Machining of High Strength Metals by Use of Cryogenic Cutting

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Motivation for Sustainability in Machining Processes

- Environment and health benign technologies are becoming important for achieving cleaner, healthier and safer machining.

- Problem and motivation:
  - Trend of HSM – higher temperatures affecting both cutting tool & part.
  - Development of CLF (Cooling Lubrication Fluid) and thermal management – inevitable and emerging R&D direction.
  - **UNSTAINABILITY FACT** – Industry is widely using conventional oil-based CLF to counter the extremely high levels of heat generated in the cutting zone, even they are environmentally unfriendly, health hazardous and relatively costly.
  - Total machining costs: 15% – CLF, 4% – tools.
  - Dry machining – huge process gain from sustainability point of view, however….
  - Nowadays extremely hard-to-machine materials are frequently used, not allowing dry machining (high-temp alloys: Nickel alloys, titanium alloys, Co-Cr, etc.).

→ Cryogenic machining
Cryogenic Machining

Cryogenic machining presents a process where cryogenic cooling media (LN) is used and delivered to the machining process instead of oil based emulsions.

In fact 78% of air that we breathe is N₂.

- N₂ is safe, noncombustible, noncorrosive, colorless, odorless and tasteless gas, with nonreactive (inert) nature:
  - Molecular weight: 28.01
  - Boiling Point: -195.8°C
  - Liquid to gas expansion ratio: 1:693
  - Liquid density: 808.5 kg/m³

Exposure to liquid nitrogen or cold nitrogen gas can cause severe burns.
High concentration of nitrogen can create an oxygen-deficient atmosphere in a confined area.

Conventional vs. Cryogenic Machining

Conventional phases:
- Machining
- CLF related labor
- Part cleaning
- Part corrosion protection
- Swarf preparation
- Disposal
- ...

Cryogenic phases:
- Machining
- CLF related labor
- Part cleaning
- Part corrosion protection
- Swarf preparation
- Disposal
- ...

Cryo benefits:
- Economical part with prolongation of tool-life.
- Increase productivity by increase of material removal rate.
- Machining performance with offer of machining hard to machine alloys.
- Sustainability in machining by: cleaner, safer, environment friendly, and more health acceptable technology.
Setup - Developed Cryogenic Machining System

- Active phase separator
- System for disconnection/connection of delivery
- Machine tool
- LN delivery
- Cutting insert
- Vacuum insulated delivery pipe
- LN storage Tank - “Dewar”
- Computer controlled system

Tool life and temperatures (INCONEL 718)

- Graph showing tool life and temperatures for different conditions.
Surface integrity – Inconel 718

- Residual stress measurements on and beneath the surface (in hoop and axial directions), machined under different CLF conditions:

![Graph showing residual stress measurements](image)

- In cryogenic machining more compressive residual stresses were obtained (lower thermal loads).
- Thicker zone of compressive RS are achieved in cryogenic machining.

Machining performance – bearing steel 100Cr6

- Technological windows – tool-material-pair for turning normalized (left, carbide tool) and heat treated (right, CBN tool) bearing steel AISI 52100:

![Graph showing technological windows](image)

- Cryogenic machining enlarge the technological windows: higher $v_c$ and $a_p$.
- Assuring desired surface roughness/integrity characteristics at higher productivity.
- Improves the surface integrity even in hard machining of bearing steel (63 HRc) – more compressive residual stresses on and beneath the machined surface.
Machining performance – Porous tungsten

- Infiltrant vs. cryogenic machining (right – desired unsmeared surface with uniformly distributed open pores, left – unacceptable surface with smeared pores).

- Material: Tungsten, Nickel, Molybdenum, etc.
- Machinable features: ±0.05 mm
- Operating temperature: from 810°C to 1300°C
- Porous tungsten impregnated with 6.5 Si/CaO/CaCO₃ (briar) based mixture enhancing material

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Machining of valve seats – automotive industry

- Determination of technological windows:

<table>
<thead>
<tr>
<th>Material A, cryogenic vs. conventional</th>
<th>Rake angle (°)</th>
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<tr>
<td></td>
<td>-3°</td>
</tr>
<tr>
<td>f (mm/rev)</td>
<td>Flood</td>
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<tr>
<td></td>
<td>++</td>
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<td>q (mm)</td>
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Range increase of cutting parameters depending on the cooling lubricant and rake angles:
- "": equal
- "++": until 2 times
- "+++": 2 times and more
- "++++": 3 times and more.
LCA (machining of Inconel 718 bars with carbide tools)

- Life cycle assessment of cryogenic machining process (left) and energy consumption of the process if cutting tool production (sintering process) is taken into account (right).

There is a threshold where cryogenic machining can be also energy efficient, while we know that nitrogen extraction of nitrogen in the air is very energy intensive process.

Influence on LN₂ on friction conditions

- Experimental measurements of friction in turning process and how is this affected by the application of cryogenic fluid/temperatures:

ENISE, Laboratoire de Tribologie et Dynamique des Systèmes, prof. dr. J Rech, France
**Lubrication of LN₂ in contact of carbide tool with Inconel 718**

- **Friction coefficient between an Inconel 718 alloy and a TiN coated carbide pin and wear debris**
- **Heat flux transfer through the pin-holder between a Inconel718 alloy and a TiN coated carbide pin**

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**SusCryMac (2009-2012)**

- Development of novel/innovative Sustainable Cryogenic Machining system/technology.
- Project within the E! 4550 – PROFACTORY, sponsored by the EUREKA initiative.
- Development of sustainable cryogenic technologies that can be accommodated over different machining operations.
- Evaluation of cryogenic machining in various industrial case studies.
- Identification of research/application demands and future industrial opportunities.