Conventional Coolants

- Safety concerns (toxicity, bacteria, fungi)
- Used cutting fluid must be disposed of:
  - Oil and other wastes present disposal impact on the environment
  - Regulation and enforcement specify mitigation to the environment and associated costs
- Significant investment costs for coolant supply, filtration, and mist collection equipment
- High on-going lifecycle costs of coolant based manufacturing systems
- Largely inefficient from a cooling and lubrication perspective
- Generally effective for chip management
MQL Alternative to Traditional Cutting Fluids

- **Minimum Quantity Lubrication (MQL)** - Technology based on supplying the cutting edge with a small quantity of lubricant mixed with air.

- MQL uses oil, mostly based on vegetables or ester:
  - Less harmful to the human body and the environment.

- **Goals of MQL Include:**
  - Economical
  - Direct lubrication (less friction in the process)
  - Increased tool life (increased machine availability)
  - Dry chips, clean work parts, reduced disposal costs
  - Less energy consumption

- **MAG is a world leader in MQL technology:**
  - Installed more than 300 MQL machines in a 10 year period ending in 2008
  - More than doubled that quantity since 2009
  - Developed significant expertise and “know-how” for dry and near dry machining.

Example: High Volume Aluminum Transmission Case
Next Generation of Dry Machining

MQL Technology:
- Yields small increases in cutting speed & tool life with better surface finish
- Eliminates coolant systems and the energy to run them
- Eliminates coolant disposal costs
- Potentially eliminates in-process washers
- Improves maintainability
- Increases value of reclaimed chips
- Reduces investment and operating costs

MAG’s Vision of Next Generation Dry Machining:
- Evolve from MQL dry machining expertise
- Replace or supplement MQL with Cryogenic technology enabling higher cutting speeds and productivity
The Basics Cutting Tool Heat

- The process of **cutting produces heat**
- The **faster** the cutting speed the **higher** the heat
- Any cooling media helps **reduce cutting heat** (water= +70° F, LN₂= -321° F)
- Each **tool material** has a **Critical Temperature** where it will deteriorate to failure quickly
- Different work materials bring tools to **critical temperatures** at **different cutting speeds**
Machining Wear Mechanisms

- **Adhesion** (Thermal mechanical) reduced with work material temperature
- **Abrasion** (mechanical) increases with heat softening of tool material
- **Oxidation** starts near critical temperature and climbs
- **Diffusion** starts near critical temperature & accelerates with heat

Cutting Temperature/Speed

Total Wear

source: König
Cryogenic “Delta T” Applied to Tool Life

- Tool Flank Wear (mm) vs. Temperature (°C)
- Typical Carbon Steel Curve
- Critical Temp.
- 1.8x Life
- 4.5x Life
- 150°C (300°F)
Why Liquid Nitrogen ($\text{LN}_2$)?

Environmental, Health, & Safety Advantages:
- Nitrogen is an inert atmospheric gas which is 78% of the air we breath
- Very easily safeguarded with an Oxygen sensor
- $\text{LN}_2$ is not a Greenhouse gas
- Eliminates disposal, management, and infrastructure associated with flood coolants
- Contamination-free for special machining requirements like medical

$\text{LN}_2$ Is The Better Choice In Comparison To Other “Cold” Alternatives:
- $\text{LN}_2$ very effective at **low flow rates** (0.1L/edge/min.)
- $\text{CO}_2$ is a Greenhouse gas
- Small difference in bulk cost of $\text{CO}_2$ vs. $\text{LN}_2$ cannot make-up for the higher $\text{CO}_2$ pressurization & flow rates
- Oxygen is a powerful oxidizing agent with flammability risks
- “400º Difference” between conventional coolant and $\text{LN}_2$ cooling technology

<table>
<thead>
<tr>
<th>Cooling Media</th>
<th>Boiling Point</th>
<th>Approximate Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Nitrogen</td>
<td>77K [-321º F]</td>
<td>1.5 bar [22 psi]</td>
</tr>
<tr>
<td>Liquid Air</td>
<td>78K [-319º F]</td>
<td>1.5 bar [22 psi]</td>
</tr>
<tr>
<td>Liquid Oxygen</td>
<td>90K [-297º F]</td>
<td>1 bar [15 psi]</td>
</tr>
<tr>
<td>$\text{CO}_2$ (Gas)</td>
<td>200K [-100º F]</td>
<td>3 bar [43 psi]</td>
</tr>
<tr>
<td>$\text{CO}_2$ (Liquid)</td>
<td>220K [-64º F]</td>
<td>7 bar [100]</td>
</tr>
<tr>
<td>$\text{CO}_2$ (supercritical)</td>
<td>300K [80º F]</td>
<td>100 bar [1450 psi]</td>
</tr>
<tr>
<td>Flood Coolant</td>
<td>294K [70º F]</td>
<td>3.5 bar [50 psi]</td>
</tr>
<tr>
<td>High Pressure</td>
<td>Operating Temperature</td>
<td>70 bar [1000 psi]</td>
</tr>
<tr>
<td>Ultra High Pressure</td>
<td></td>
<td>150 bar [2175 psi]</td>
</tr>
</tbody>
</table>
MAG’s Cryogenic Evolution

- **Research and Development since 2003**

  - **Phase 1** development in partnership with the Small Business Innovation Research (SBIR), US Navy, and Bell Helicopter (V22 program)

