Minimum Quantity Lubrication (MQL)

Benefits and Lessons Learned for Production Implementation

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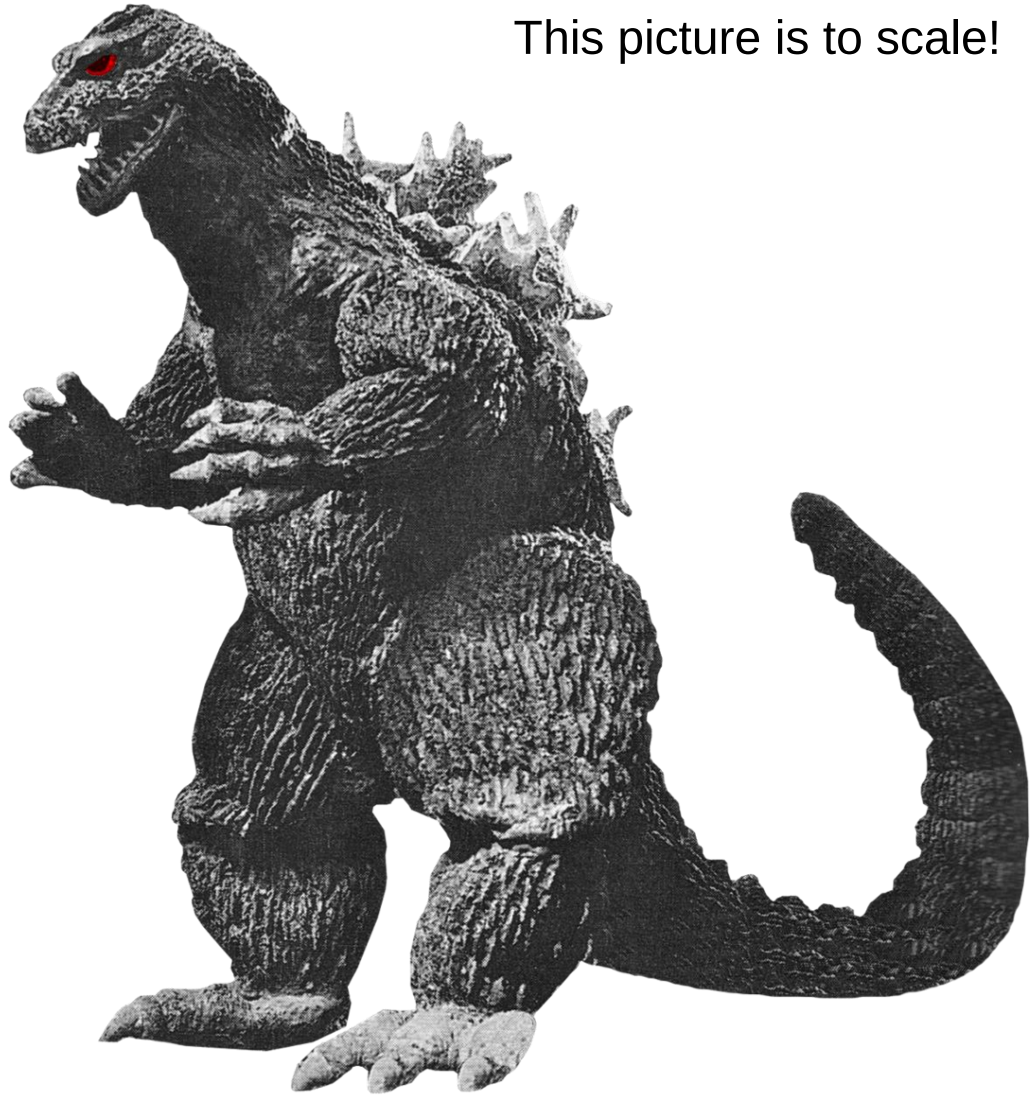
What is MQL?

- Minimum Quantity Lubrication (MQL) is just what the name implies:
  - **Minimum Quantity**: a very small amount of a fluid
    - "Minimum" varies depending on who you ask
    - DIN 69090 puts it up to 50 mL/hour of lubricant (1.7 oz./hour) and in exceptional cases up to 150 mL/hour (5 oz./hour)
    - Other have put the cap at 500 mL/hour (17 oz./hour)
  - **Lubrication**: A fluid whose primary purpose is to lubricate – not cool – and so reduce the friction between a cutting tool and the work piece
- Considered a near-dry process, with less than 2 percent of the fluid adhering to the chips

What is MQL?

This picture is to scale!



- This is much less than the 30,000-60,000 mL/hour (8 to 16 gallons/hour) typically used with flood coolants!

Why MQL?

- Three main areas of benefit: Environment-Employees-Enterprise

Help The Enterprise

- In large facilities, such as automotive production plants, MQL permits
  - Moving manufacturing cells closer together, reducing movement and transport waste.
  - Smaller cell footprints
  - Reduced cycle times
  - Lower variable costs
- Better Machine Life
  - Electronics on the machine tool controls are not adversely affected by coolant
  - Paint not destroyed
  - Coolant related corrosion eliminated

Help Employee

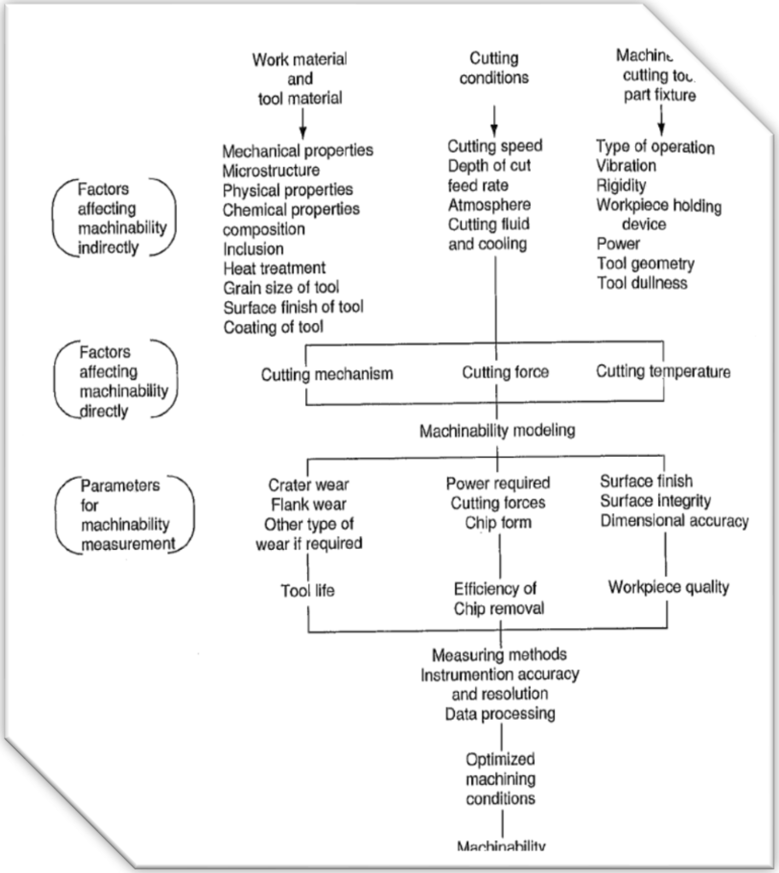
- Health and Safety
  - Eliminates dangerous, slippery floors. No kitty litter or coolant mats needed
  - Improved safety in handling parts, they are not slippery
- Reduced workforce exposure to mists
- Greatly reduced dermatitis issues among machine tool operators

Help Environment

- No cutting fluid waste.
- Reduced energy and water use.
  - Can result in a 15% lifecycle cost reduction compared to conventional high-volume water based coolant.
  - Processing waste can be greatly reduced.
    - one plant halved the energy needed to produce diesel engines (elimination of pumps, recirculation units, etc.)
    - Cut their water requirement by 99.8%.

