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Additive Manufacturing of H-13 Inserts for Optimal Extrusion Die Cooling

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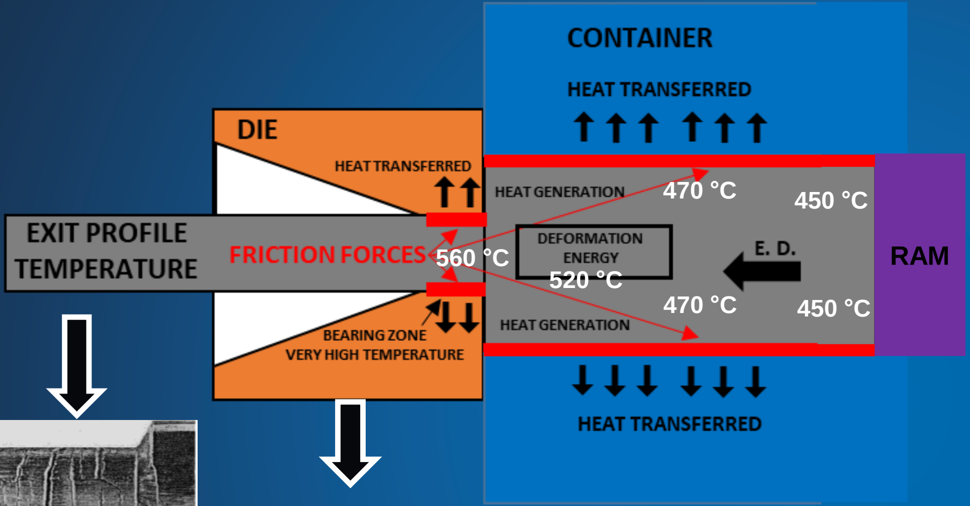
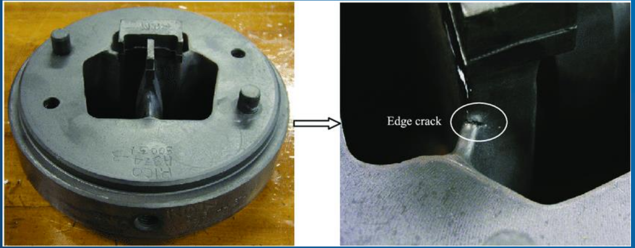
Hot Aluminum Extrusion



An excessive exit profile temperature **promotes** surface profile defects



The thermal gradient can **reduce** the service life of tools

EXTRUSION SPEED IS CONSTRAINED BY PROFILE TEMPERATURE

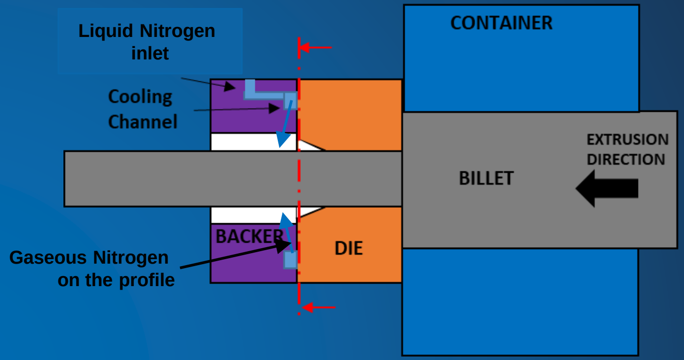
Industrial solutions

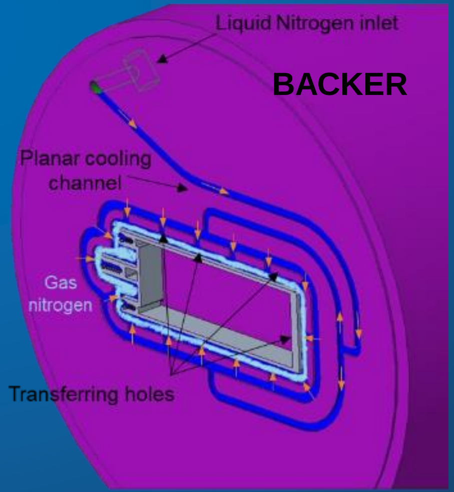
- Isothermal extrusion → Control of thermal gradient with tapered billet temperature and thermal regulated container → **Higher extrusion load** and **high stress** on the die
- Isothermal extrusion → Regulation of extrusion speed with exit profile temperature → Productivity **could be limited**
- **Liquid nitrogen die cooling**

The Extrusion Process with Nitrogen Cooling

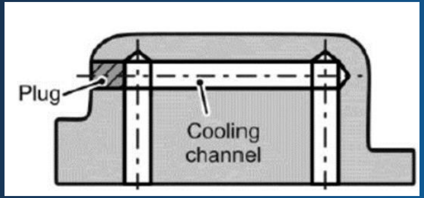
Benefits of Liquid Nitrogen Cooling:
-Exit profile temperature decrease;
-Die Temperature decrease;
-Extrusion Load increase negligible;
-Increase of extrusion speed;
-Reduction of profile oxidation.

Improvement of actual system:
-Cooling channels nearer the bearings
-Geometrical constraint with milling and drilling
-Channel design very often based on die makers experience



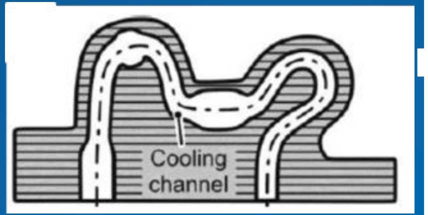


The Conformal Cooling Channel



NO CONFORMAL COOLING CHANNELS: Channels with simple shapes by milling/drilling
On backer

FROM MILLING



CONFORMAL COOLING CHANNELS (CCC):
Channels that follow the shape of the die opening.
Targeted Cooling in the die.

