Cryogenics in Machining

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Cryogenic fluids in machining

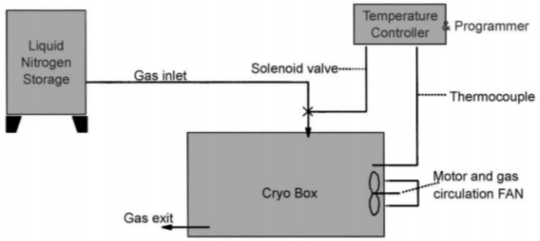
Cryo-fluids (N_2 and CO_2) have 2 main employs:

1. can be used as media for thermal treatments of tools and parts before machining
   - Shallow or Deep cryogenic treatment
2. can be used as cooling agent while machining
   - Rough or finish turning, milling, grinding

Shallow cryogenic treatment (SCT)

The shallow cryo-treatment hardening effects are limited to the surface, and do not reach the core of the treated part.

- The piece is cooled down at *-196 Celsius* degrees for at least *5 hours*, and then is brought back to room temperature
- Temperature must be precisely controlled



Cryo-thermal treatments can be performed both on WC tools and on HSS

Deep cryogenic treatment (DCT)

Similar to the SHT, the effects on the part are deeper because of a longer exposition to cryo-temperatures:

- Cooling down of the piece to -196 Celsius degrees in 4÷10 hours;
- Keeping of the piece at -196 Celsius degrees for 6÷40 hours;
- Warming up of the piece to ambient temperature (or also above if another heat treatment is required) in 4÷10 hours

Comparison between 2 inserts with same geometry:

- **Insert 'L'** – sintered WC with TiAlN coating (4 µm)
- **Insert 'LC'** - sintered WC with TiAlN coating (4 µm) and DCT treatment

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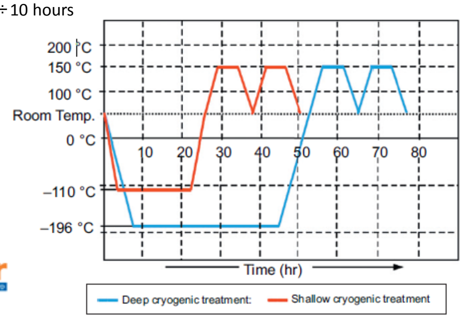
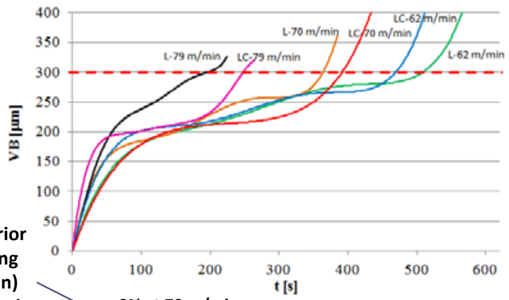


Deep cryogenic treatment (DCT)

Surface hardness test results
- Insert 'L': 2037 HV
- Insert 'LC': 2259 HV

About 10% of improvement

Experimental turning plan
- Vc=62;70;79 m/min
- f=0,3 mm/rev
- b=1,5 mm
- 2 replicates
- Oil-Water emulsion 5%
- Material: Ti6Al4V bars



Cryo-tools offer superior tool life at high cutting speeds (70-79 m/min) compared to untreated ones

+9% at 70 m/min
+30% at 79 m/min

Machining with a cryogenic cooling system

1. **Cryo-Machining is dry**
2. **Cryo-Machining reduces the temperature in the cutting region**

- Improvement of tool life, specially for low thermal conductivity materials (i.e. Ti-alloys, INCONEL)
- Increased performance in terms of MRR especially in hard to cut materials

Roughing

- Avoiding of chemical diffusion wear
- Improvement of surface
- Reduced residual stresses on the workpiece

Finishing

- Environmental safe machining
- More value for the chip when reselled

Environmental sustainability

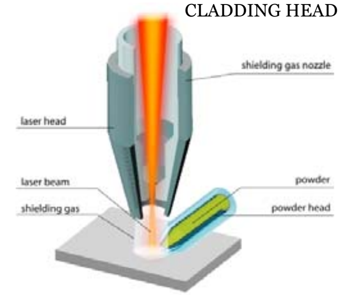
Cryogenic-fluids for hybrid processes

Liquid nitrogen or carbon dioxide can replace the conventional cutting fluid if it is necessary the maximum cleaning of the workpiece for successive process steps