Need to Consider Entire Ecosystem

- Machining is a complex set of interrelated operations
- Getting the most when changing from flood to MQL means more than just switching lubricators
- Tools, machine layout, cutting parameters can all be optimized

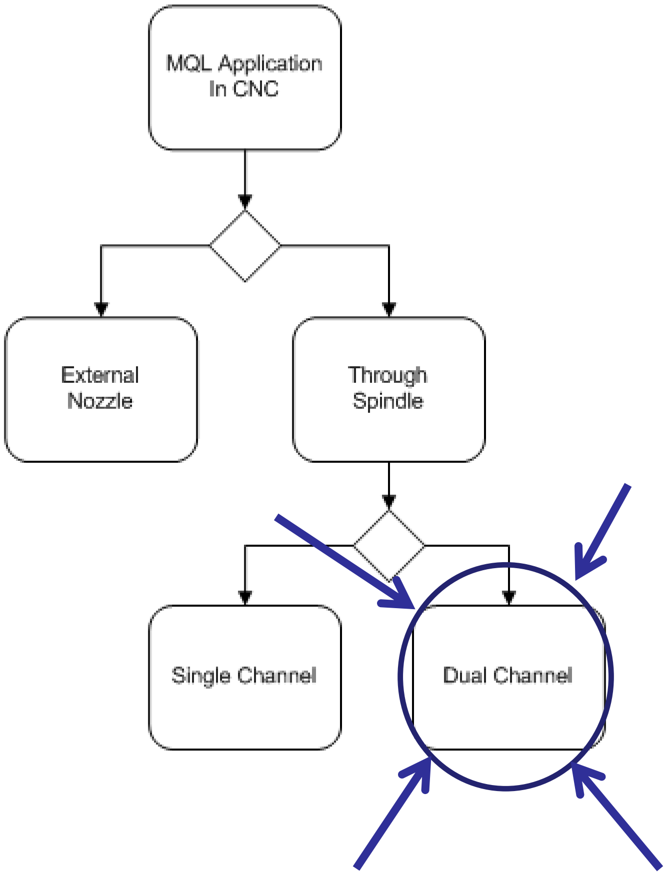


MQL Special Considerations

- Two issues where MQL application is more process sensitive than flood coolants
  - It is important ***where*** the lubricant is applied
  - It is important ***how much*** lubricant is applied

Approaches to MQL

- Several ways to apply MQL
- Today we focus on Dual Channel Through Spindle (DCTS)
- Within a CNC, this is the best technical approach
- Requires some initial planning and effort, but is worth it



Dual Channel Through Spindle?

- **Dual Channel**: Air and oil transported separately and mixed close to workpiece
    - contrast to Single Channel where the air and oil are mixed in the applicator and the aerosol is transported

- **Through Spindle**: Same as coolant, but an extra tube is put down through the center of the spindle to carry the oil

The Technical Solution

- Rate MQL system based on STAR criteria

Timely
How quickly do things start and do changes take effect?

Simple
How simple is it to implement and maintain?

Repeatable
Does the system do the same thing every time?

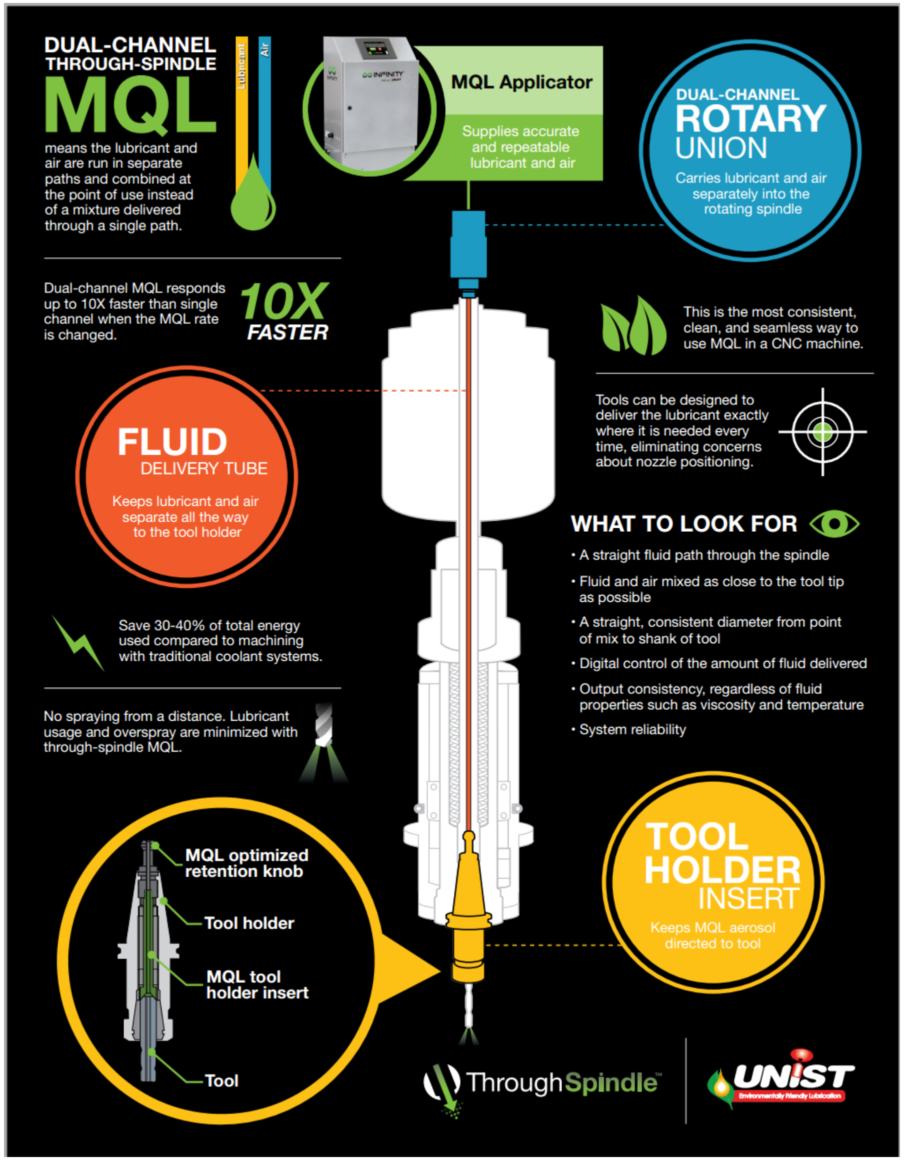
Accurate
How close is the output to the specified amount and how much get to the needed place?

The DCTS STAR

- Dual Channel Through Spindle gets the gold star for CNC's because
  - **Simple**: No operator intervention needed to adjust or select nozzle position. In essence, nozzle is built into tool. (TS)
  - **Timely**: Low response time. Do not have to wait for changes to move though tubing and spindle (DC)
  - **Accurate**: MQL delivery "where" is consistent because nozzle part of tool (TS). Best "how much" accuracy since not filtering for particle size and applied right at cut (DC)
  - **Repeatable**: MQL delivery "where" is consistent because nozzle part of tool (TS). Best "how much" accuracy since no buildup of fluid inside spindle giving more repeatable delivery (DC)

Understanding the pieces

- The Four Pieces
  - Applicator
  - Rotating Union
  - Spindle
  - Tool Holder



Applicator

- Delivers the air and the oil
- Two basic types used in DCTS

Criteria	Volumetric	Time based flow
	Volumetric pump moves piston to dispense the specified amount of fluid at the given rate	A valve opens and closes for the amount of time needed to dispense the specified amount of fluid at the given rate
Simple	• Fewer pieces, insensitive to fluid type. Sensitive to elasticity in system components.	• More moving pieces. Sensitive to fluid characteristics.
Timely	Good response time since dual channel	Good response time since dual channel

Applicator

- Two basic types used in DCTS (cont)

Criteria	Volumetric	Time based Flow
	Volumetric pump moves to dispense the specified amount of fluid at the given rate	A valve opens and closes for the amount of time needed to dispense the specified amount of fluid at the given rate
Accurate	• Volumetric accuracy inherent to pump, can be easily monitored for change.	• Assumes fluid properties do not change (e.g. viscosity with temp) • Calibration based with interpolation between points
Repeatable	Volumetric pump is very repeatable and can be easily monitored for change.	Assumes fluid and mechanical properties do not change, with limited monitoring for change.