TO ADDITIVE MANUFACTURING

EXCESSIVE MANUFACTURING COST FOR THE WHOLE EXTRUSION DIE

The Aim of the Work: The multi-die concept design for nitrogen cooling

MULTI-DIE CONCEPT

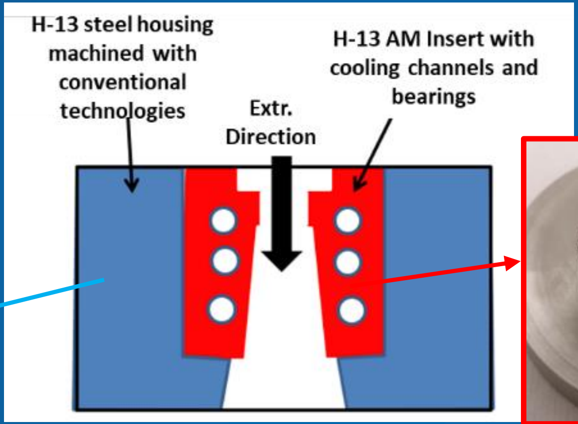
Conventionally machined

H-13 steel housing:

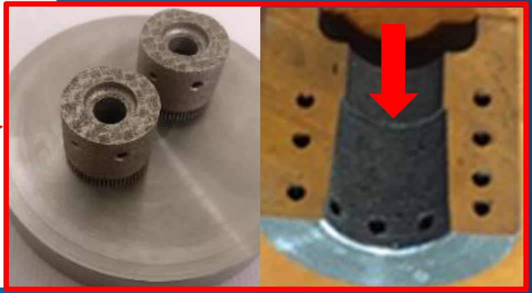
-Support the insert

-transfers the nitrogen to the inserts

-interference coupling



Selective laser melting (SLM) additive process.



H-13 AM insert:

-good tolerances and not high costs

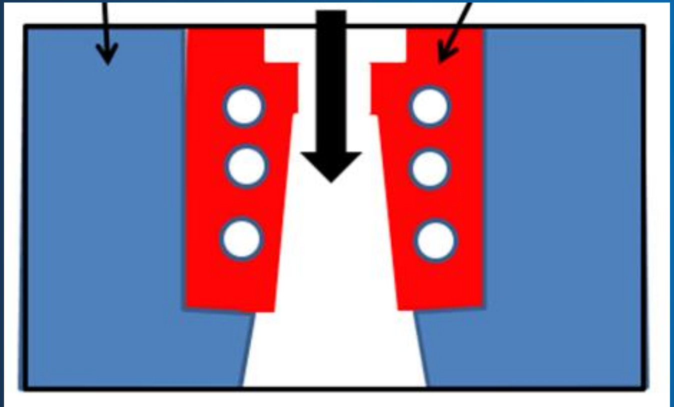
-machined for required finishing

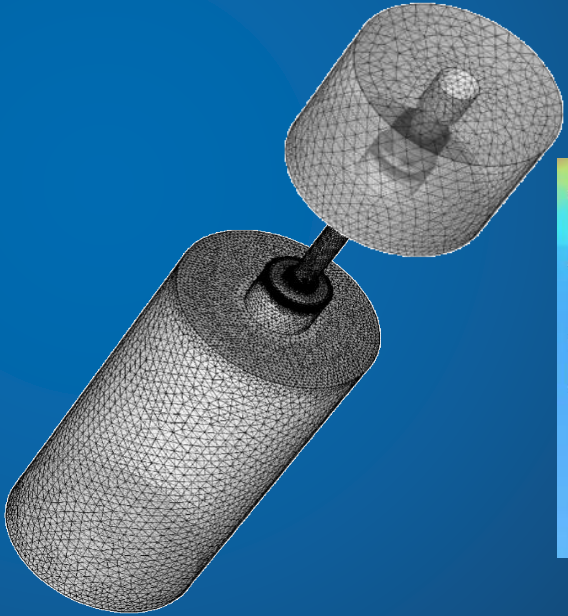
-Easily exchangeable

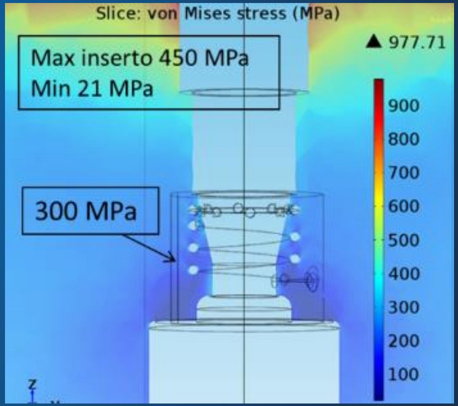
Insert design tools

Insert design, cooling performance and resistance

FEM predictions (nitrogen cooling added later)







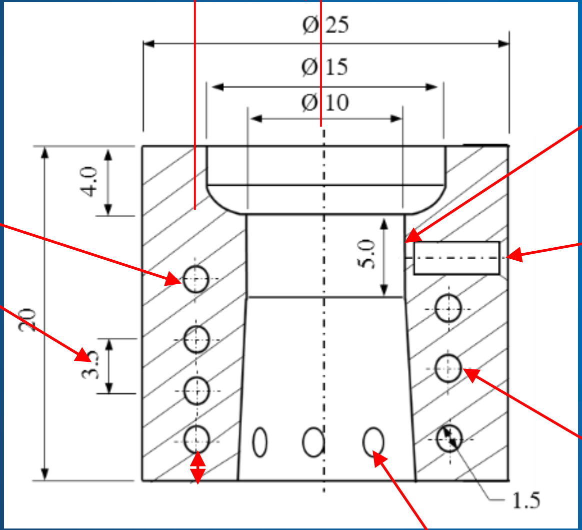
Design of SLM insert with conformal cooling channel

Helix diameter affects the distance of the channel from bearings (safe distance required)

