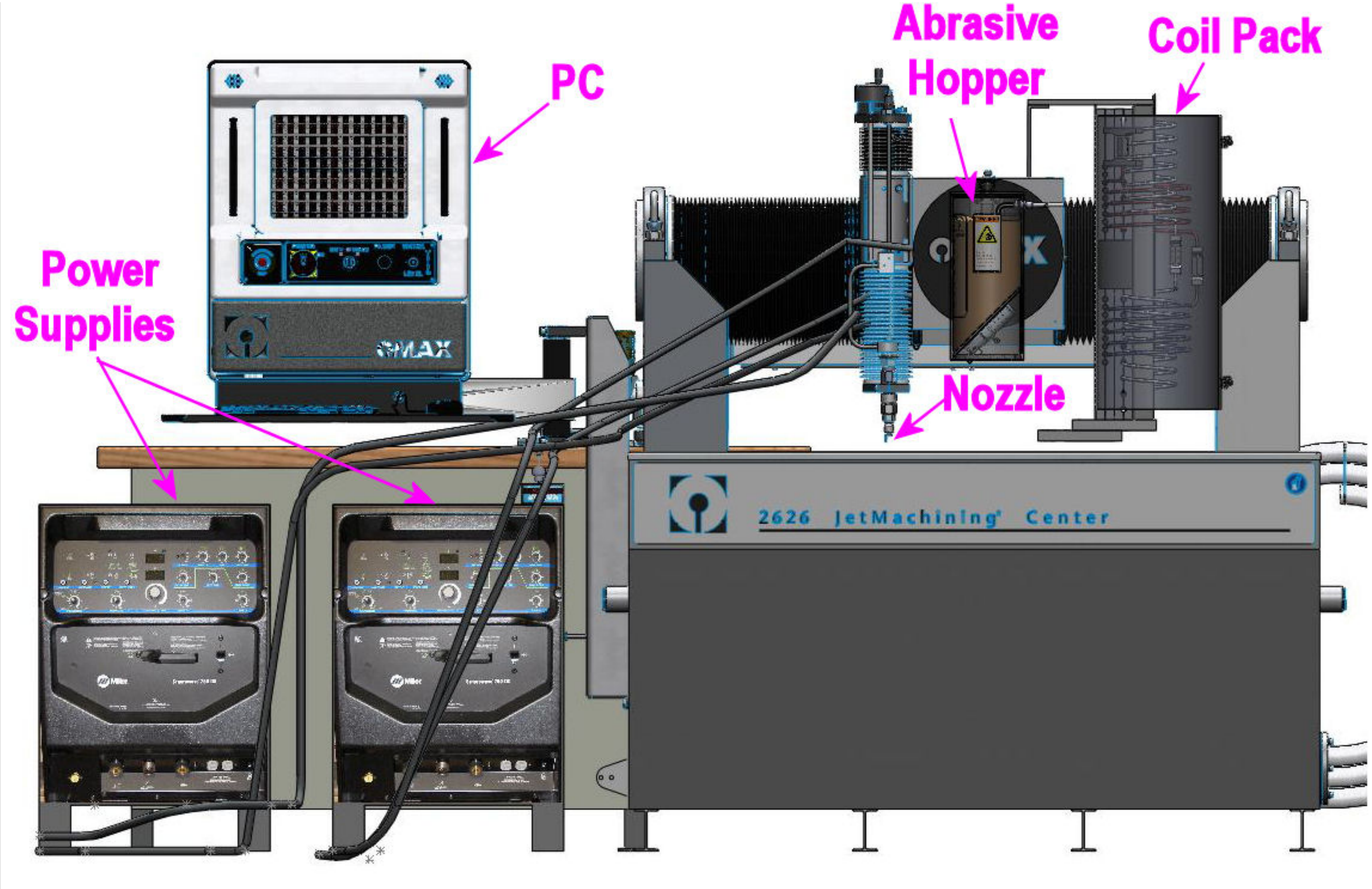
- NSF SBIR Phase II Grant
  - Title: Ultrahigh-pressure flash abrasive-waterjets (FAWJs) for precision machining[1]
  - Objectives: Mitigate damage induced by AWJs due to piercing pressure buildup inside blind holes during initial stage of piercing
  - Application: Brittle/delicate materials such as glass, Plexiglas, laminates, and composites with weak tensile or adhesive strength

[1]Patented: Liu, H.-T. (2007) "Flash Vaporizing Water Jet and Piercing with Flash Vaporization," US PATENT NO. 7,815,490..

