Advanced multi-physics models for the optimization of the hot extrusion process of light alloys

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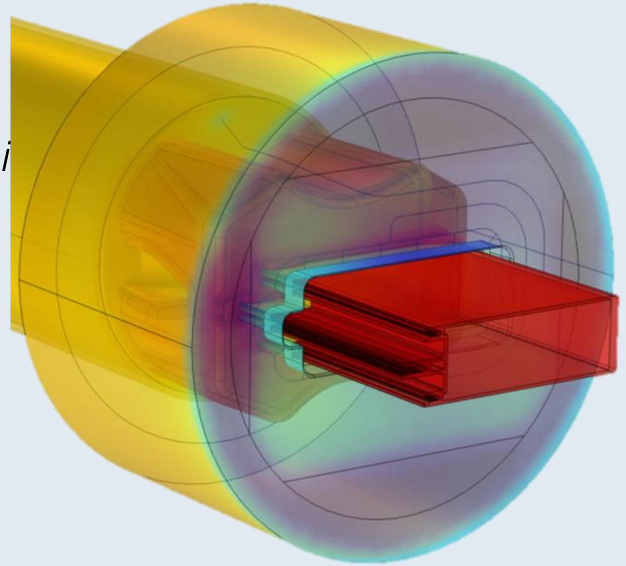

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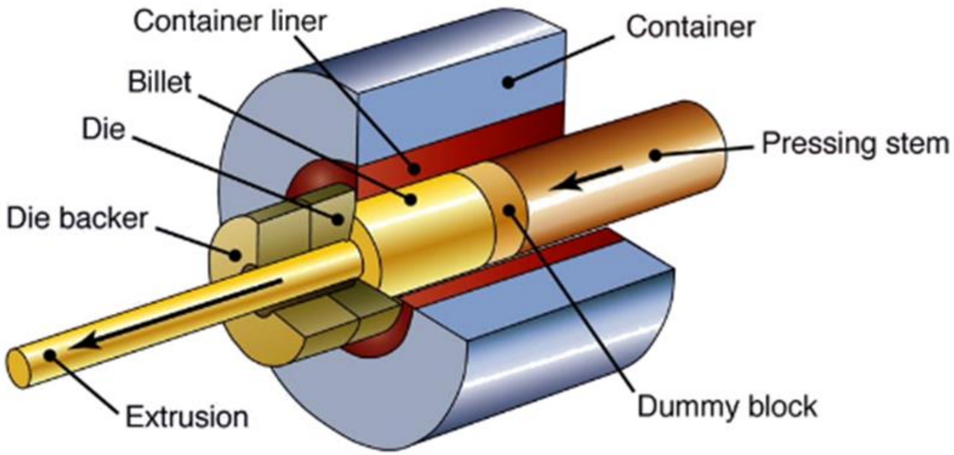
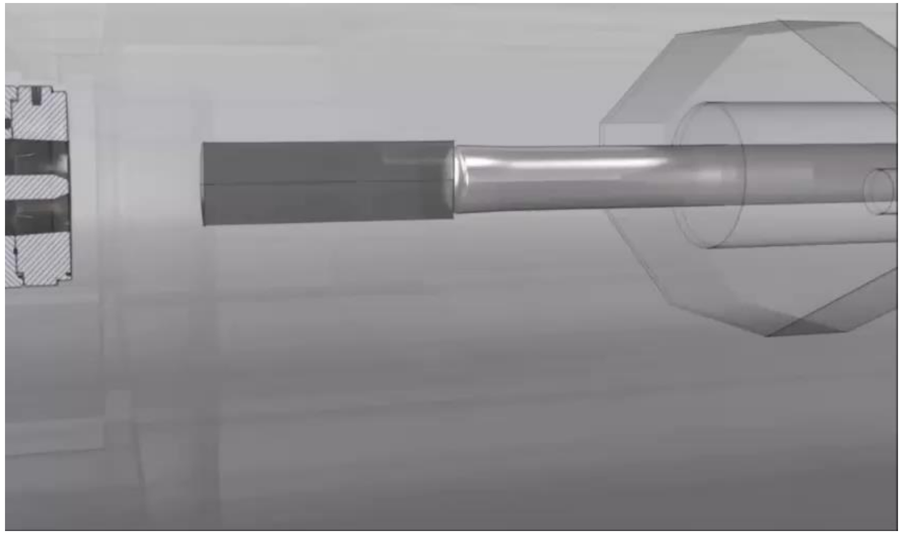
The hot extrusion process of light alloys