Helicoidally channel to follow the profile along the extrusion direction

Helix pitch small= channel length increase (higher cooling power)

Helix pitch small= percentage of void increase (possible yielding during printing process, mechanical resistance decrease)



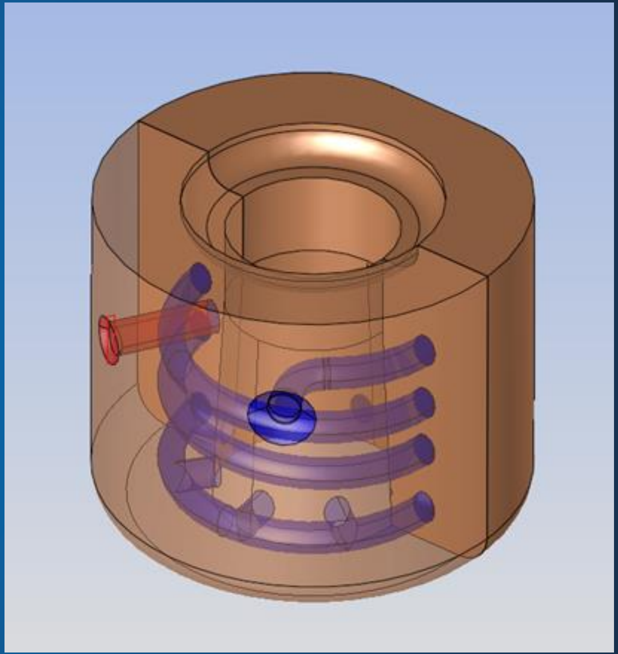
Bearings

Thermocouple hole to monitor the insert temperature

Channel diameter big to facilitate the nitrogen flowing, but not excessive to avoid weakening

Safe distance to avoid yielding

How many exit holes?



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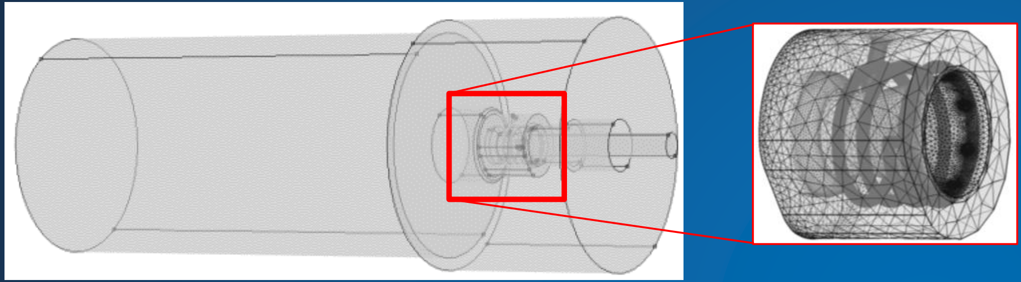
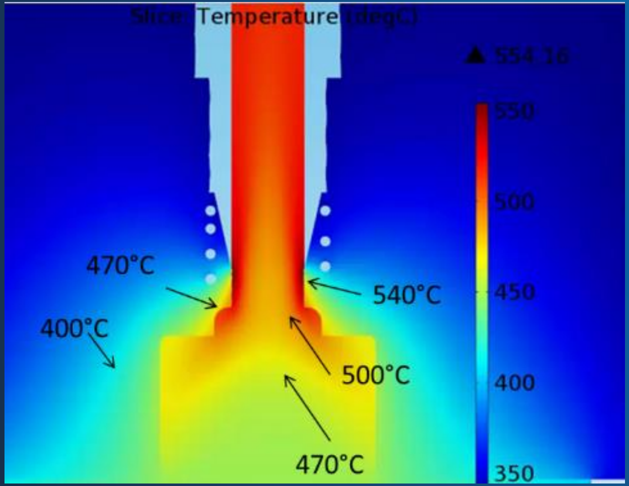
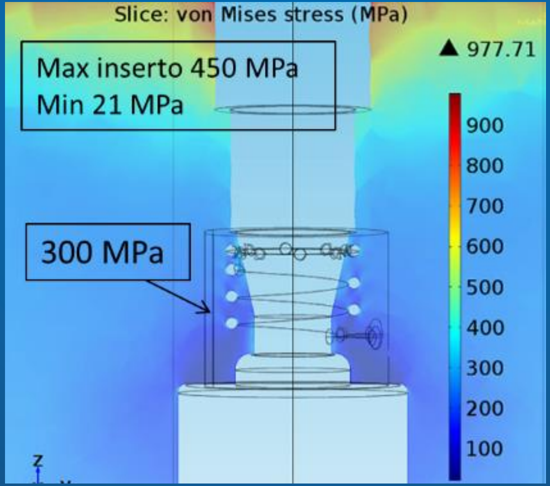
FEM analysis of SLM insert with conformal cooling channel



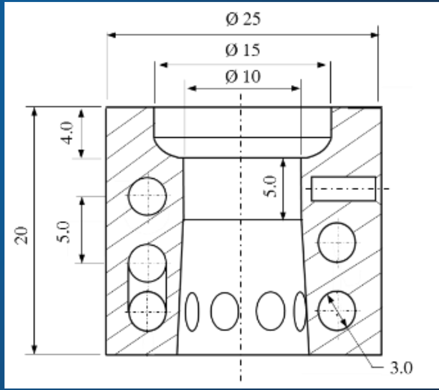
Simulation parameter COMSOL code:

- Eulerian Approach (already deformed billet)
- Un-coupled Thermal-Structural analysis
- Extruded material AA 6063 aluminum alloy
- T_{billet} 450°C
- $T_{die/insert}$ 450°C
- T_{ram} 300°C.
- Extrusion speed 5 mm/s.