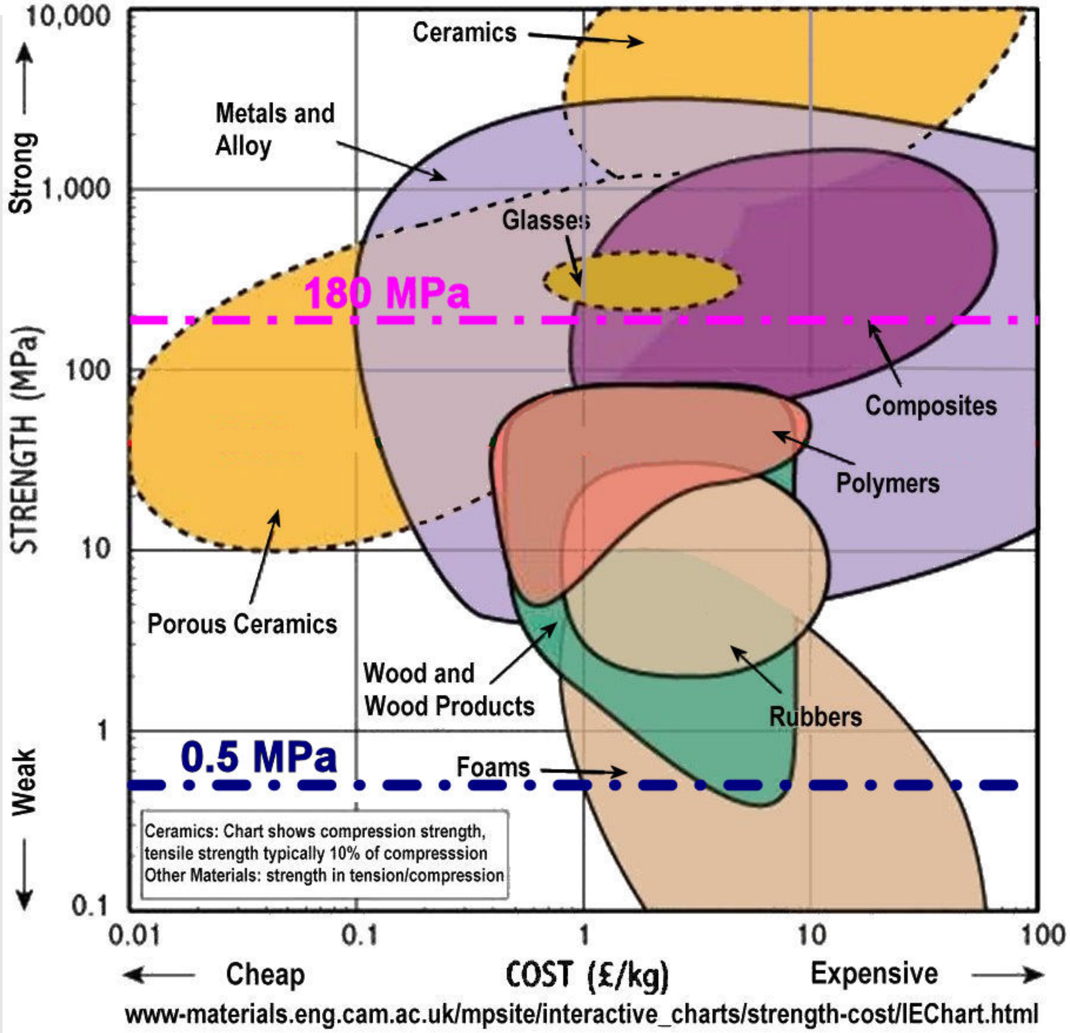
FAWJ Innovation

- Superheat the UHP water upstream of the orifice but downstream of the pump
- Phase change of superheated water minimizes buildup of static or piercing pressure in blind holes during initial piercing
- Demonstrated the mitigation of piercing damage such as delamination and cracking induced by AWJs

FAWJ Setup


PC
Abrasive Hopper
Coil Pack
Power Supplies
Nozzle
2626 JetMachining Center

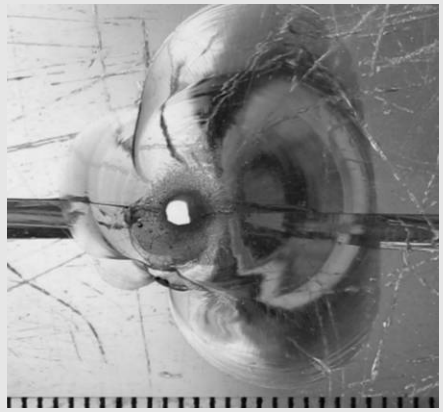
Piercing Damage to Materials

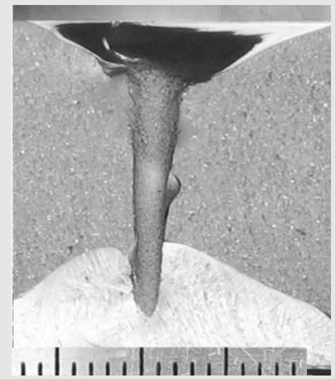


Performance of AWJs vs. FAWJs

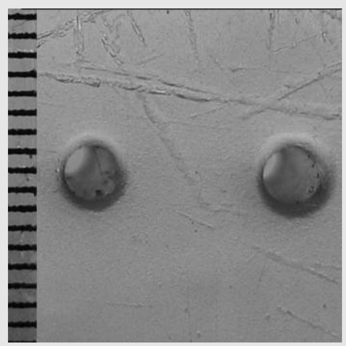
Float Glass

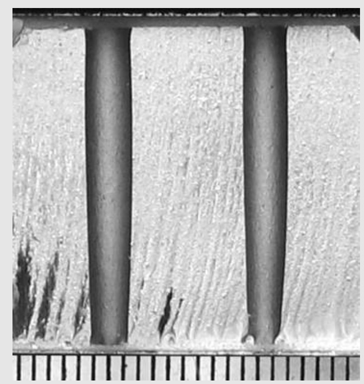
AWJ





FAWJ



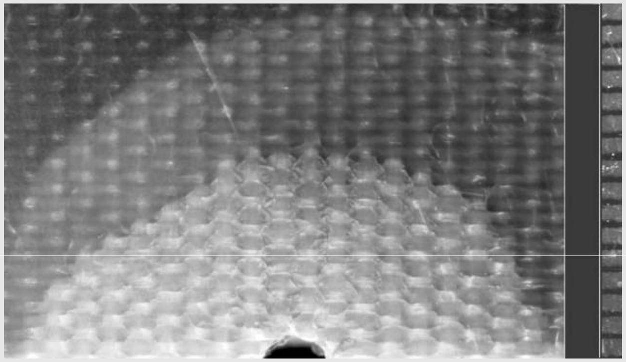


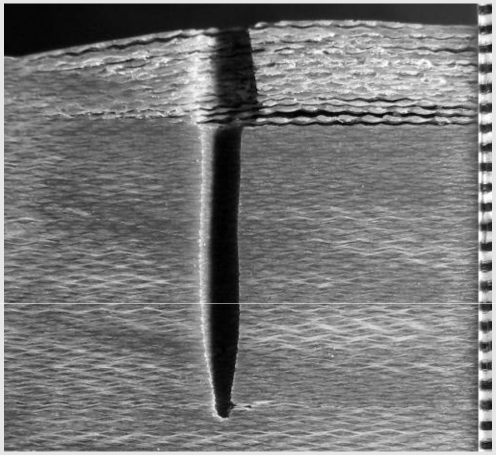
Top view - entry **Side view**

Performance Comparison (cont'd)