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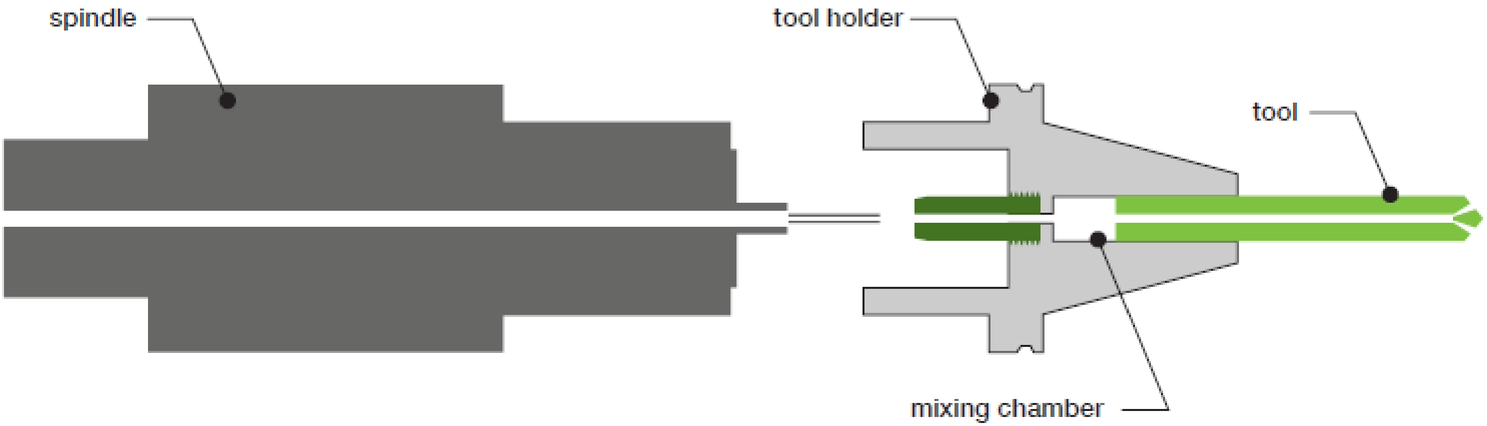
Spindle

- Spindle requires a straight shot from the rotating union to the tool holder with sufficient size in draw bar hole to allow oil tube and surrounding air flow.



Rotating Union

- Requires rotating union designed for DCTS.
- Union likely be matched to the type of applicator. The different types of applicator require different characteristics from the union to optimal performance
  - Minimize air pockets
  - Work with metering valve

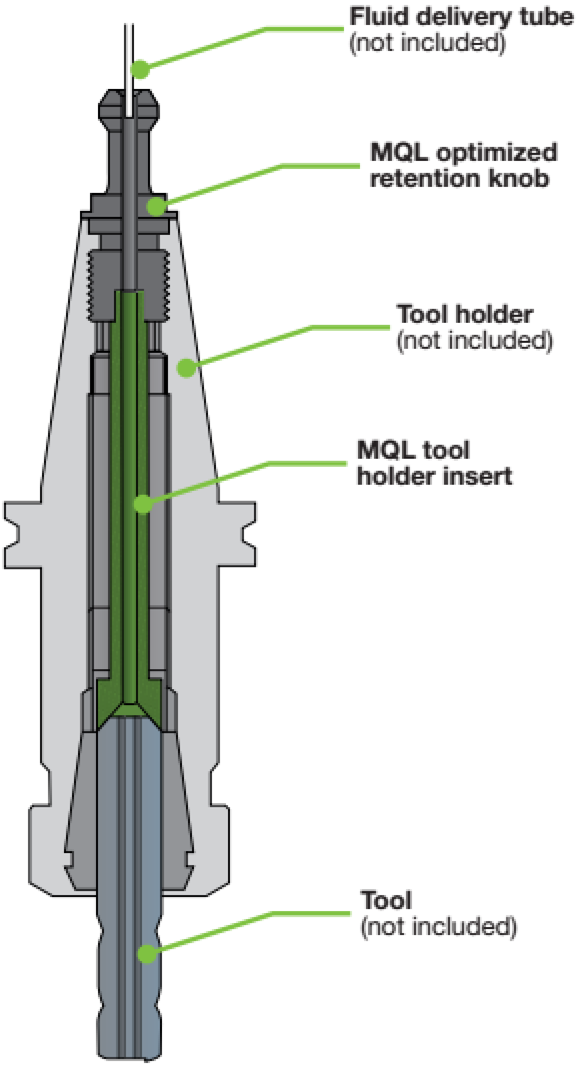
Example: *DEUBLIN* 1109 series

Example: *DEUBLIN* 1109 series

Example: *DEUBLIN* 1129 series

Tool Holder

- MQL Insert important to avoid aerosol fluid from being centrifuged away from the shank of the tool inside the holder.
- Several solutions commercially available for HSK style holders
- Talk to Unist for recommendations on CAT style inserts



Outline

- MQL at Ford—overview
- Safety
- Machine tools for 2-Channel through-spindle MQL
- Processing and dimensional control
- MQL Oils
- Tooling

MQL at Ford

- Two Channel through-tool MQL is the standard (BoP) machining method for
    - Aluminum transmission prismatics
        - Converter housing
        - Valve Body
        - Case
    - Aluminum engine heads
    - Aluminum and gray iron engine blocks
    - Cast and forged crankshafts—
      oil/cross holes and balancers

MQL at Ford

- In production since 2004
    - Livonia & Van Dyke Transmission
    - Cologne and Craiova Engine
    - Recent installations in NA, EU, India, China, Brazil
- Machine suppliers: MAG, Grob, Heller, Etxe-Tar
- System suppliers: Bielomatik 2-Channel (since 2004), UNIST Infinity (since 2017)
- Approximately 700 2-channel systems in production globally

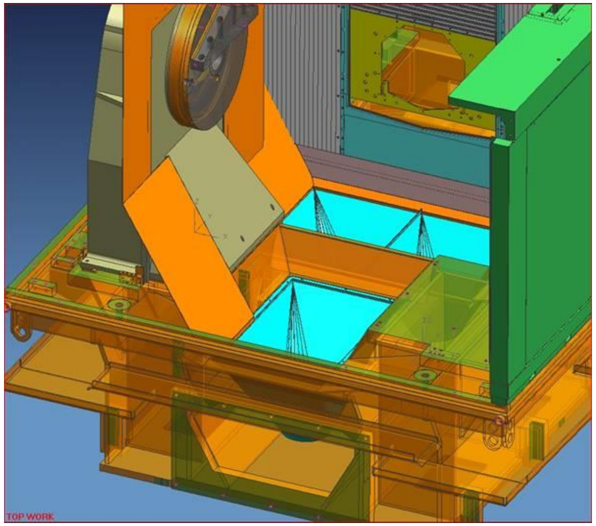


Image source: Etxe-Tar, MAG Automotive

Current MQL Installations—Prismatic Aluminum Machining

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MQL at Ford—Benefits and Challenges (2-Channel Through Tool)

- Benefits
  - Reduced operator mist exposure
  - Lower system lifecycle cost
  - Improved throughput
  - Reduced floor space
  - Reduced energy and water usage
  - Increased flexibility

- Challenges
  - HEAT
  - Machine tool design and integration
  - Dimensional control without coolant
  - Oil Effects (dosage/residue)
  - Tooling performance and cost
  - Supply base familiarity (NA)

Safety

- Potential hazards are:
  - Aerosol mists
  - Fire and explosion potential

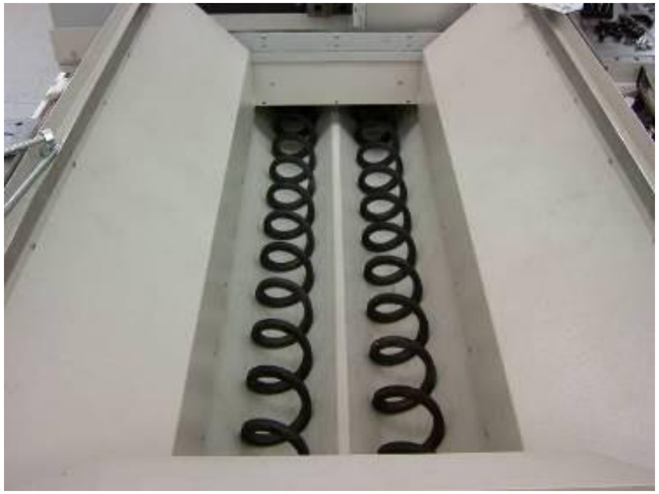
- For mists (also a concern for water-based coolants)
  - Use in well ventilated area
  - For higher volume applications, enclose machines with negative internal pressure, use HEPA mist filter
  - Risks associated with mists are summarized in NIOSH 98-116 (1998)

- For fire/explosion protection (especially for Al)
  - Standard precautions for neat oil machining in lower volume applications
  - For high volume production, use dry filter with spark detection and fire suppression
    - Dry filter systems also generally provide mist filtering

Machine Tools for Two-Channel MQL

Machine Tools for Two-Channel MQL--General

- Should be designed as a dry machine
- Steep vertical walls
- Open bed to chip drag
- Auger/gravity chutes to move chips
- Avoid protruding bolts, exposed piping and wiring, anything that can grow a “beard” of chips
  - **Also applies to fixtures**
- Stainless steel or specially painted internal walls to reduce oily chip adhesion



Machine Architectures—A Axis

- Horizontal Spindle for maintenance and untended operation (automotive standard)
- A-axis permits rotation to dump chips and suspended (upside down) machining for chip clearance