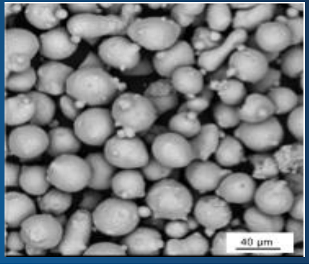


OPTIMIZED DESIGN

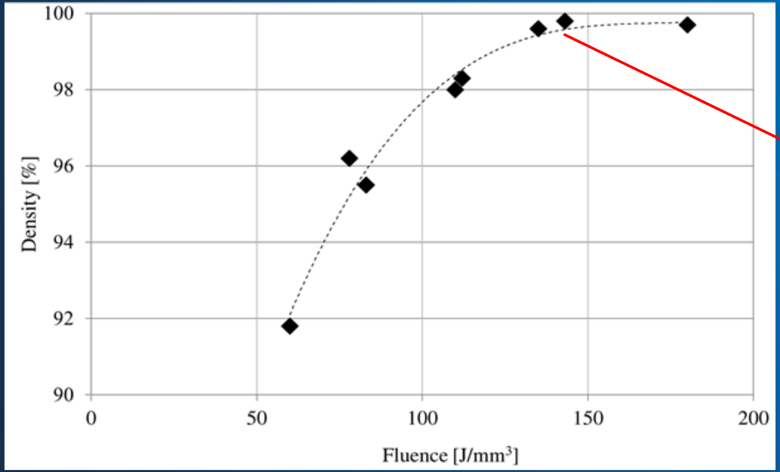


Insert Manufacturing

- SLM: Sisma MySynt 100
- Working chamber dimension: Ø100 x H160 mm
- Maximum laser power: 150 W
- Laser spot: 50 µm
- 1.2344 (H13) Powder provided by LPW SOUTH EUROPE SRL



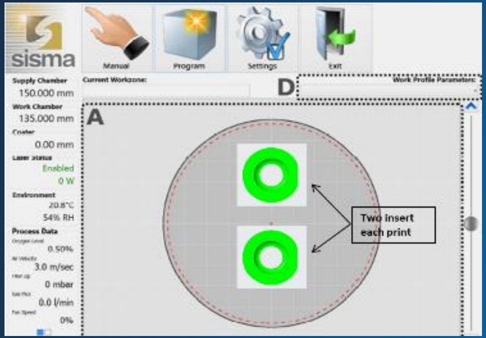
	C	Cr	Mn	Mo	Ni	Si	V	Fe
wt %	0,32 - 0,45	4,75 - 5,50	0,2 - 0,5	1,10 - 1,75	≤ 0,3	0,8 - 1,2	0,8 - 1,2	Balance



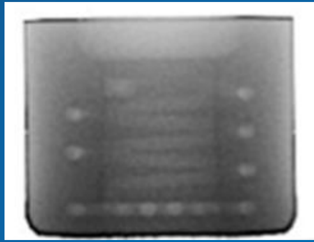
Fluency [J/mm³]	Power [W]	Laser velocity [mm/s]	Hatch distance [mm]	Layer thickness [µm]
143	100	700	0,05	20

Optimized laser parameters for H13 ⟶ 99% density obtained

Insert Manufacturing



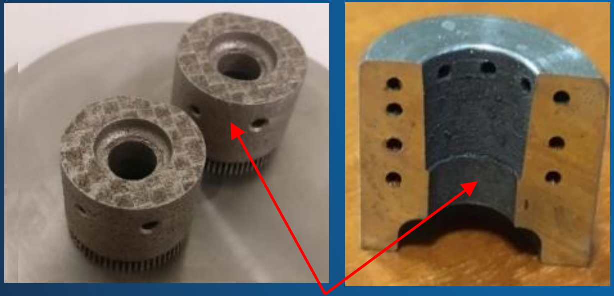
X-Rays
analysis



Microstructure
analysis

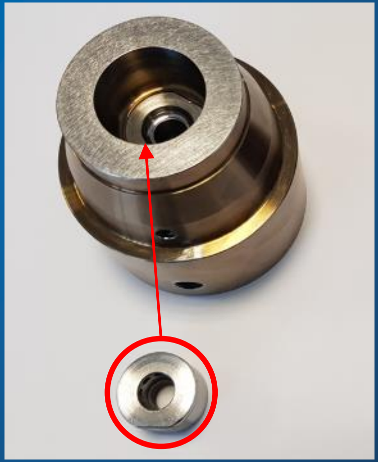
Quality inspection:

- No cracks
- Density>99%
- Unobstructed channels
- Fine grain structure



- Bearings and outer surface machined with EDM process
- Heat treatments: Annealing, quenching and tempering (Hardness: 45 HRC ± 3)

Insert mounts in
the steel housing



Die Testing- Experimental Trials

Process parameters:

- 2.5 MN testing press
- Final profile: 10 mm diameter round bar
- 24 AA6063 billets
- 18 ZM21 billets

- Billet length: 100 mm
- Billet Ø: 45 mm
- Container Ø: 50 mm
- Billet/die pre-heat: 450°C (AA6063) /300°C (ZM21)
- Container T: 375°C
- Extrusion speeds:
  - AA6063: 4.2 mm/s and 6.5 mm/s
  - ZM21: 4 mm/s
- Liquid N_2 stored at 5 bar in a tank of 230 l