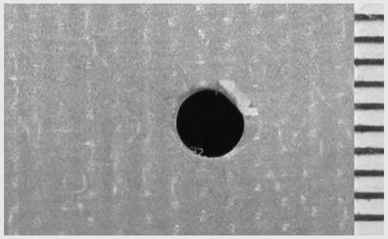
Melamine

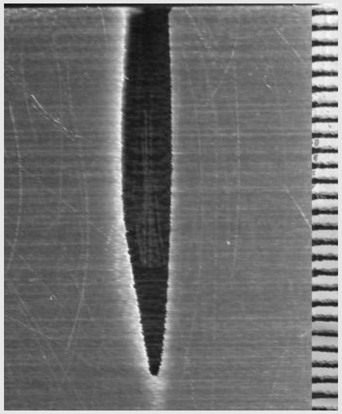
AWJ





FAWJ



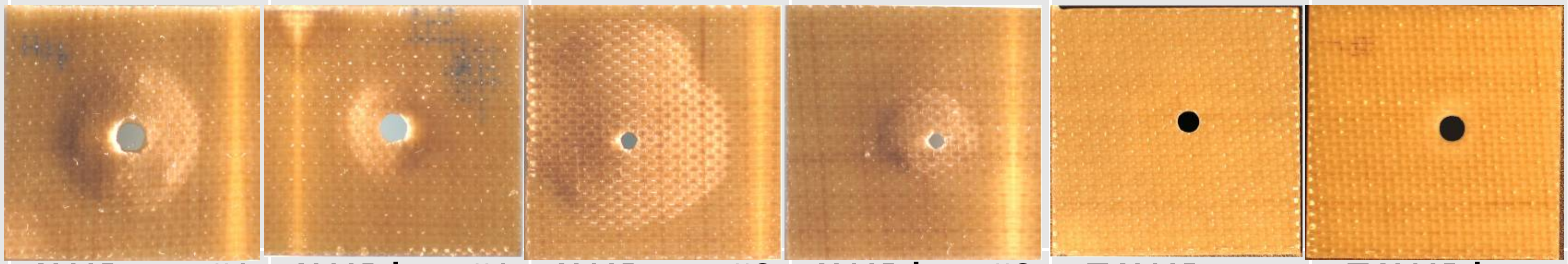


Top view-entry

Side view

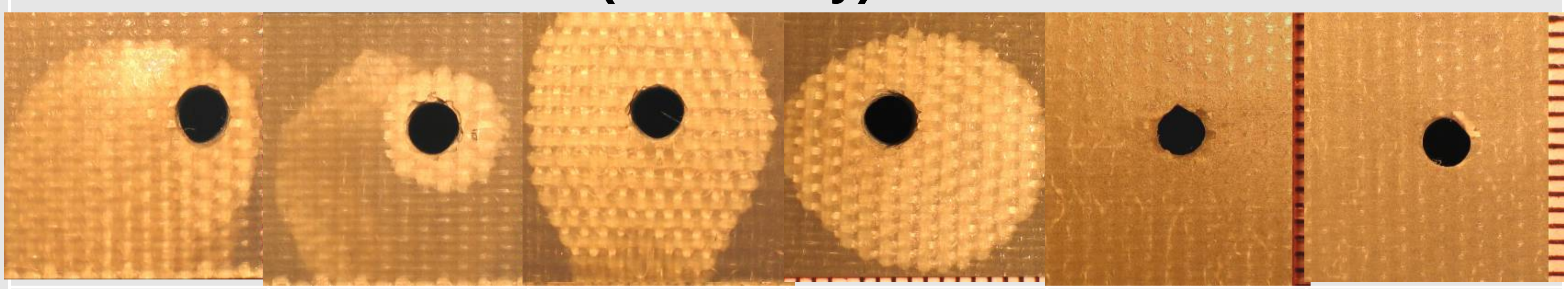
More Comparisons

Fiberglass Composite (Beige) - 1.3 mm thick



AWJ-top #1	AWJ-bot #1	AWJ-top #2	AWJ-bot #2	FAWJ-top	FAWJ-bot

Melamine (Dark Gray) – 5.1 cm thick



AWJ-top #1	AWJ-bot #1	AWJ-top #2	AWJ-bot #2	FAWJ-top	FAWJ-bot

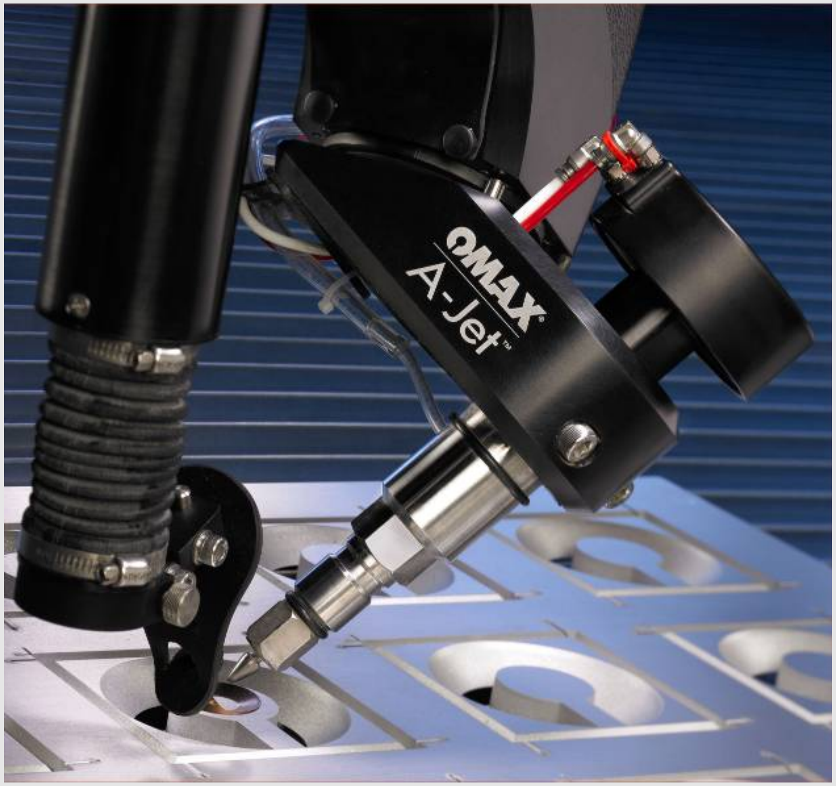
Other Developments

- Accessories for smooth pressure ramping and minimizing pressure spikes (patent pending)
- Emulation of ACJ/FAWJ (patent pending)