Image source: Grob

Machine Architectures—B Axis

- B-axis HMCs are also widely used for MQL applications
  - Often with W-axis and ram spindle
  - Good for overhead gantry loading
  - Good for deep hole drilling and internal feature boring/milling
- Same rules regarding protruding bolts exposed piping, etc. apply—B-table increases the engineering challenge
- In high feed operations, often need to account reduced compliance at top of part

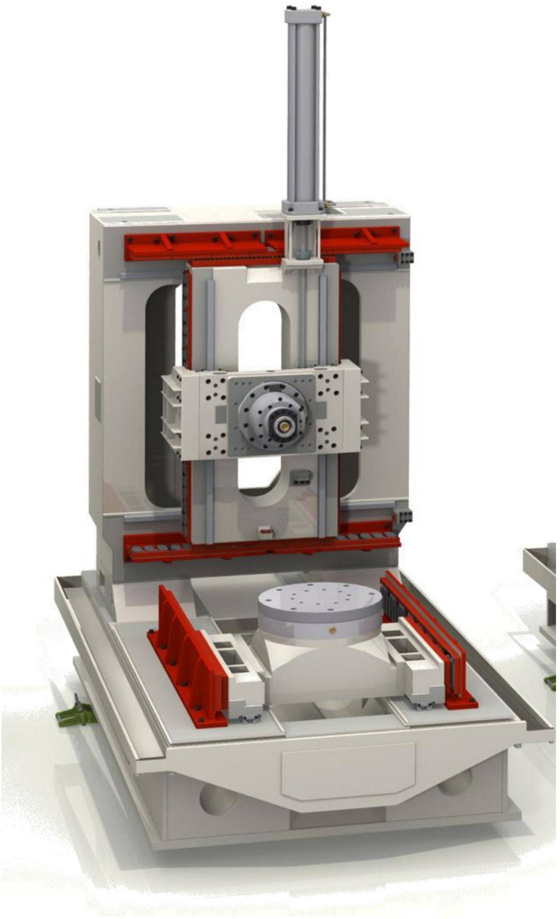
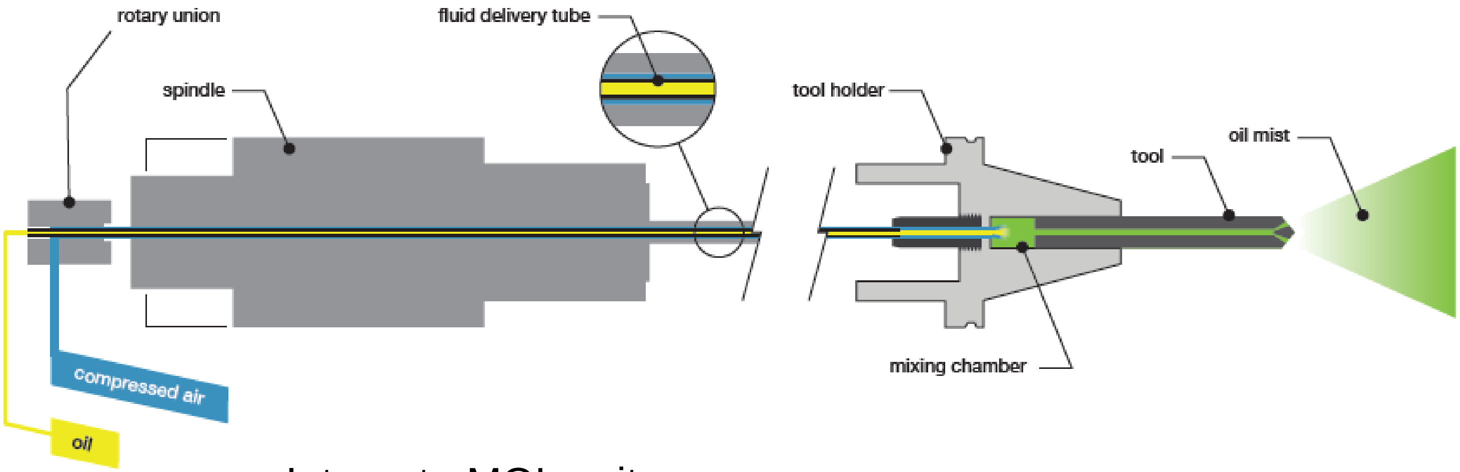


Image source: MAG Automotive

Machine Modifications For 2-Channel MQL implementation

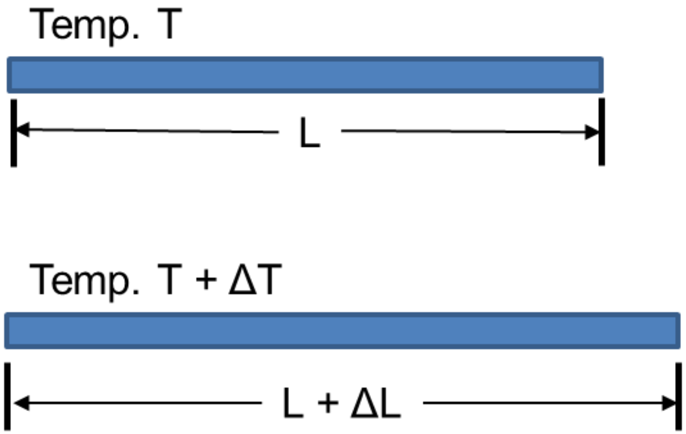


- Integrate MQL unit
  - Mount somewhere, usually near back end of spindle
- Special rotary union and lance
  - Rotary union must be two-channel, able to run dry (w/o coolant bleed-off)
  - Lance from rotary union to toolholder must match spindle length
- Controls Integration
  - M-codes to turn MQL on/off
  - Disable coolant pressure faults

Machining Process Design and Dimensional Control

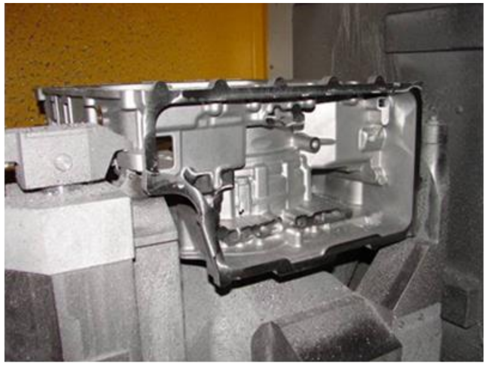
Machining Process Design and Dimensional Control

Major issue is **thermal expansion in the absence of coolant**



$\Delta L = \alpha L \Delta T$

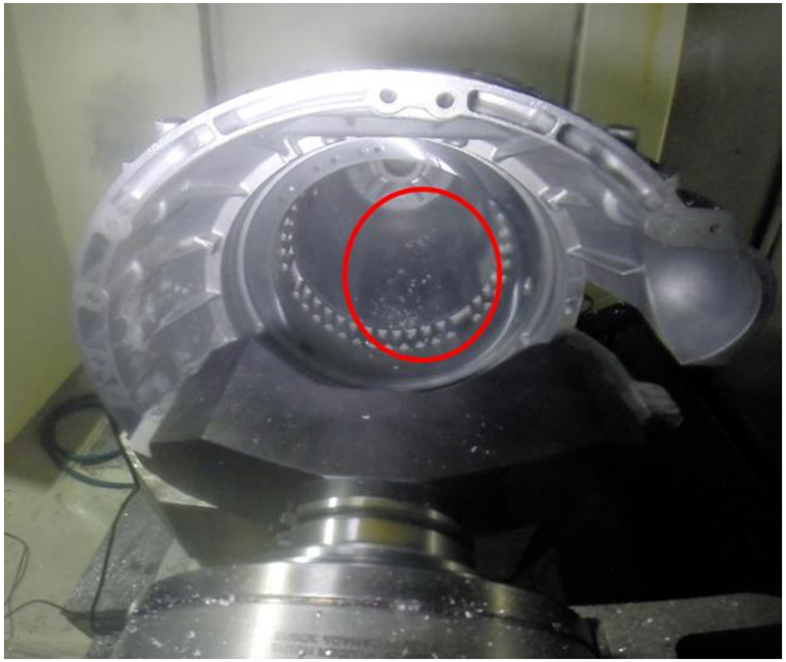
α = thermal expansion coefficient (μm/m/C)



- **Example: manufacturing hole separation, transmission case**
  - Nominal locating hole separation 40 cm
  - **Aluminum part, expansion 22 μm/m/C**
  - 10 C temperature variation changes hole separation by 88 μm