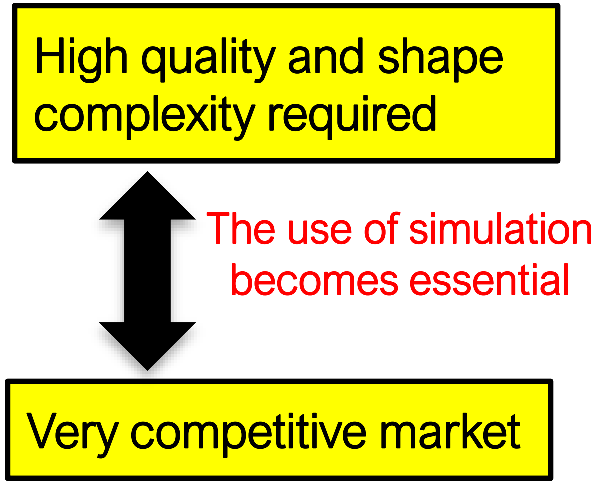


Some Fields of Application:

- Furniture design
- Automotive
- Aeronautics
- Railway transportation
- Construction…

Extruded Aluminum:

- High geometric complexity
- High strength-to-density ratio
- High Corrosion Resistance
- High Crash Resistance…



High quality and shape complexity required

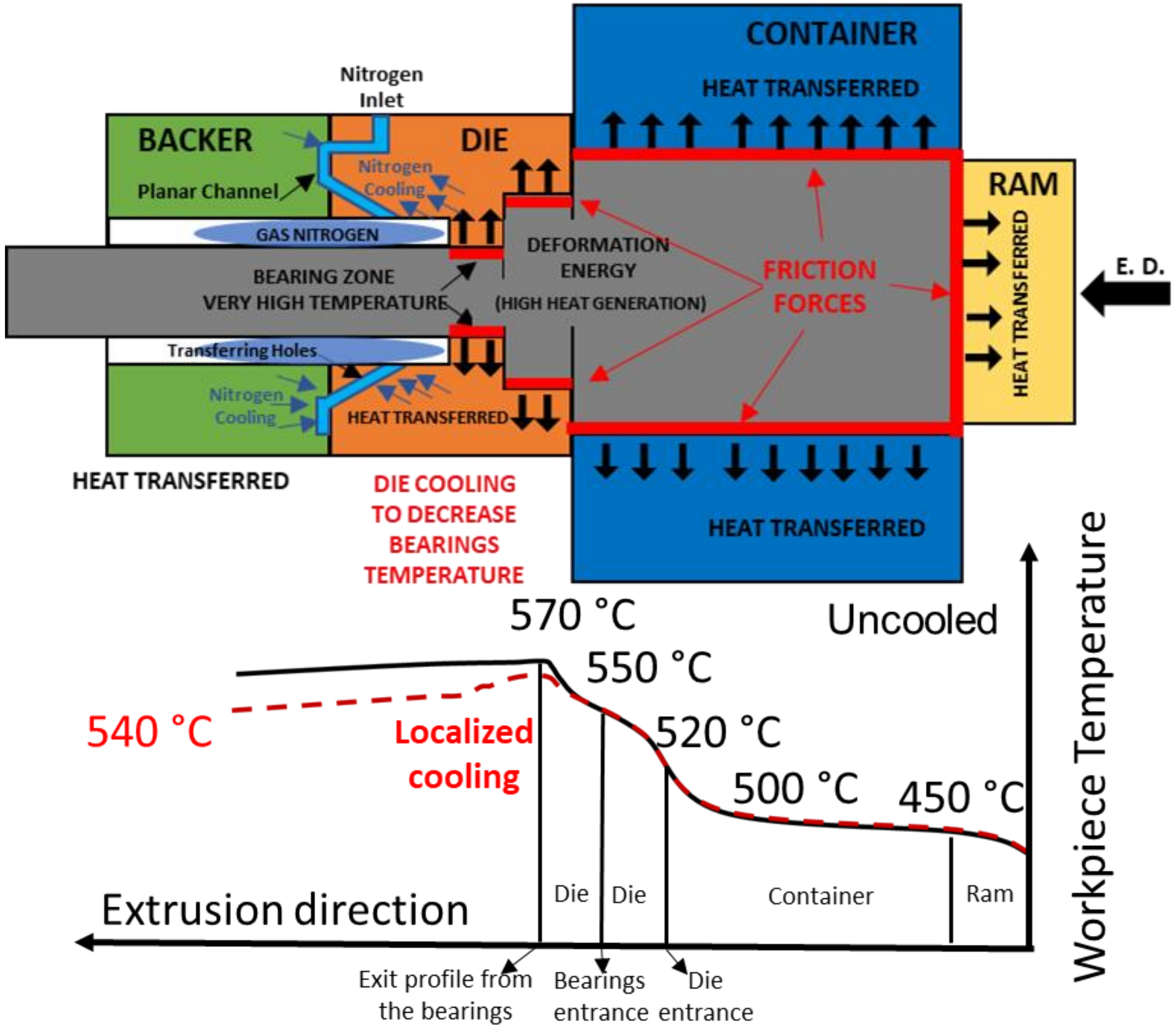
The use of simulation becomes essential

Very competitive market

Aim of the work

Show the recent advancements in the simulation of the extrusion process

From real process to numerical simulation



Involved phenomena

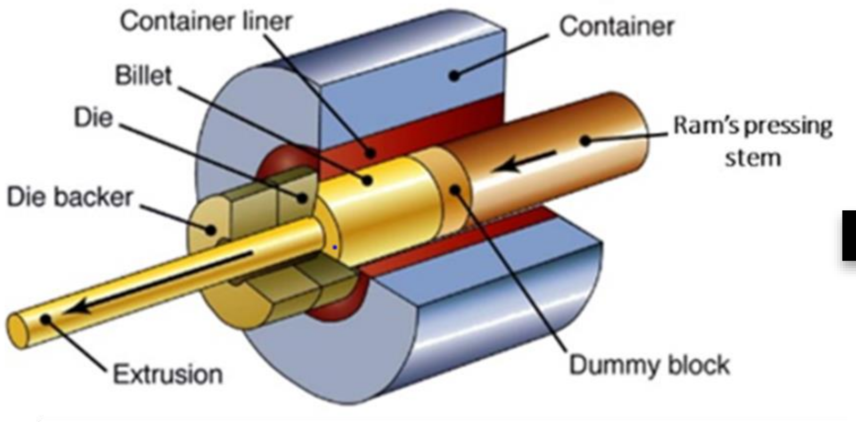