Accessories for 3D Machining

Rotary Axis

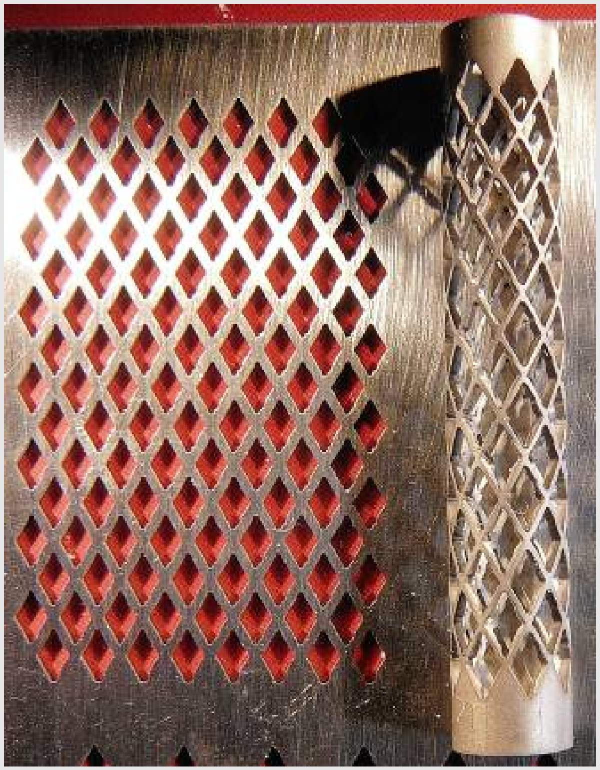
A-Jet

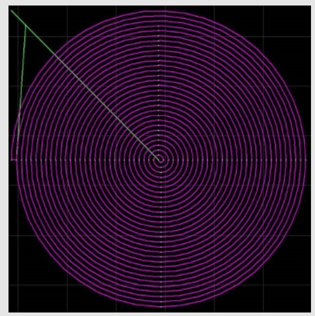


AWJ 2D/3D Machining

2D/3D diamond holes

3D decorative parts





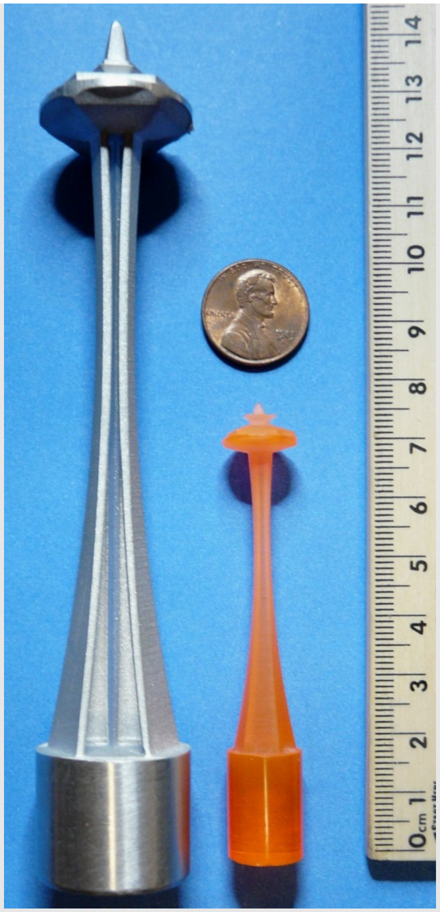
Tool Path

Diamond holes

Spiral

OMAX

AWJ-Machined 3D Parts



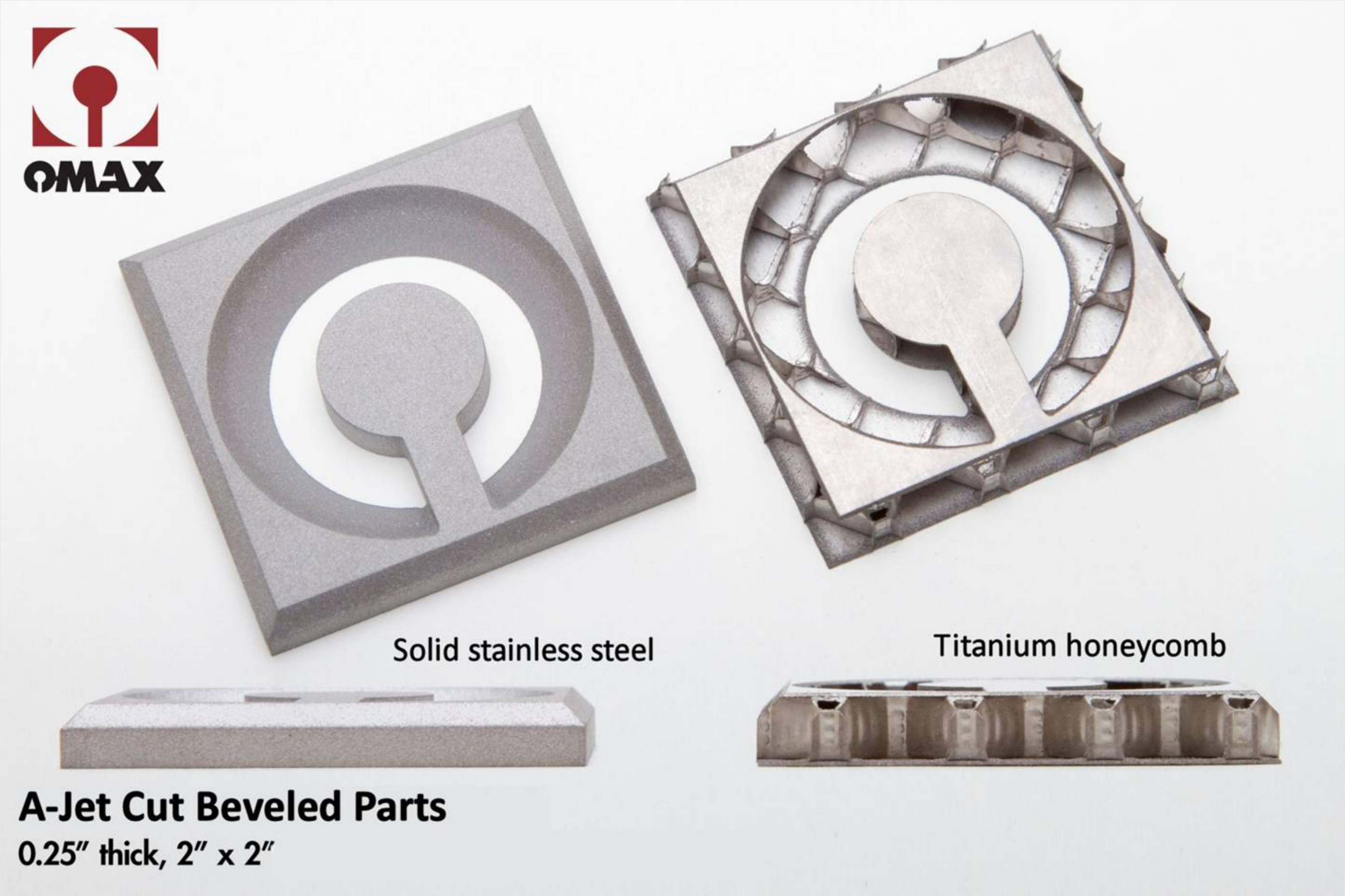
Space Needle

Ti Interlocking Link

Blisk

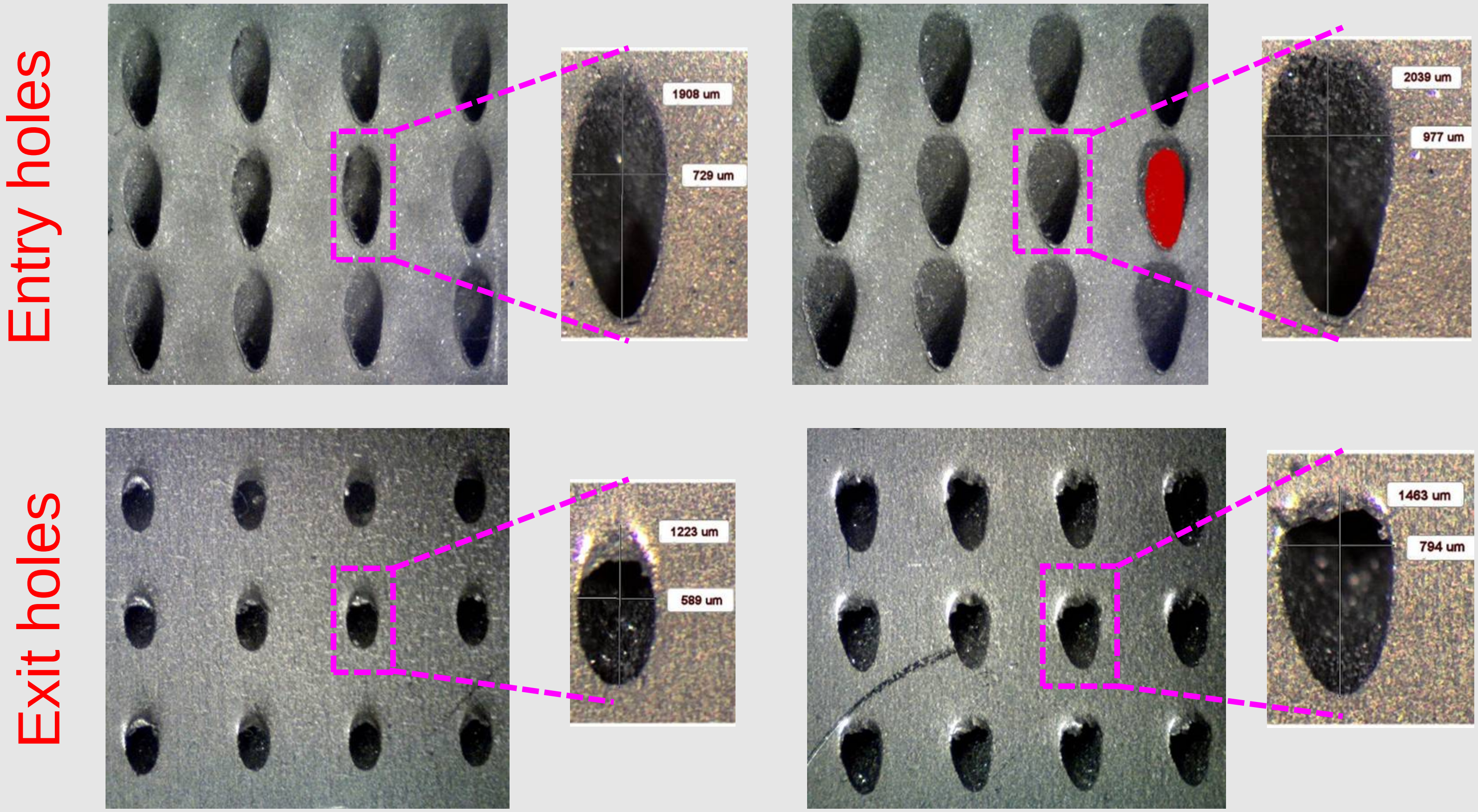
AWJ-Machined 3D Parts **(cont'd)**

Beveled Parts



AWJ Hole Drilling (cont'd)

Pierced and Shaped Holes on Stainless Steel Plates



Micro AWJ Technology

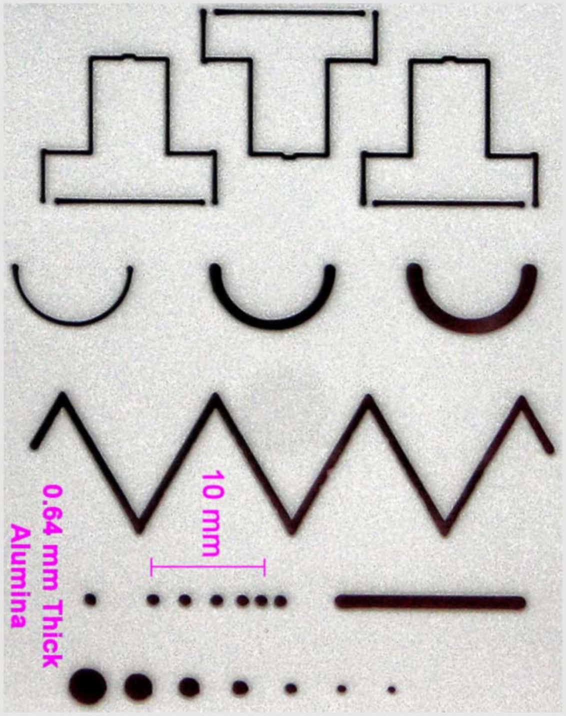
- Supported by an NSF SBIR Phase II grant
- Develop μAWJ technology for machining features 100 μm and smaller