Sources of Heat Buildup in Machined Parts

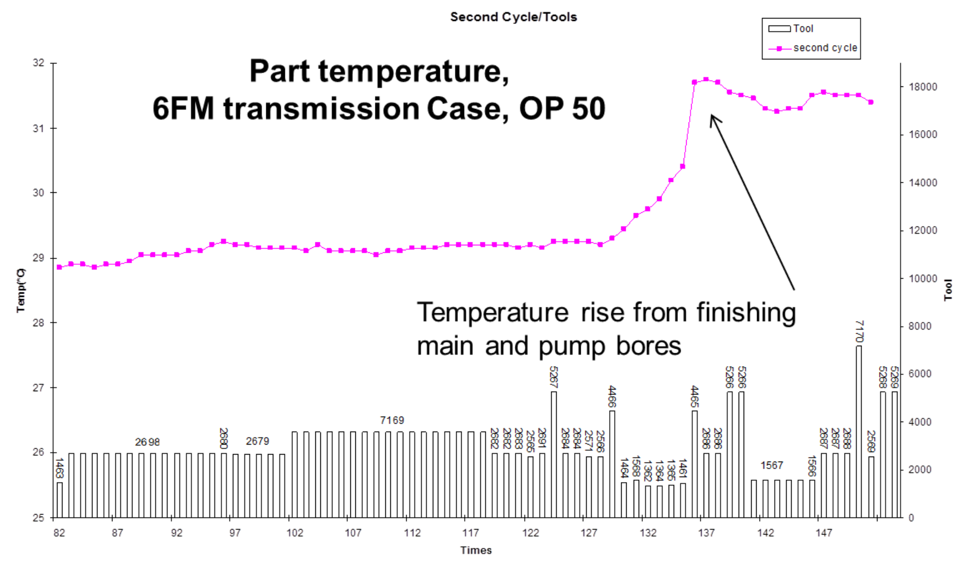
- Ambient temperature variation (not process)
  - am to pm
  - Summer to winter
- CHIPS IN CONTACT WITH PART
  - Internal bores and features
  - Chips in drill flutes
- Roll form taps
  - – Cut taps produce a chip which remove heat
  - – In roll form tapping, most deformation energy goes into part
- Low speed or high flank wear processes
  - – Center of drills
  - – Abrasive workpiece materials
- Order of operations
  - – Do high heat operations at end of cycle when possible



Chips in part after early test on RWD transmission main bore

Dimensional Control Strategies—Part/Process

- Use higher feeds in drilling to reduce heat in part
  - Minimize time in part and time for chips in flutes to contact part
- Reduce content per operation and increase number of operations to limit part heating
  - Current trend is in the opposite direction—fewer setups for quality
- Perform high heat cuts at end of operation to avoid dimensional changes in early steps



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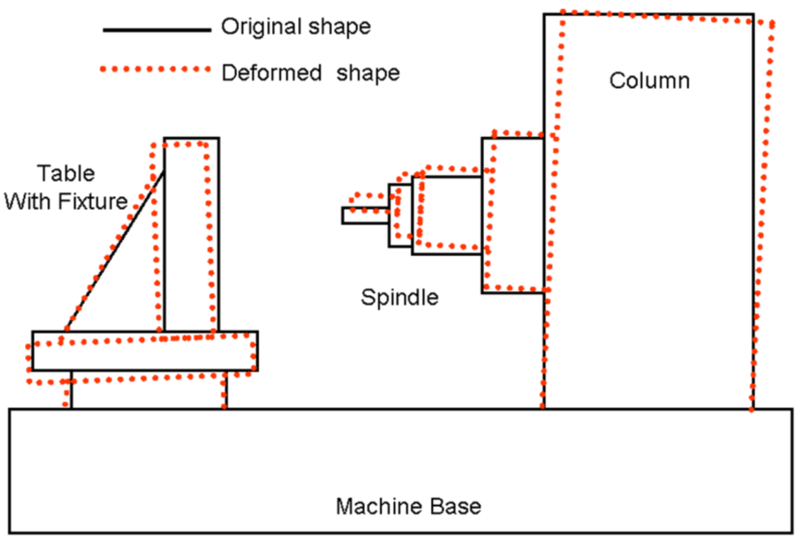
Dimensional control strategies—Machine/Fixture

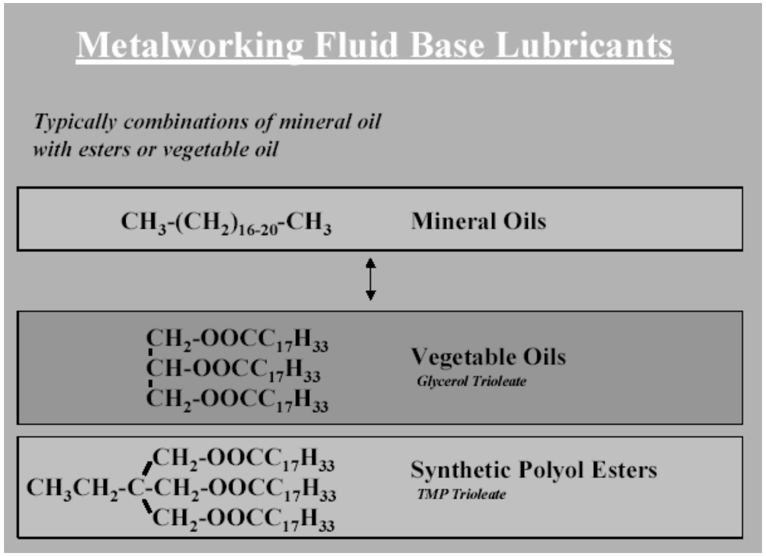
- Machine Tool Design
  - Open bed, steep walls
  - Thermal isolation of some structural elements
  - No protruding screws etc. to catch chips
- Thermal compensation of machine
  - Requires machine sensors and algorithm
- Part temperature control (cooling between OPS)
  - Limit on part temperature for cycle start
  - Requires waiting periods and/or cooling tunnels, discipline
- Air tempering in plant
  - Basically a requirement for high volume aluminum parts
  - Also done for wet (non-MQL) plants



MQL Oils

MQL Oils--Requirements

- Oils must have high lubricating ability, since only a small amount is used
- Must be nontoxic and biodegradable, since they are released into the manufacturing environment, and not collected
- Ford specifications:
    - Viscosity between 20 and 100 mm^2/s at 25 C
    - Flash point > 160 C
    - Ignition Temperature > 450 C
    - Lower explosion limit > 20 g/m^3
- Requirements generally drive use of vegetable-oil based lubricants (due to biodegradability and high molecular weight)



Representative mineral oil, vegetable oil, and synthetic ester chemical structures

Image source: Quaker Chemical

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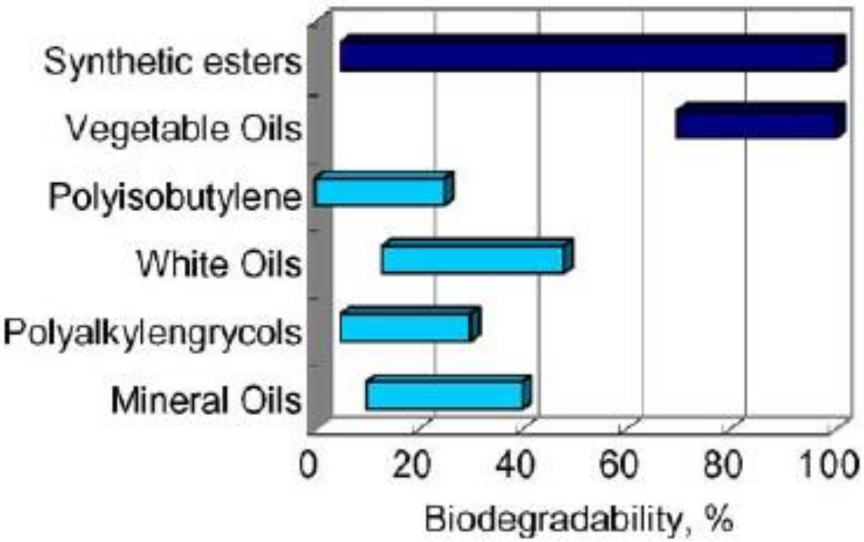
MQL Oils—Synthetic Esters

- Usually derived from vegetable oil stocks
- Relatively high molecular weight, viscosity, and flash point
- Good lubricant (due to high viscosity/MW)
- Relatively little evaporative cooling effect, increased tendency to leave residue
- Increased tendency to clog washers (due to chemical reactions with washer fluid or chip drag-in)
- In the past, recommended for applications requiring primarily lubricity (e. g. aluminum machining)
- Used for all early Ford MQL applications