- Deformation energy and friction forces are converted into heat
- High temperatures are necessary to promote the proper material flow and to reduce the extrusion load
- Exit profile temperature can limit the maximum productivity (**nitrogen cooling possible solution**)
- Continuous process (**high productivity**) lead to interaction between two subsequent billet (**unavoidable defects**)

Identify what is necessary to simulate

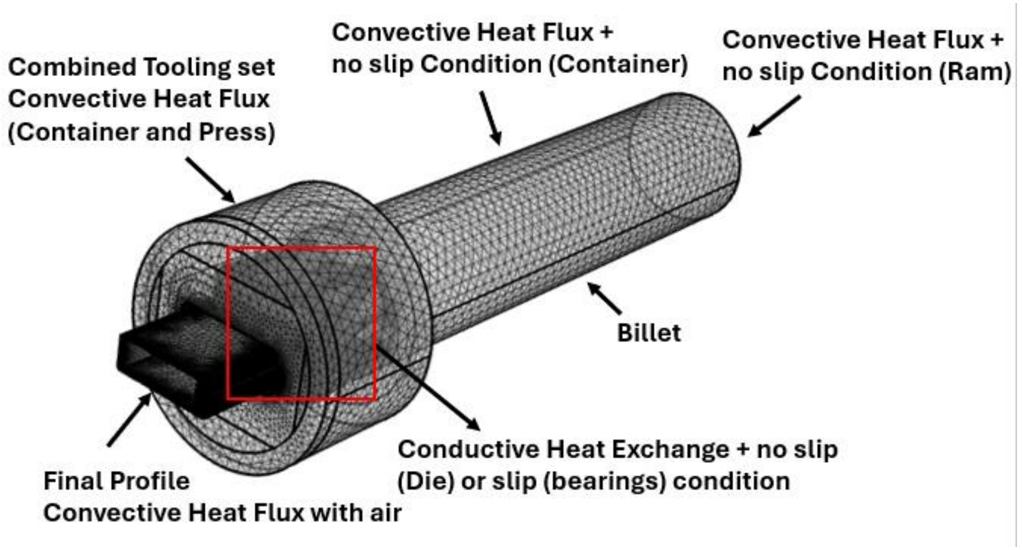
- Prediction of thermal field and extrusion load
- Prediction of material flow behavior
- Tooling-set stress analysis
- Prediction of extrusion defects

Model Implementation (Uncooled Extrusion Process)