  - Downsize AWJ nozzles – 5/10 (beta) and 3/8
  - Improve feeding of fine abrasives (patents pending)
  - Develop ancillary devices (patent pending)
  - Develop and commercialize a MicroMachining Center (μMC) (Refer specs in Appendix)

Challenges

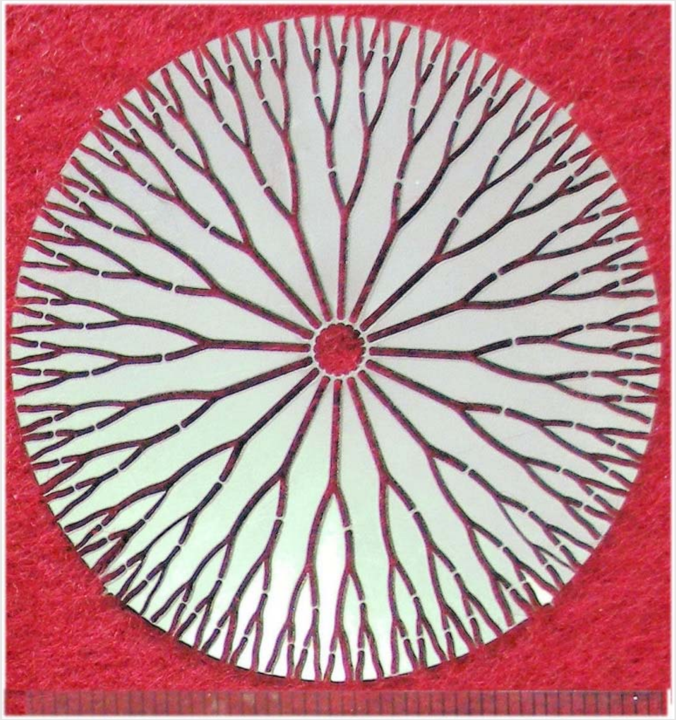
- Nozzle alignment issue
  - Tolerance stack error becomes critical
- The AFJ changes from gravity to capillary dominated flow regime
  - Presence of meniscus column in mixing tube
    - Back flush of water may lead to nozzle clogging
  - High head loss through mixing tube as
    - Hagen-Poiseuille flow $h_{f,\ell} = \dfrac{128 \mu L Q}{\pi \rho g \, d^4}$
- Flowability of abrasive decreases with decreasing particle size