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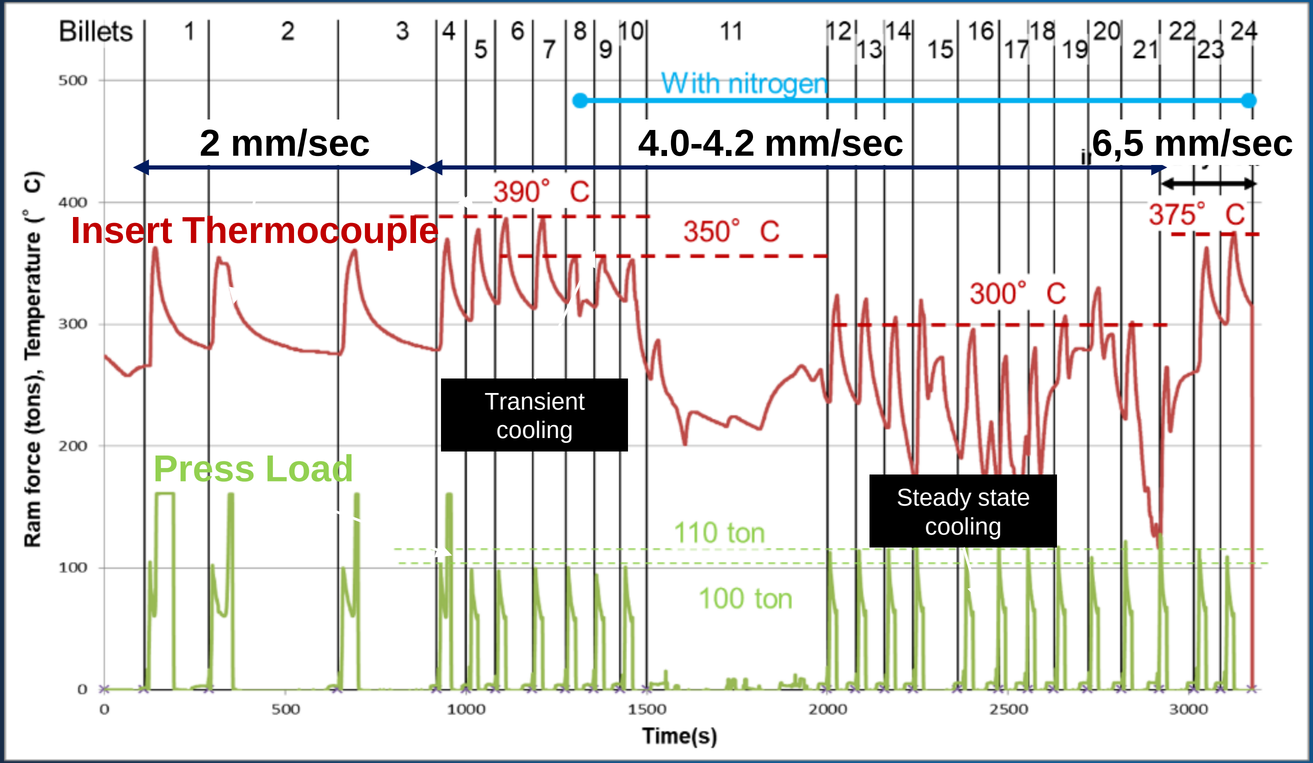
AA6063 Trials



Main Results:

- Insert resisted the whole campaign
- Extrusion load **increased only by 10%** with cooling (from 100 to 110 tons);
- In the steady state cooling condition the insert temperature **decreased up to 90 °C;**
- The increasing of ram speed produced a lower exit temperature with respect to uncooled conditions at lower extrusion speed;
- Nitrogen flow has to be turned off during billet change in order to avoid excessive die cooling;
- Not easy to understand if liquid or gas nitrogen is flowing into the channel.

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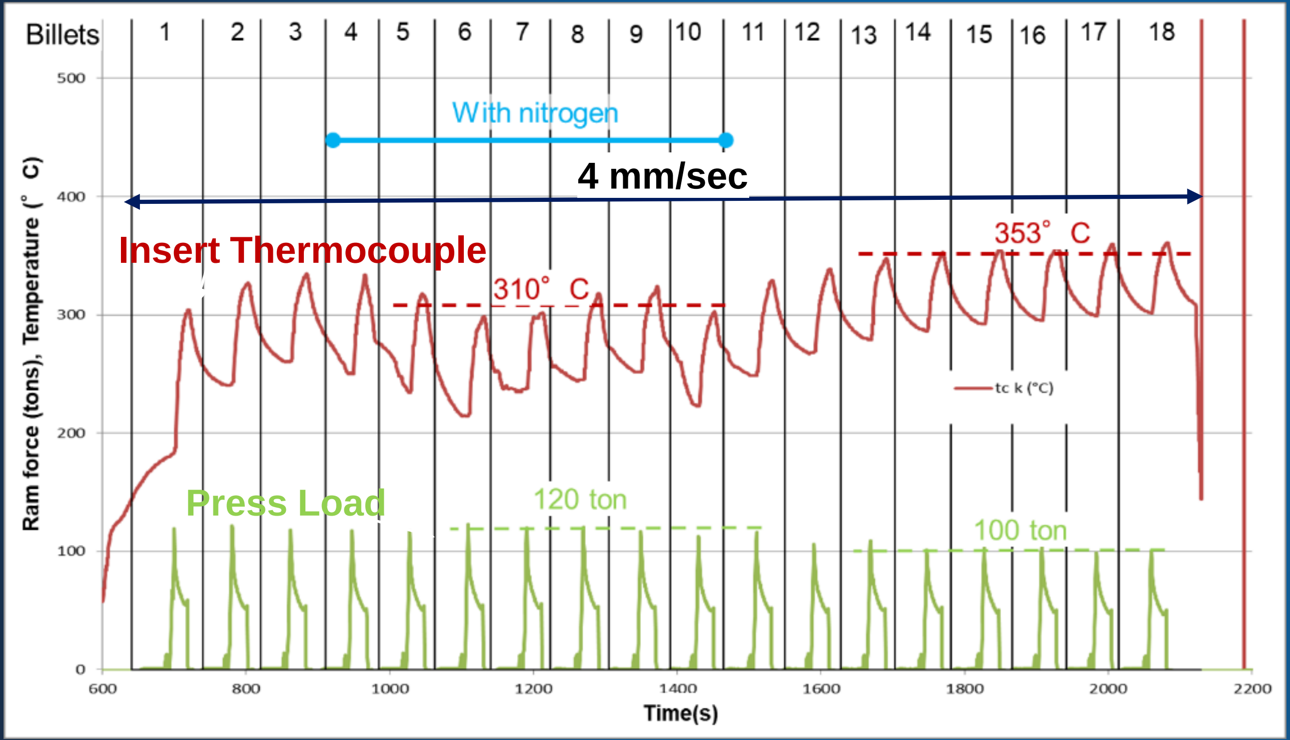
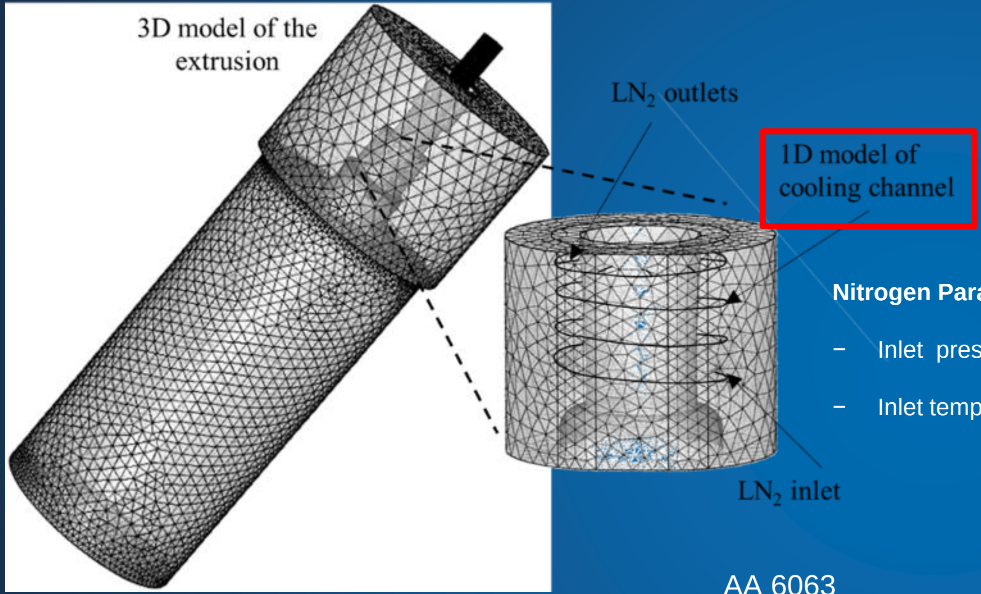
ZM21 Trials