Hybrid machining subtractive / additive with laser powder deposition

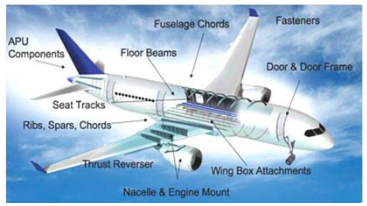
The metallic powder deposition process need to work on clean surfaces to melt powders and base-material

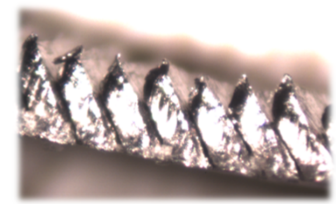
For hybrid machining the subtractive phase can be cooled by cryo-fluids to avoid oil-dirty surfaces and optimize A.M. process



Grade 5 Titanium (Ti6Al4V)

Aerospace industry employs about 80% of Titanium production





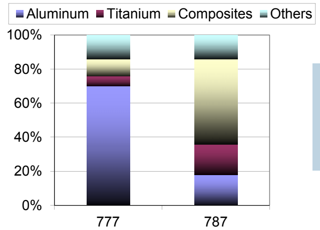
Excellent mechanical properties
- Yield strength: up to 1200 MPa
- Low density (4500 kg/m^3) but high specific resistance 288 kN·m/kg (254 kN·m/kg for steel)
- High elasticity: Young modulus of 110 GPa
- Biocompatibility
- High fatigue resistance, high resistance to thermal stresses

Hard to machine material
- Low thermal conductivity, high temperatures and tool-workpiece chemical diffusion phenomena
- Serrated chip and instability of cutting forces
- Reduced tool-chip contact zone and high stress concentration on a small area

Machining of Ti-6-4

High Buy-To-Fly ratios (from 5:1 to 20:1) are typical of aeronautic industry → Roughing operations represent the most important cost

High productivity is required!



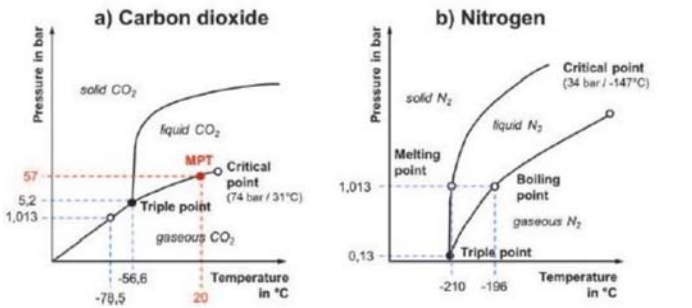
Example 787 - Machining
Raw Material: 90.728 kg
Fly Away: 11.340 kg
→ buy to fly of 8:1

	Roughing	Finishing
Vc	35-70 [m/min]	80-100 [m/min]
f	0.2- 0.4 [mm/rev]	0.1-0.2 [mm/rev]
b	1.5-2 [mm]	0.25 [mm]

Very low cutting parameters with respect to steel and aluminium

Cryogenic machining: N_2 vs. CO_2

Substitution of traditional oil-water emulsion with a liquid gas jet localized in the cutting zone



Experimental setup for turning tests

Inserts CNMG 12-04-08 SMR 1115 WC with TiAlN (2 μm) + AlCrO (1 μm) coating layers

Main cutting angles

- Entry angle κ_r: 95°
- Top rake angle γ: -6°
- Side clearance angle α: 5°
- Back rake angle λ: -6°
- Honing radius 0.05 mm

Material

- Titanium alloy Ti6Al4V annealed bars with 55 mm diameter and 500 mm length

Acquisitions

- Kistler 9265 dynamometer
- M-NI 6259 acquisition board
- Industrial Optika stereomicroscope

Cooling conditions (wet machining)

- Water-oil emulsion 2 l/min
- Hocut 795/I at 5%

Cooling conditions (cryogenic machining)

- LN2 flow rate of 0.9 l/min

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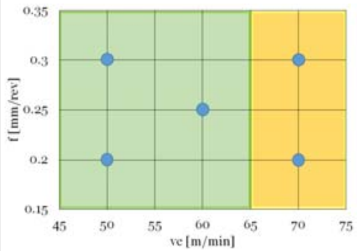
Experimental setup for turning tests

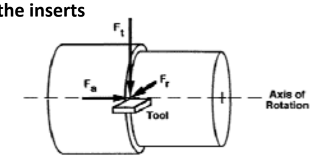


2X2 plan with central point

- CompaFixed depth of cut set at 2 mm
- 3 replicates for each experimental condition
- 30 tests in total (15 cryo and 15 traditional)