  - **Phase 2** development displayed at IMTS 2010

  - **Phase 3** development in partnership with Lockheed Martin Aeronautics:
    - Focus on cost reduction for the F-35 JSF program
    - Approved for F-35 Titanium roughing; finish machining expected by Q4 2012
    - Development displayed at imX and EMO 2011
    - Seven new MAG Cryogenic machine platforms demonstrated at 2011 trade shows

- **Production ready new machines and aftermarket retrofits available now**

- **Strategic-range of Cryogenic CYCLO CUT ® cutting tools**

- **Exclusive license to the intellectual property of Creare:**
  - Multiple Creare & MAG patents issued & pending
Development and Intellectual Property:

- Expanding Intellectual Property; Cryogenic processes, tooling, spindles, & LN₂ delivery
- Machine development and integration on (7) MAG platforms (HMC, VMC, and V&H Lathes)
- Expanding application parameters for workpiece materials (Ti, Composite, CGI, Steels, Inconel)

Commercialization:

- Collaborating with strategic Customers:
  - Securing Customer sponsorship
  - Focused tool & process tests for strategic partners
- Cryogenic trade shows & displays:
  - 2010 IMTS Intro, imX learning lab, VMC 960, & HMC 1600 5 axis
  - (5) Cryogenic platforms of milling, turning, & boring of Ti, CGI, Steel, Inconel, & Composites at EMO
  - EMO innovation award
  - Gold recipient for King awards
Cryogenic System Components
(Source, Brain, Feed, Spindle, Tool)

Cryogenic Source (Dewar or Generator)

Cryogenic Liquid

Locking Ball Valve

Vacuum Insulated Feed Lines

Sartorius Scale \( \frac{\text{weight}}{\text{time}} \)

Variable Cryogenic Feed System

Cryogenic Through Spindle Delivery

Cryogenic Cutting Tool

Brain VCFS Control

Meter

On/off

Feed System
Cryogenic Spindle Technology

- **Cryogenic Delivery Through Spindle:**
  - Vacuum insulated spindle tube insures the “cold” cools the tool, not the spindle
  - Flow control behind spindle meters an engineered volume of LN$_2$

- **Excellent R&M:**
  - Long seal life
  - No thermal cycling issues
  - No affect to spindle bearings
  - Over 3 years of continuous testing

- **1st Generation:**
  - Non-rotating vacuum insulated tube
  - Axial tube actuator / valve

- **2nd Generation:**
  - Rotating vacuum insulated tube for high speed horizontal applications
Cryogenic Cutting Tools

- **CYCLO CUT® Brand**
  - Patents Issued & Pending
  - Cryogenically optimized
  - Insulated durable tooling
  - Cryogen to the cutting edge
  - Solid carbide end mills and drills
  - Indexable end mills, face mills, turning and boring tools

- CHIP FLOW MAG Cryogenic Vented, Heat-sink application

-321°F
Titanium Link Machining (imX) - Aerospace -

Application:
- Machine: VMC 960
- Material: Ti-6Al-4V
- Face, plunge, & peripheral milling, as well as drilling
- Indexable and solid carbide tools
- “Real” part manufacturing (25 links produced @ imX)

Advantages of Cryogenic technology:
- In comparison to flood coolant:
  - Up to 2X increase in processing speed
  - Improvement in tool life
  - LN₂ usage cost less than coolant
- Official JSF certified technology for “roughing” Ti
5-axis Titanium Blisk Machining
- Aerospace -

Application:
- Material: Ti-6Al-4V
- Cryogenic machining with MQL
- Tool diameter: 16mm and 18mm
- Trochoidal 5 axis milling
- Cutting speed: 72 m/min

Advantages of Cryogenic technology:
- 30% higher feed rate
- 60% increase in tool life
Titanium Facing / Turning  
- Aerospace / Industrial Equipment -

Application:
- Material: Ti-6Al-4V
- Cryogenic machining
- Cutting Speed: 450 SFM

Advantages of Cryogenic technology:
- 2X tool life compared to wet

Machine, MAG VTC2500
HMC 1600 With 5X Cryogenic Head
- Industrial Equipment -

**Application:**
- Machine: HMC 1600 5X
- Cryo delivery through tilt head (Patent Disclosure Filed)
- 1st generation 2-dewar feed system (source & pressure)
- Medium Alloy & medium carbon steel work piece
- High-feed helical milling process

**Advantages of Cryogenic technology:**
- No coolants, near dry chips
- More than three times (3X) tool life gain:
  - Only (0.012” flank wear) after 435 cubic inches
  - Manageable notch wear (see photo below)
Composite Milling and Drilling - Aerospace -

**Application:**
- Barrel Drill & Trim Machine:
  - Carbon composite material
  - Dry machining parameters

**Advantages of Cryogenic technology:**
- Control machining temperatures below resin critical temperatures:
  - Prevents melt-out as tools wear
  - Reduction of fiber pull-out increases grip load against the less affected composite fibers
  - Temporarily and locally increases composite strength to provide clean drill exit edges
- Control tool edge temperature to maintain cutter edge sharpness and prolong tool life:
  - Tool life increases in trimming compared to industry standards for dry machining
  - Drilling speed increases compared to industry standards for dry machining
Open Discussion

Entering The Cryo Age