Main Results:

- Insert resisted the whole campaign
- Extrusion load **increased only by 20%** with cooling (from 100 to 120 tons)
- Also with non conformal cooling the insert temperature **decreased of 40 °C**
- Insert re-design is necessary to avoid transferring gaseous nitrogen holes obstruction.

Numerical Model with Nitrogen Cooling



Nitrogen Parameters:

- Inlet pressure 4 bar
- Inlet temperature -200 °C

Modelling Setting:

- Comsol Multiphysics® software
- **3D model of the extrusion process is coupled with 1D model of cooling channel**
- Pure Eulerian approach (billet shape as aluminum already extruded)
- Steady-state study of the extrusion process (**low computational time**)
- Ram and Container replaced with equivalent thermal and load boundary conditions

Flow stress of AA 6063 and ZM21 with the Sellars–Tegart inverse sine hyperbolic model

$$\sigma = \frac{1}{\alpha} sinh^{-1}[[\frac{1}{A}\dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)]]^{\frac{1}{n}}$$

AA 6063

Parameters	Value
α	0.0456 1/MPa
A	6.063E12 s^{-1}
Q	2.044E5 J/mol
R	8.314 J/(°K mol)
n	5.18

ZM21

Parameters	Value
α	0.0238 1/MPa
A	1.35E12 s^{-1}
Q	1.414E5 J/mol
R	8,314 J/(°K mol)
n	3.6

Parameters	Value
$HTC_{steel\text{-}steel}$	3000 W/(m²K)
$HTC_{alum\text{-}steel}$	11000 W/m²K)
Bearings friction	Slip condition
Container friction	No Slip condition

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Numerical Model

1. **Conservation of the momentum**

Term for pressure drop due to viscous shear

$$\rho\frac{\delta u}{\delta t} = -\nabla p + f_D\frac{\rho}{2d_h}u|u|$$

2. **Conservation of the mass**

$$\frac{\delta A\rho}{\delta t} + \nabla(A\rho u) = 0$$

3. **Heat transfer equation**

Internal friction contribute

$$\rho A c_p\frac{\delta T}{\delta t} + \rho A c_p u\nabla T = \nabla A k\nabla T + f_D\frac{\rho A}{2d_h}|u|^3 + Q_{wall}$$

Total derivative of Temperature

Conductivity contribute

Convective contribute with the insert

4. **Laminar o Turbulent Regime**

$$f_D = f(R_e)$$

Reynolds number

5. **Convective contribute with the insert**

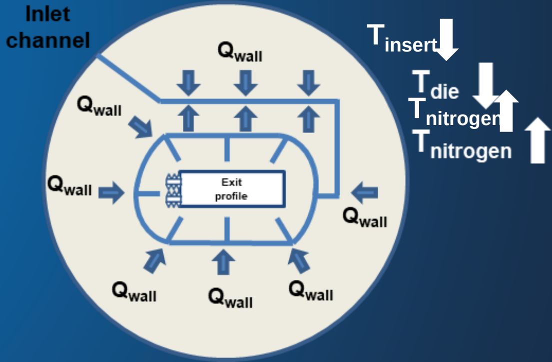
$$Q_{wall} = hZ(T_{insert} - T)$$

6. **Heat transfer equation for the insert**

$$\rho_2 C_{p2}\frac{\partial T_{insert}}{\delta t} = \nabla\cdot k\nabla T_{insert}$$