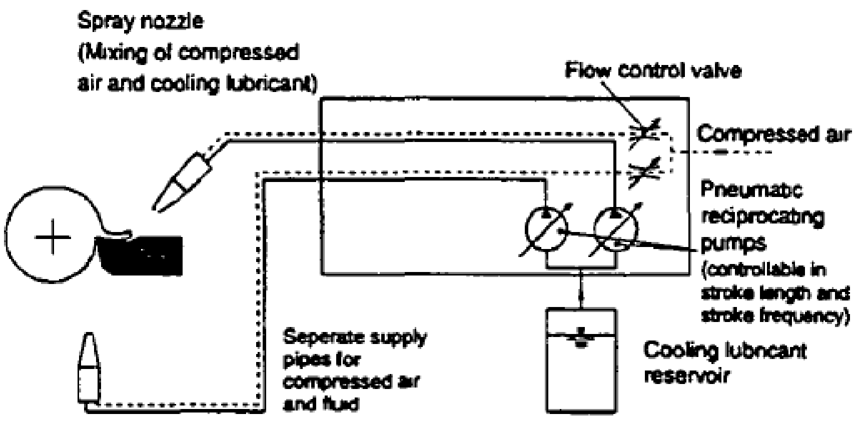


Biodegradability of oils investigated in early Japanese research

Image source: S. Suda et al, “A Synthetic Ester as an Optimal Cutting Fluid for Minimal Quantity Lubrication,“ *CIRP Annals* **51** (2002) 95–98

MQL Oils—Fatty Alcohols

- Usually derived from vegetable oil stocks
- Lower molecular weight, viscosity, and flash point than synthetic esters
- Less effective lubricant
- Provides more evaporative cooling, has less tendency to leave residue on part
- In the past, recommended for applications requiring cooling as well as lubricity (e. g. cast iron machining)
- Used in recent Ford applications (since roughly 2016), can be used for both iron and aluminum parts

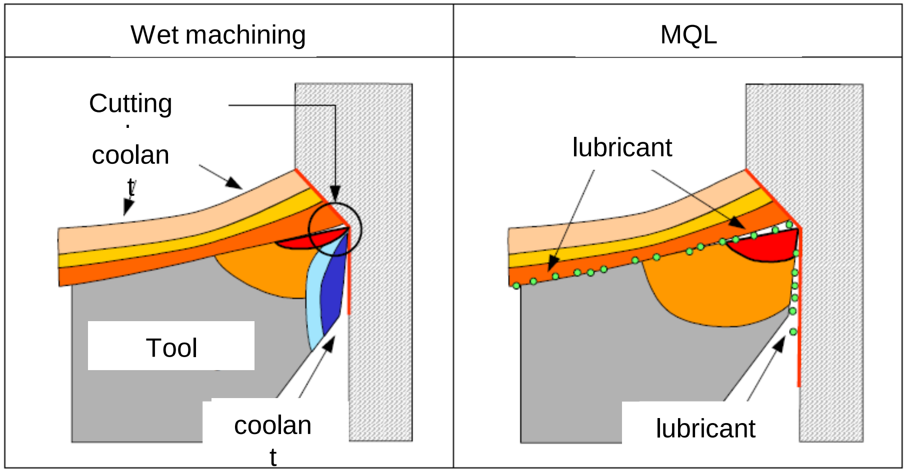


TU Stuttgart two-nozzle single channel system, c 1993

Image source: U. Heisel et al, “Application of minimum quantity cooling lubrication technology in cutting processes,“ *Prod. Eng.* **II/I** (1994) 49–54

MQL Oils--Dosage

- Objective is to consume oil entirely in the process—no residue on part or chips
  - No wasted oil
- Currently MQL rates are set largely by experience based on tool size (e. g. drill diameter—25-40 ml/hr for M8, etc.) and material
  - Little guidance from system suppliers and standard handbooks
- **The "M" in MQL is unknown**

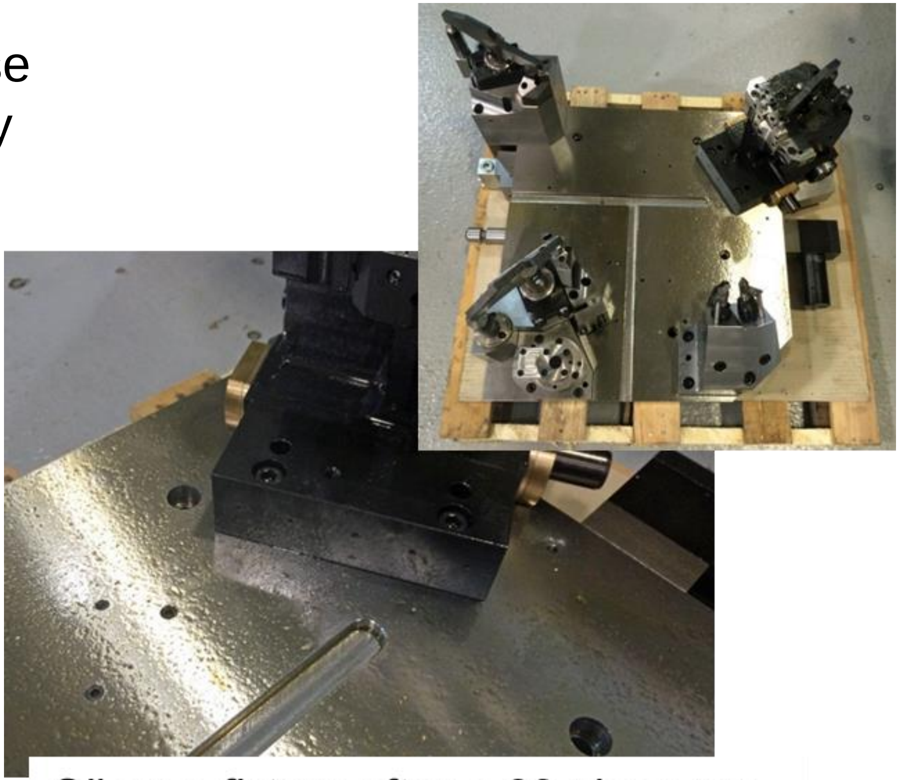


- In wet machining, a large volume of a dilute lubricant floods the system
- In MQL, a small, targeted volume of concentrated lubricant is delivered to the cutting edge, reducing friction, buildup, and heat generation

Image source: Komet Gruppe, *Handbuch Minimalmengenschmierung*

Consequences of High Oil Dosage

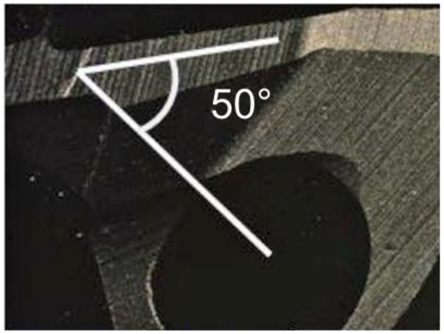
- Oil buildup and caking in the workspace
  - Oils are biodegradable, so these are the end products of a decay process
- Residue on part
- Clogged or damaged filters in washers
- Oily chips—may need to be pressed before transport
- Dimensional errors and misloads due to chips on locators
- Damage to spindle socket due to chips trapped between taper and socket

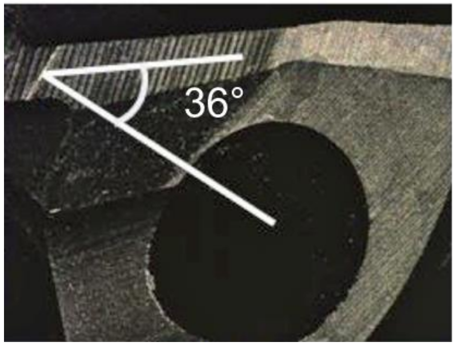


Oil on a fixture after a 30 piece run

Causes of Variation in Dosage levels

- Lack of physical understanding and well-defined method to select oil level
- Calibration variation
- **Uncontrolled variation in tooling**
  - Position, condition, and size of MQL delivery ducts (coolant holes)
  - Variation in drill point grinds, especially for resharpened drills
  - Variation in tooling assemblies (transfer pipes and adjustment screws)
- Need to solve production problems for delivery
  - Increasing the oil is often the only knob to turn
  - Once turned up, oil is never turned down





Variation in coolant hole position relative to cutting edge for two nominally identical production drills