μMachined Parts (cont'd)

AWJ micro machining



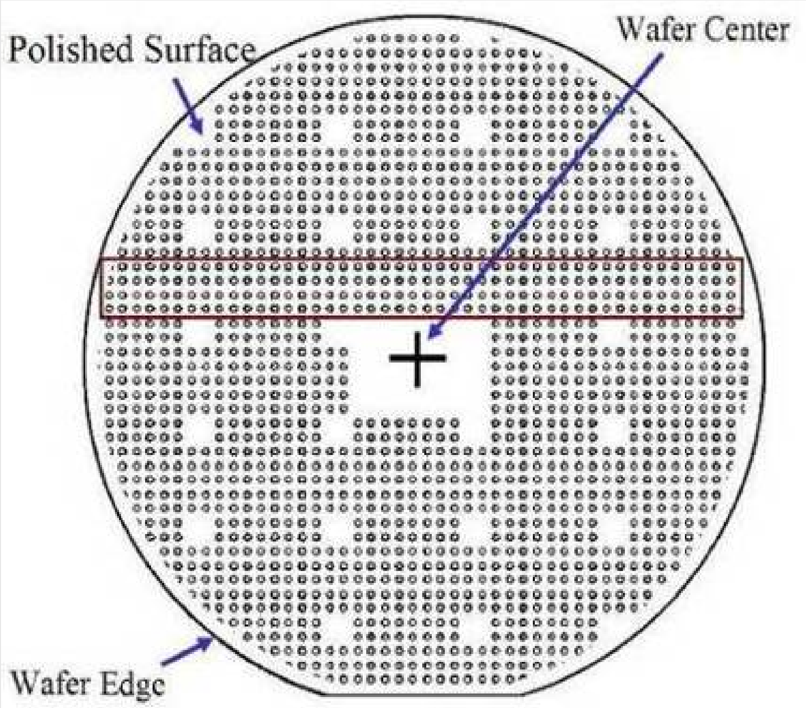
Alumina sheet



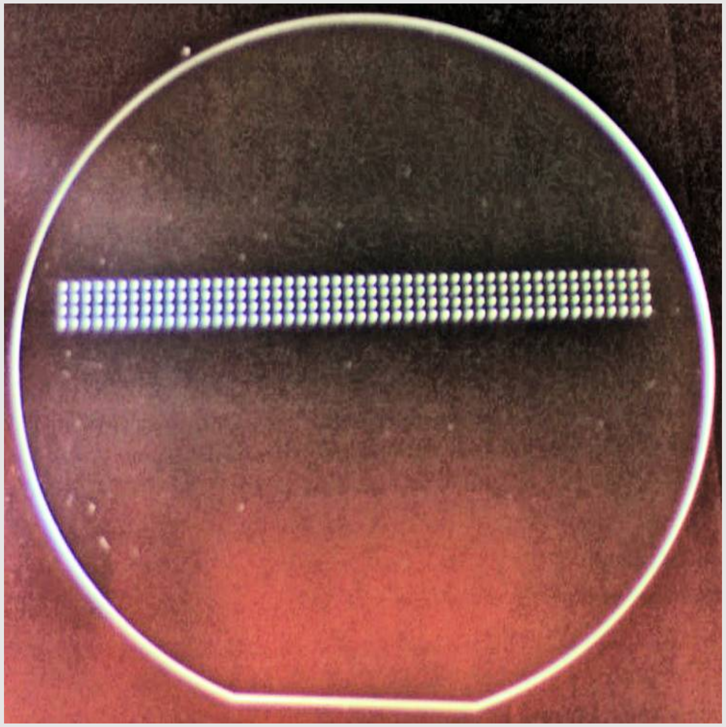
Stainless Steel Sheet

μMachined Sample Parts

AWJ pierced holes in 0.6 mm thick Pyrex Glass



Hole pattern (46 x 46)

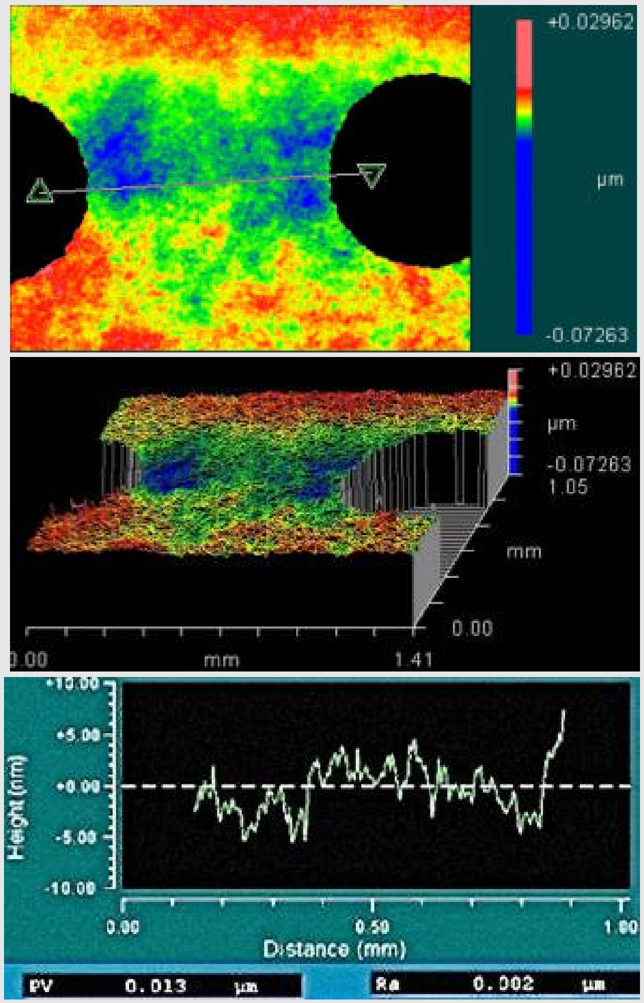


Actual holes pierced (46 x 4)