7. **Convective heat transfer coefficient**

$$h = f(R_e)$$



-u cross section averaged fluid velocity (m/s)
-A cross section area (m^2)
-r density of the fluid (kg/m^3)
-p fluid pressure (N/m^2)
-d_h hydraulic diameter
-f_D friction factor

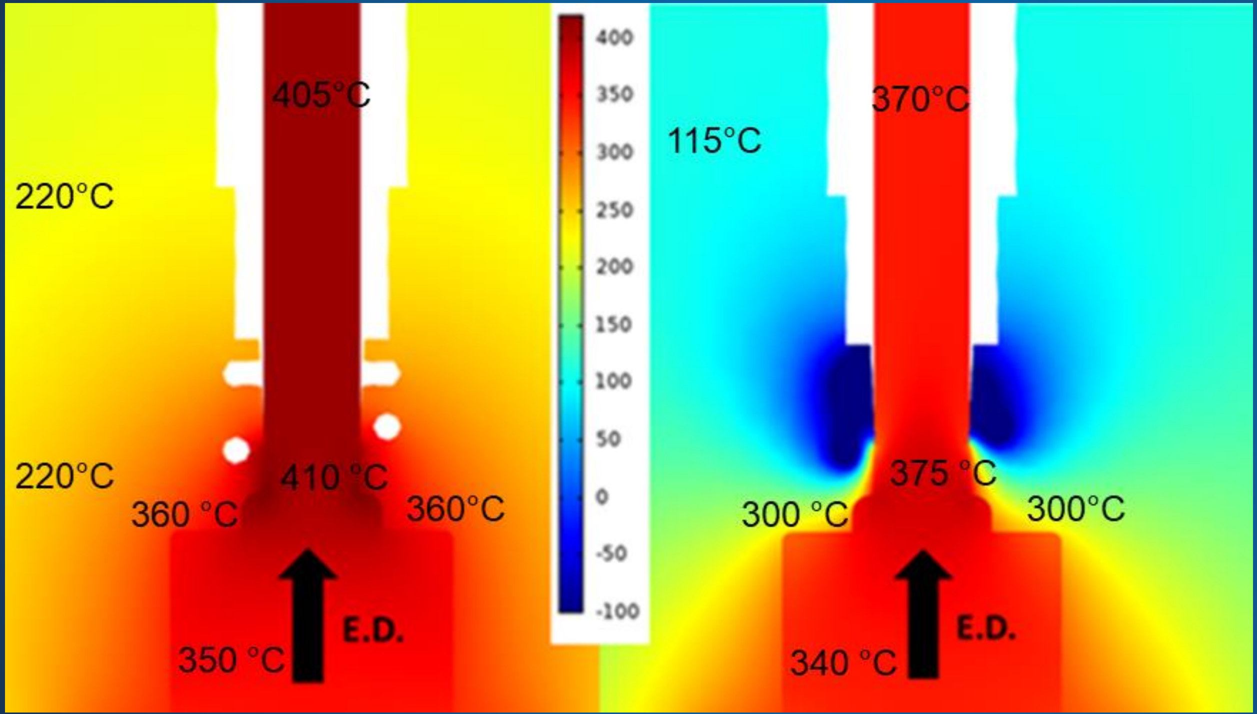
-C_p heat capacity at costant pressure
-T cooling fluid temperature (K)
-k thermal conductivity (W/(mK))
-Q_{wall} term for heat-exchange with the die
-Z perimeter of the section channel
-h convective heat transfer coefficient

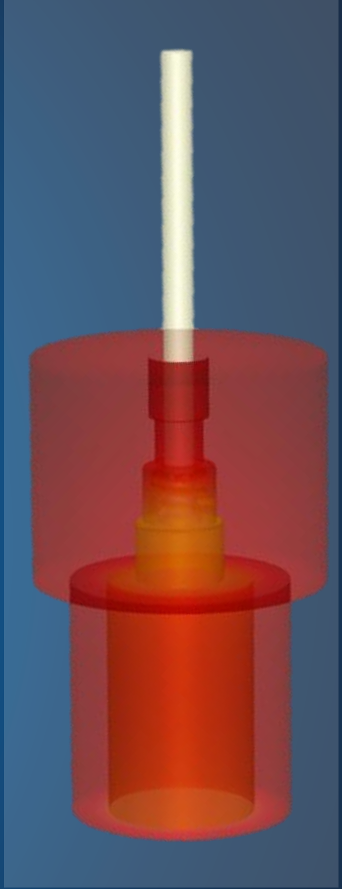
N.B. Phase change of nitrogen is not considered
C_p, ρ, k constant