Recommended range of cutting conditions for the inserts

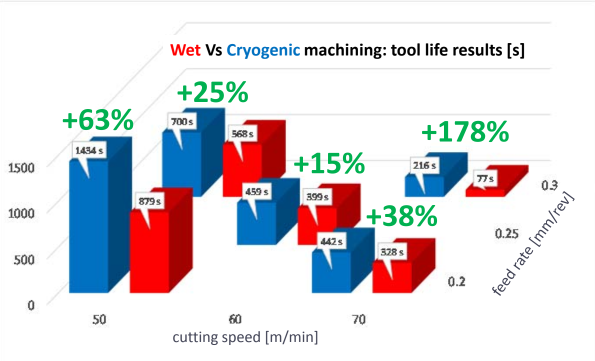
- Cutting speed: 40 : 65 m/min
- Feed rate: 0.1 : 0.4 mm/rev



Parameters were pushed to the limit to test cryogenics benefits with high M.R.R.

Experimental setup for turning tests

Results of turning tests: tool life



- Cryogenics improves tool life in all cutting conditions
- At the highest MRR (70 m/min and 0.3 mm/rev) cryogenics offers the highest improvement (+178%) with respect to traditional machining
- It can be considered the ideal cooling technology for the improvement of productivity

Results of turning tests: forces and friction coefficient

A slight increase in cutting forces was found with the cryogenic method

		Fc [N]			Ff [N]			Fr [N]		
vc [m/min]	f[mm/rev]	Lubro	Cryo	Diff% Cryo Vs Lubro	Lubro	Cryo	Diff% Cryo Vs Lubro	Lubro	Cryo	Diff% Cryo Vs Lubro
50	0.2	818	857.0	+5%	434	465	+7%	230	235	+2%
50	0.3	1045	1073	+3%	404	419	+4%	253	269	+6%
60	0.25	894	923.7	+3%	372	420	+13%	214	195	-9%
70	0.2	752	822	+9%	358	423	+18%	196	219	+11%
70	0.3	1051	1053	0%	460	469	+2%	263	237	-10%

ANOVA tests show that:

- The specific cutting force 'Kc' is influenced by the cooling method, with a 4% increase of Kc in cryo-machining
  - The increase can be attributed to a hardening effect on the workpiece
  - Care must be taken in design of the fluid feeding system
- The friction coefficient 'μ' is not influenced by the cryo cooling
  - Liquid nitrogen has both cooling and lubricating effect

Production times and costs in turning

Once the Taylor's law coefficients are known it's possible to predict the tool life 'T' for each combination of cutting conditions inside the experimental range

Time ('t_p' [min]) and costs ('C_p' [€]) of production

$$t_p = t_0 + \frac{V}{Z} \cdot \left(1 + \frac{t_{cu}}{T}\right)$$

Where:

- t_0 represents the setup time and is fixed [min]
- V is the total amount of material that has to removed [mm³]
- Z is the M.R.R. [mm³/s]

$$C_p = C_0 + C_m \cdot t_p + C_{ut} \cdot \frac{V}{Z \cdot T}$$

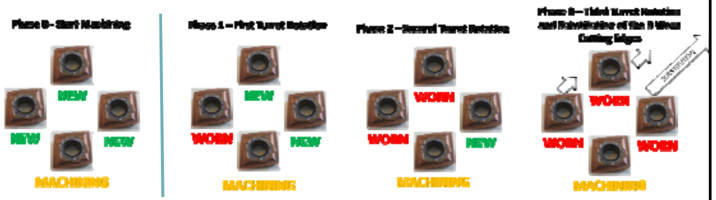
Where:

- C_0 represents the setup costs and is fixed [€]
- C_m is the cost per hour of the machine tool [€/h]
- C_{ut} is the cost of a cutting edge of the insert

Adopting some hypothesis it's possible to define a realistic productive scenario to compare costs of production both with cryogenic and traditional machining

Hypothesis for the production scenario - 1

- Turning center with **automatic tool change** and a buffer with 4 slots: it is assumed that the tool change is carried out for 3 worn cutting edges in the cutting time of the 4th tool



During production this sequence of steps cycles from phase 1 to 3

- Production lot of 10 pieces in Ti6Al4V with B2F of 8:1 for a volume (V) from the total removal of about 0.46 mm³
- Cost machine C_m equal to 130 €/h, cost of LN2 0.2 €/l and cost of lubro 0.17 €/h
- Fixed time 't_0' of 90 minutes and fixed cost C_0 of 200 €
- Cutting edge cost= 3 €/edge
- Time of cutting edge change (rotation of the insert or replacement) = 2 minutes