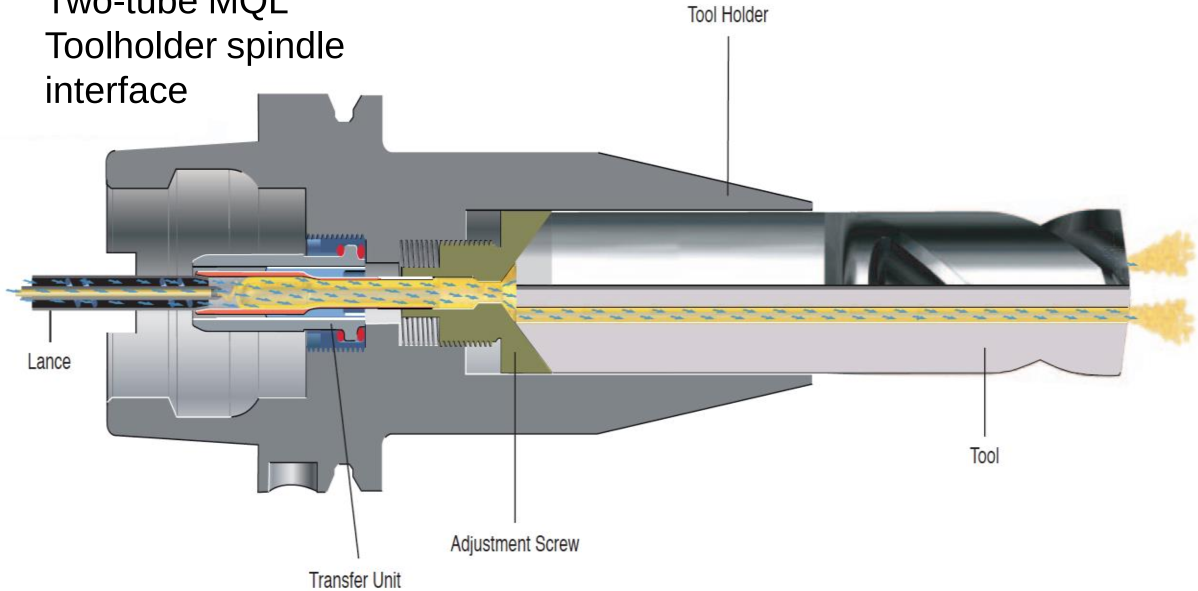
Tooling

Tooling

- Differences between MQL and Wet Tooling
  - Interface connection point
  - Premium materials / Premium geometry
  - Intricate internal geometries

MQL Toolholder Interface

Two-tube MQL Toolholder spindle interface



90 deg cone MQL shank interface

Toolholder used for two-channel through-tool MQL require special tooholder interfaces for:

- Proper mixing of MQL mist
- Robust oil delivery with multiple tool changes

Proper tool shank interface also required—Ford PTO uses 90 deg cone interface.

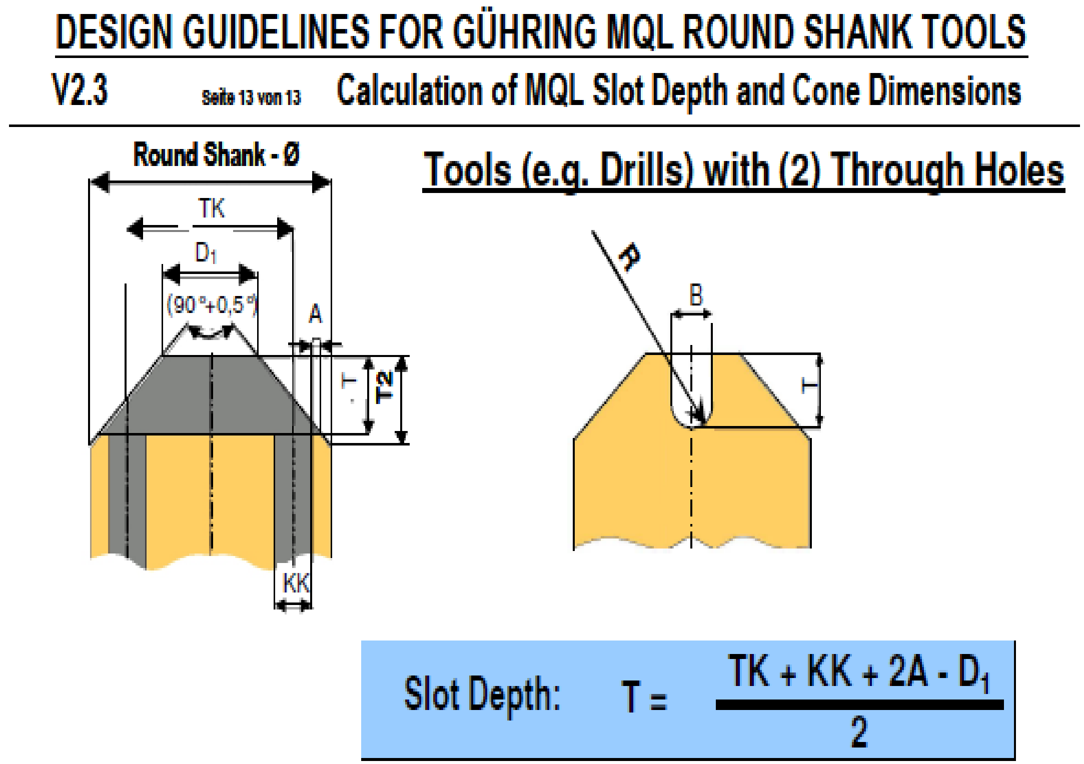
Standards:

- DIN 69090-1:2011-12—toolholder components
- DIN 69882-8**,** DIN 6535 Form HA—cone shank interface for shrink fit

Image sources: Bielomatik, Gühring

Shank Interfaces

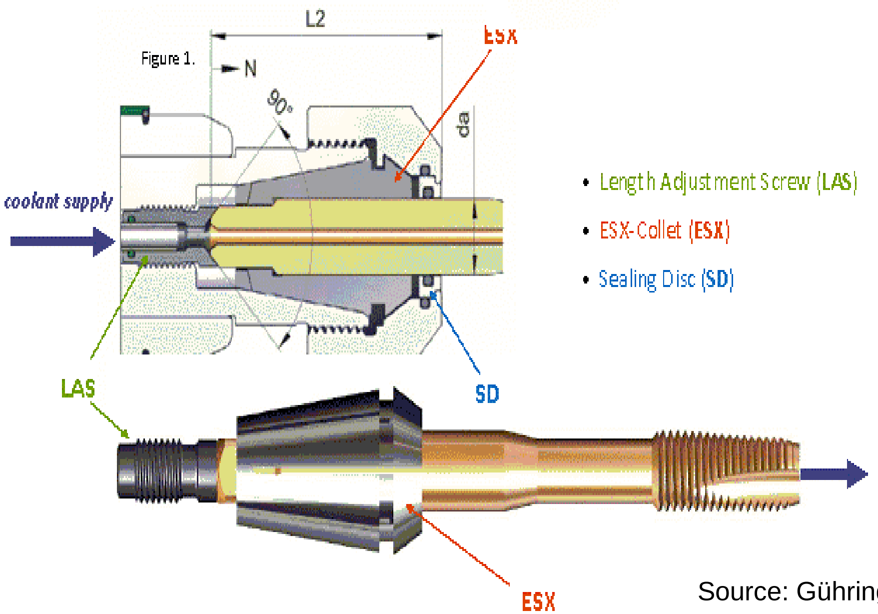
- Holes should be centered in the slot
- Slot width should not vary tool-to-tool



- Dimensions vary with diameter
- No slot required for tools with single central coolant hole

Taps (for Through Tool MQL delivery)

- Bottoming taps for blind holes may have a single central coolant hole exiting at the end
- Chamfer taps for through holes should have radially directed coolant channels (often 90 deg from axis) with central hole plugged
- Cut taps should have higher relief angles, higher back taper, and narrower lands than wet taps to reduce friction and heating
- Form tap thread form should be designed for MQL (lower friction)
- May need special toolholder elements to seal collet and adjust length (supplier specific)
- Torque lower than for wet tapping due to improved lubrication



Source: Gühring

Material Requirements—Tooling Substrates for Dry/MQL machining

- Compared to wet tooling, MQL tooling is subjected to
  - Higher temperatures due to lack of coolant
  - Higher stresses due to more aggressive cycles
- In aluminum MQL, this drives the use of micrograin carbides for strength and heat resistance for drills and reamers
  - Still primarily unalloyed (ISO K) or lightly alloyed (ISO P) substrates
- For ferrous MQL, fine grain carbides are used, as well as new hardened metal (ISO H) or superalloy (ISO S) substrates

Greatest Hardness		
Ferrous Metals (Long Chips)	P01	Finishing
	P10	
	P20	
	P25	
	P30	
	P40	
	P50	Roughing
Ferrous Metals (Long or Short Chips)	M10	Finishing
	M20	
	M30	
	M40	Roughing
Ferrous Metals (Short Chips)	K01	Finishing
	K05	
	K10	
Nonferrous Metals	K20	
	K30	
	K40	Roughing
Greatest Toughness		