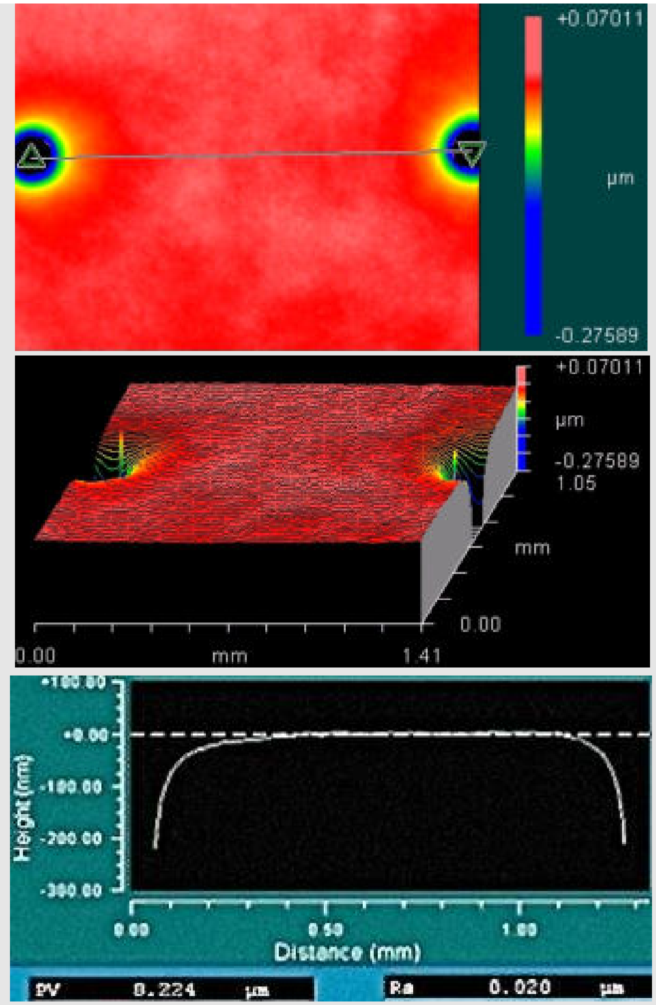
µMachined Sample Parts (cont'd)

WYKO Hole Profiles

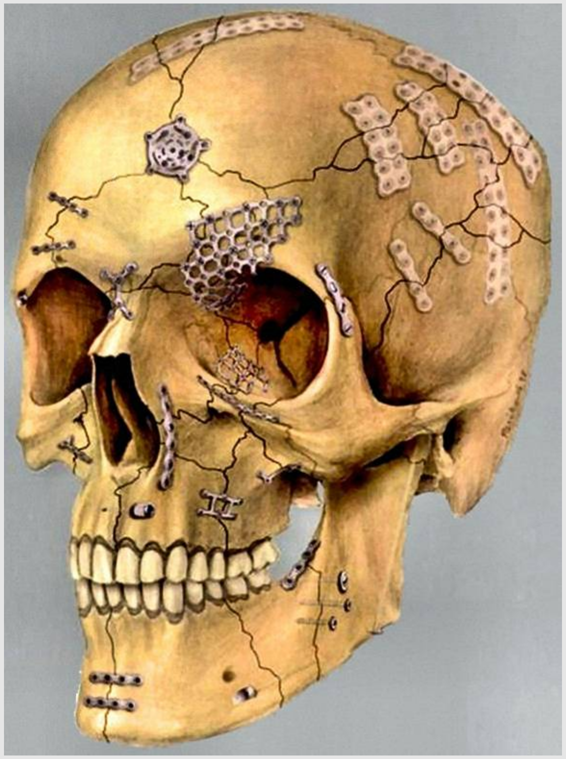
Entry surface



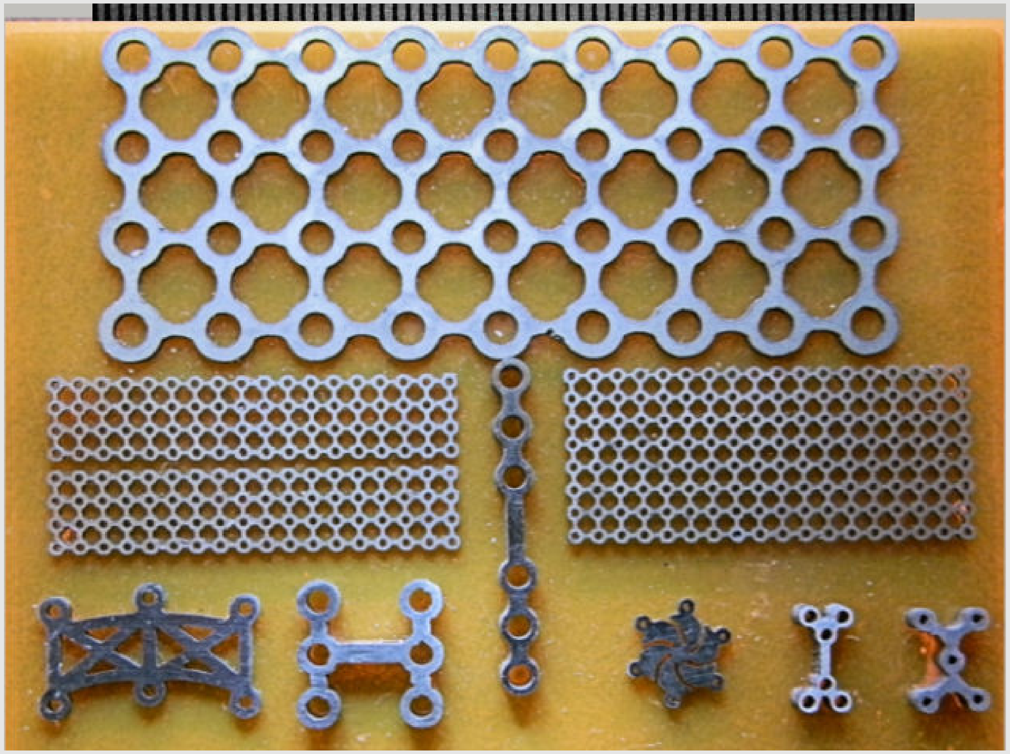
Exit surface



μMachined Parts (cont'd)



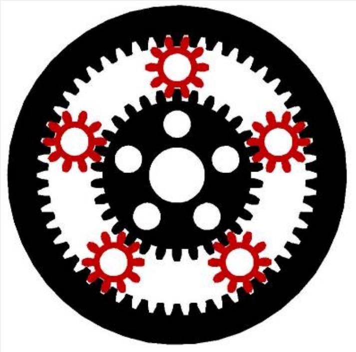
Micro-plates and mini-plates for skull/facial reconstruction (Haerle et al., 2009)



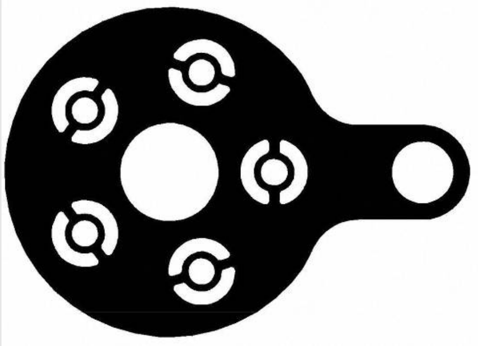
AWJ-machined micro-plates and Mini-plates (titanium and stainless steel)