Hypothesis for the production scenario - 2

- This type of management (for not having long downtime) imposes a minimum life of the insert > or = to 6 minutes, because operator replaces all the 3 worn inserts (3x2 min) during phase n. 3
- Considering any hitches (quantified in a minute), it is assumed that the minimum life time 'T' for the insert must be 7 minutes to guarantee a continuous production. If 'T' is lower the production stops because all the four tools are failed for a certain period of time (7 – 'T' min)

If T > 7 minutes t_{cu}=0.1 min

If T > 7 minutes t_{cu}=0.1 + (7 - T)

$$t_p = t_0 + \frac{V}{Z}\cdot\left(1+\frac{t_{cu}}{T}\right)$$

$$C_p = C_0 + C_m\cdot\left[t_0+\frac{V}{Z}\cdot\left(1+\frac{t_{cu}}{T}\right)\right]+C_{ut}\cdot\frac{V}{Z\cdot T}$$

Production times in turning

Traditional machining optimal conditions

Minimum t_p at 52 m/min and 0.29 mm/rev

Time of production: 1659 min

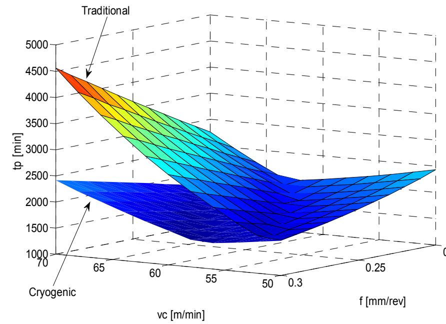
Optimal T= 7.1 min

Cryogenic machining optimal conditions

Minimum t_p at 58 m/min and 0.29 mm/rev

Time of production: 1497 min

Optimal T= 7.1 min



*In the optimal conditions, a production time compression of about **10%** is achieved with cryo-machining*

Production costs in turning

Traditional machining optimal conditions

Minimum C_p at 50 m/min and 0.3 mm/rev

Cost of production: 4411 €

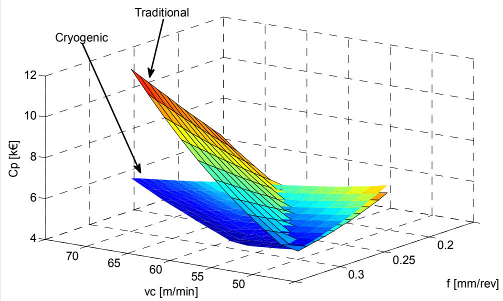
Optimal T= 7.8 min

Cryogenic machining optimal conditions

Minimum C_p at 56 m/min and 0.3 mm/rev

Cost of production: 4254 €

Optimal T= 7.5 min



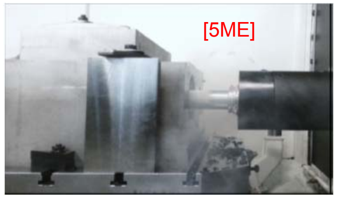
- *In the optimal conditions, a production cost reduction of nearly **4%** is achieved with cryo-machining*

Cryogenic machining: other applications

- N_2 cryo-grinding

[IIT, Chennai]

- N_2 cryo-milling

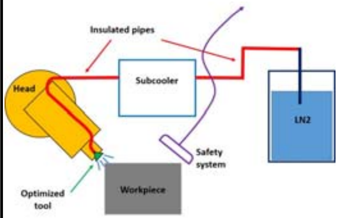


- CO_2 cryo-milling

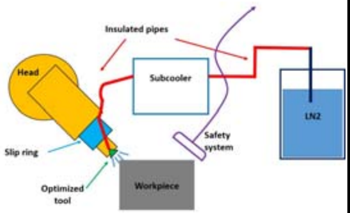
[Starrag - Walter]

Cryogenic milling

- **3 layouts can be adopted:**
  - External flood cooling
    - Very simple, but cools down the work, too!
- Internal delivery through the spindle



- Internal delivery through a slip ring



Alternative milling layouts

Internal delivery through the spindle:

Pros
- Clean machine design, no pipes in the working zone
- Milling head length is not increased, no risks of vibration

Cons
- Constructive difficulties due to passing insulated pipes through the rotating spindle, possibility of reliability problems
- Hard to integrate in old machines not designed for this task

Internal delivery through a slip ring:

Pros
- Suitable also for old machines with an adaptor (Slip ring);
- Cryogenic fluid does not pass near critical components (i.e. no effects on spindle bearings);

Cons
- Insulated pipes around the working area;
- Increased head length (bending under load)

Conclusions

- Cryogenic machining can offer a significant improvement of tool life and reduce the environmental impact of machining, among other potential advantages
- Cooperation is required, for a successful implementation, among
  - R&D institutes,
  - Machine tool producers
  - Tool makers
  - Gas plant providers