Traditional ISO carbide grades

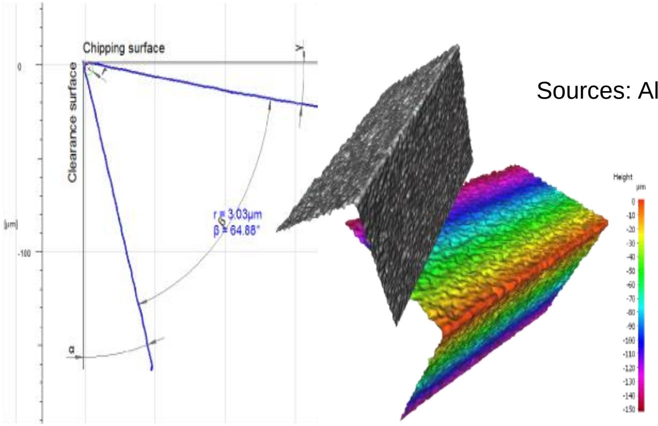
- P ISO P = Steel
- M ISO M = Stainless steel
- K ISO K = Cast iron
- N ISO N = Non-ferrous material
- S ISO S = Heat resistant super alloys
- H ISO H = Hardened materials

New grade system from 2012 standard (ISO 513 2012)

Sources: ToolingU.com, Sandvik

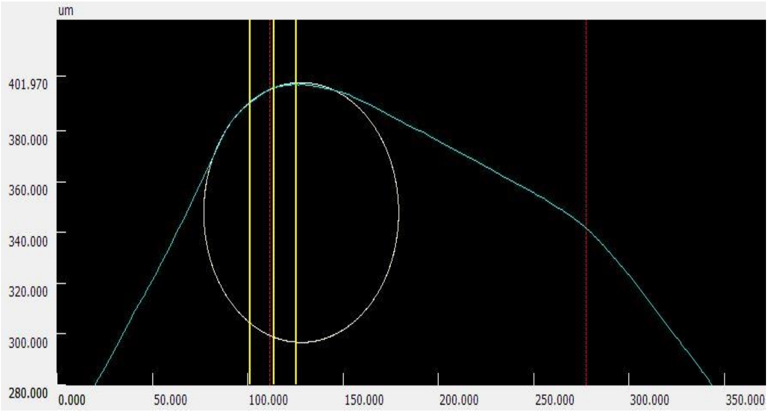
Edge Preparations and Surface Finish

- For aluminum, generally want:
  - Up-sharp edge
  - Uniform edge preparation across edge
  - Polished flanks—remove electrodischarge machining slag on PCD (Polycrystalline diamond) edges
  - Finest grain size (especially for PCD)
  - For drills, polish flutes to prevent chip adhesion and buildup
- For ferrous MQL
  - Generally honed edge
  - Chamfered edges used on some ferrous MQL drills
  - Uniformity of edge not as critical



Sources: Alicona,

Uniform, up-sharp PCD edge

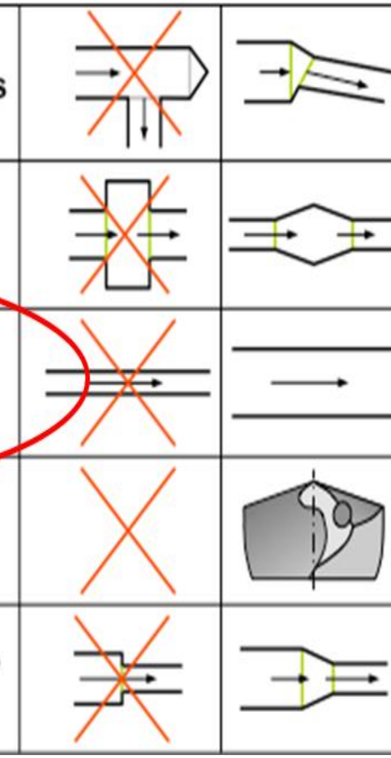


50 µm honed edge on a valve seat blade

Internal Coolant passages for Multidiameter tools—General Rules

- Air flow is critical in MQL
- Internal coolant passages must be more carefully designed in MQL than wet machining
  - 1000 psi water overcomes most obstacles
- In principle, need larger coolant hole diameters in MQL than in wet machining
- Handbooks recommend a minimum passage diameter of 0.5 mm for two-channel MQL
- **Ford experience: minimum is 0.6-0.7 mm (for straight rod, no branching)**

No right-angled coolant hole outlets with step tools
No reservoirs, in which separation takes place
Diameters of the coolant holes are dependent on the lubrication system, as in principle large as possible
Cooling ducts in such a way position that an optimal wetting of the cutting edges is ensured
Variations of the inner diameter of the coolant hole with conical transition



Source: Komet

Internal Coolant Passage Manufacturing Methods

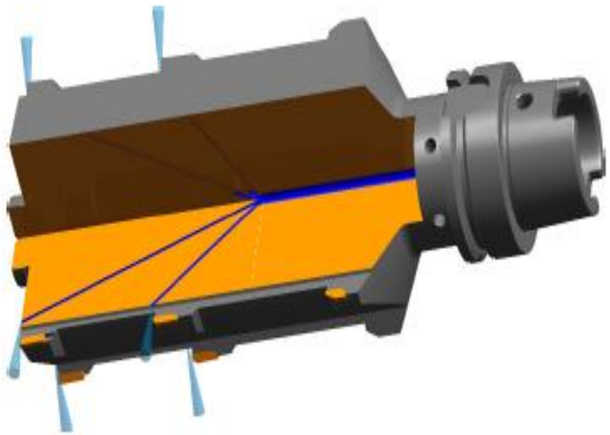
Image Sources: Gühring, HB Carbide, Komet

Extrusion

- Standard carbide rod
- Used for simple drills
- Most repeatable
- Blanks are engineered for stress

Perform drilling (carbide)

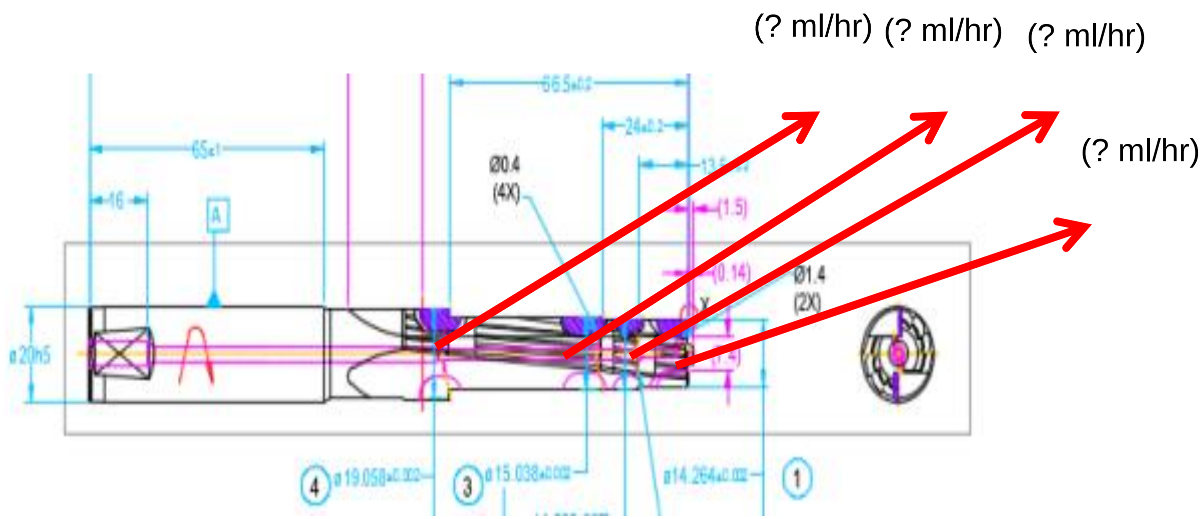
- Holes drilled in carbide preform prior to sintering
- More variation due to drilling variation
- Shrinkage and flaking concerns also need to be taken into account



EDM (steel or carbide)

- Holes machined by EDM (after sintering for WC tools)
- More variation due to EDM process

Oil Balancing—Multidiameter Tools



- How much oil is distributed to each of the 8 cutting edges?

- For multidiameter tools (cutting different diameters at different axial levels), internal passage angles and diameters must be properly chosen to ensure oil delivery to all edges
  - Standard water-based tooling not designed for compressible gas lubrication (1000 psi water overcomes most design flaws)
  - Ideally want to dose oil at each edge based on metal more oil at the front, less for clearance or countersink cuts
  - Improper balancing leads to buildup and premature tool failure

Thank you