µMachined Parts (cont'd)

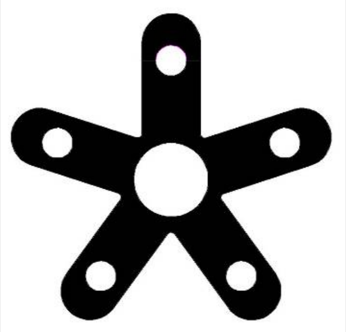
Components of Planetary Gar



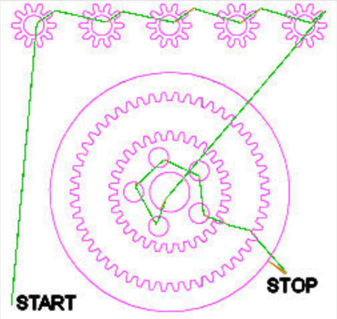
Gear pattern



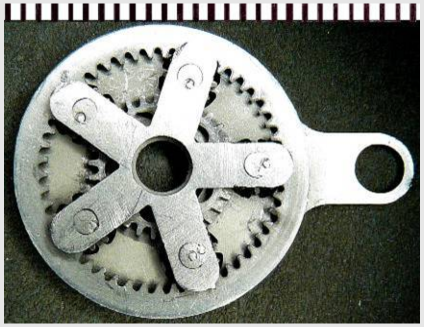
Mounting Plate



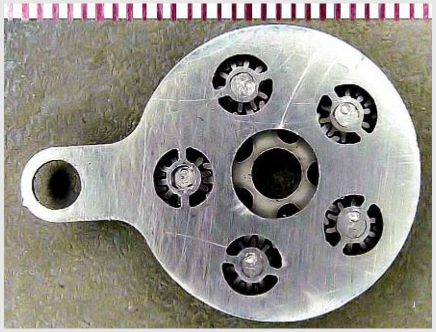
Gear Carrier



LAYOUT Display



Assembled (front)



Assembled (back)

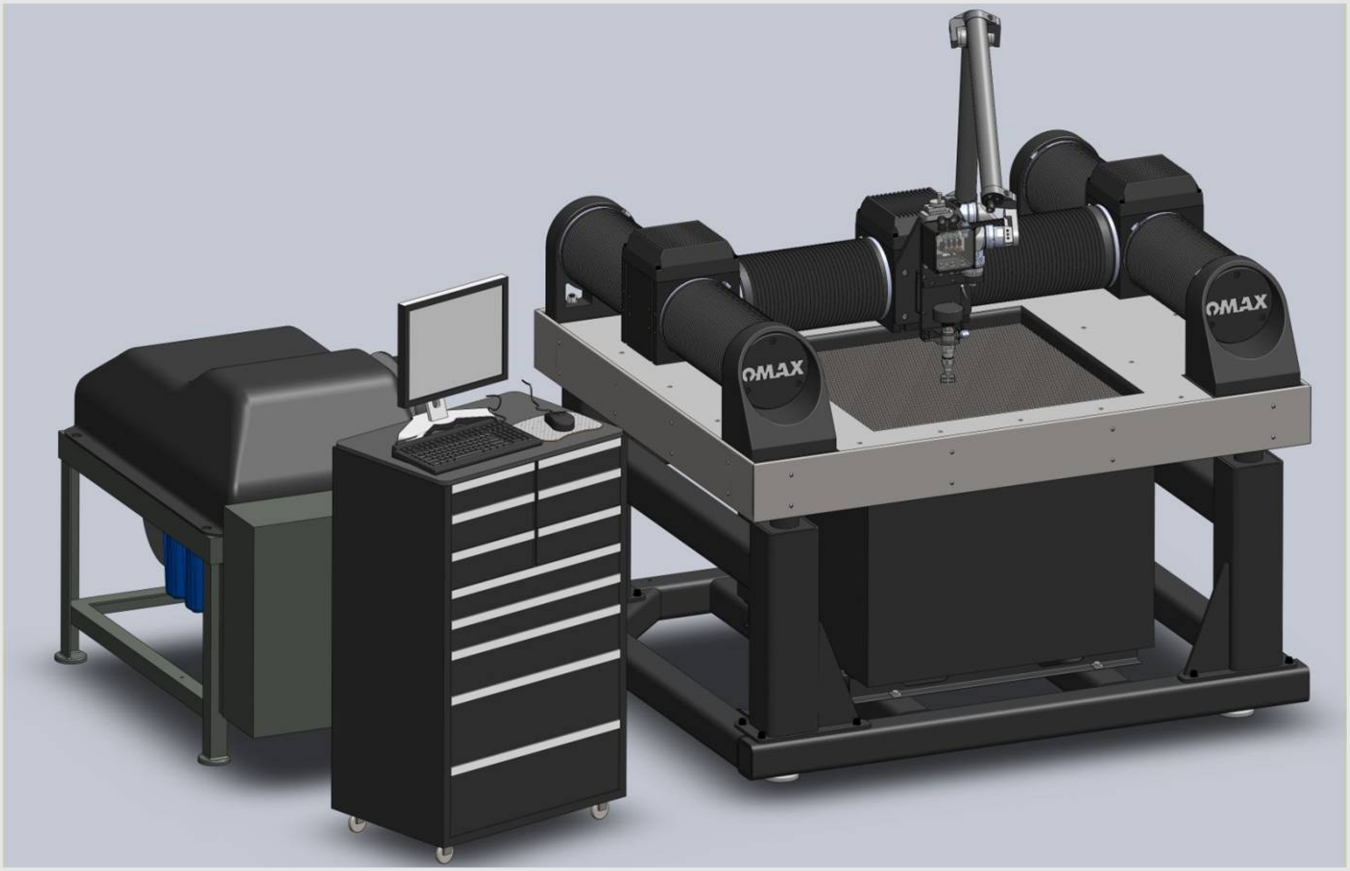
μMachined Parts (cont'd)

http://www.livescience.com/20200-miniature-gears-jets-water.html

http://www.livescience.com/20418-miniature-gears-jets-water.html

Work in Progress

Prototype μMC



Summary

- Aspects of AFJ for numerical modeling
  - AFJ phenomenon
    - Optimize jet formation (entrainment and slurry modes)
    - Abrasive feed and entrainment – constant feed rate
  - Nozzle design
    - Maximize abrasive acceleration
    - Minimize jet spread and diameter
    - Minimize nozzle wear
  - AFJ Machining
    - Maximize cutting speed for a given edge quality
    - Minimize piercing damage of delicate materials
  - Others – minimize induced vibration

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