FE modelling results

AA 6063

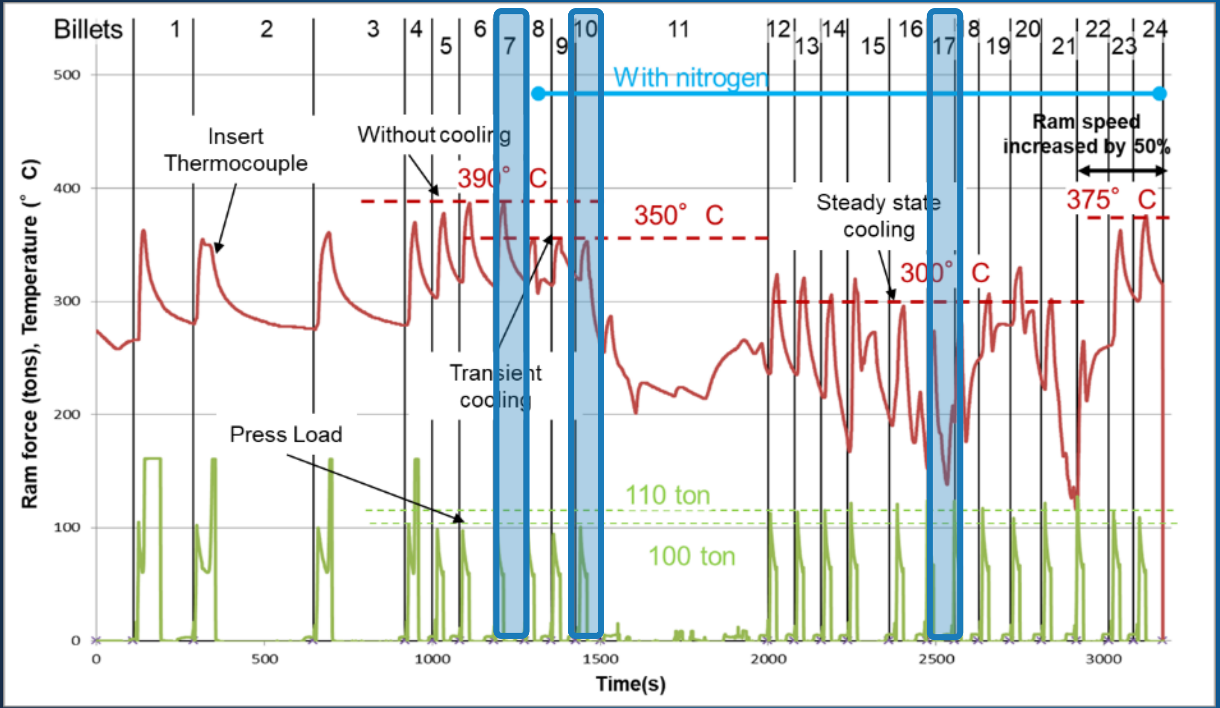
- uncooled -   - cooled -





Experimental vs Numerical Results

AA 6063

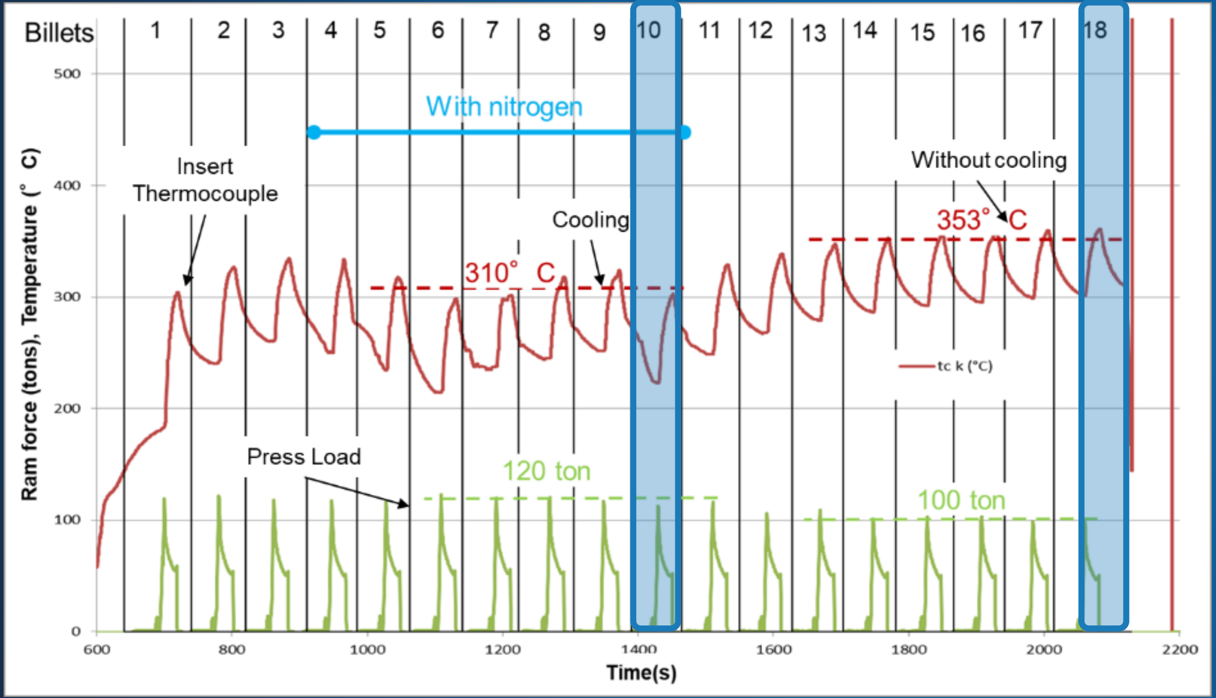


	Temperature (°C)	Load (MN)
Experimental no cooling	387	0.98
Numerical no cooling	392	1.09
% Err	1.3%	11%
Experimental gas cooling	353	0.99
Numerical gas cooling	342	1.13
% Err	-3%	14%
Experimental liquid cooling	275	1.21
Numerical liquid cooling	285	1.19
% Err	3.6%	-1.65%

Good matching of numerical results

Experimental vs Numerical Results

ZM21



	Temperature (°C)	Load (MN)
Experimental no cooling	361	0.99
Numerical no cooling	347	1.03
% Err	-3.9%	4%
Experimental cooling	308	1.11
Numerical cooling	331	1.06
% Err	7.5%	-4.5%

Good matching of numerical results

Conclusions

- The multi-die concept was validated and the insert was successfully SLM printed
- Insert resisted the whole experimental campaign
- The conformal cooling channel solution allowed a maximum temperature decreasing up to 90 °C nearby the bearings, with a slightly increase of extrusion load (10-20%)
- Experimentally, the channel design allowed to remove heat where required and to double the production rate
- The developed coupled FE model with nitrogen in conformal channels was found able to properly predict the cooling effect (maximum error of 11% in terms of load, 3.6% in terms of temperature)

THANK YOU FOR YOUR ATTENTION…
…questions?

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