Real Extrusion Process

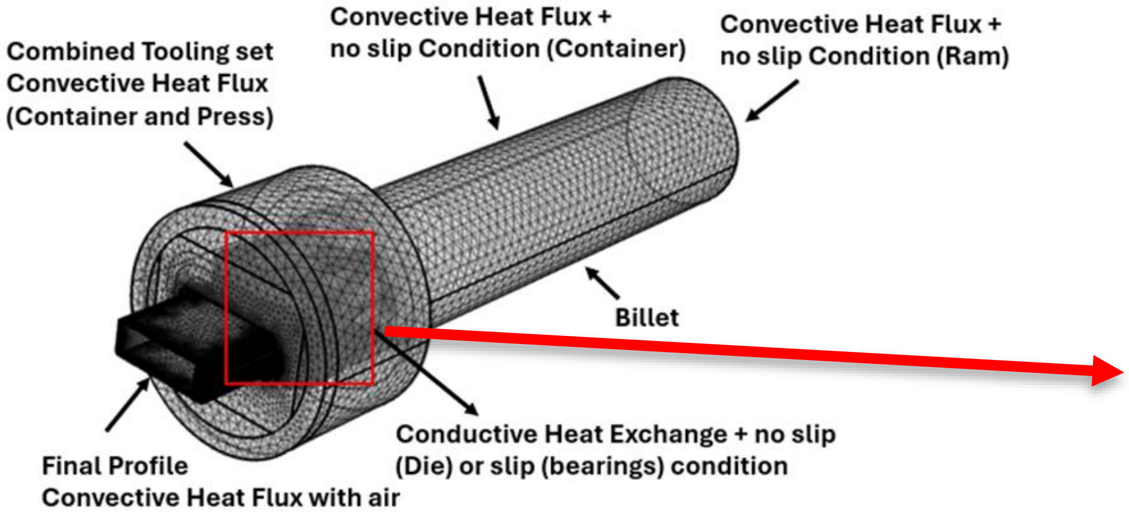


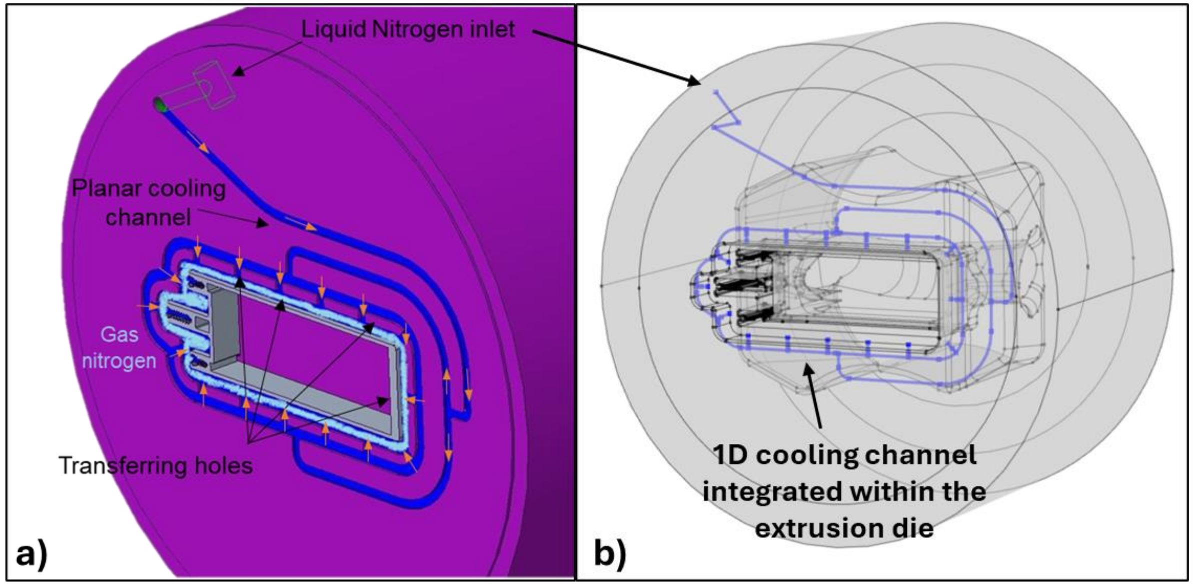
COMSOL Model



- Container and Ram replaced with equivalent thermal and frictional conditions (**Eulerian approach)**
- Material under deformation treated as a **fluid at very high viscosity (Laminar Flow)**
- **Viscosity is temperature and strain-rate depended (Zener-Hollomon model)**
- **Heat Transfer and Laminar Flow equations are coupled**
- **Solid Mechanics Interface is added for the tooling set stress analysis**

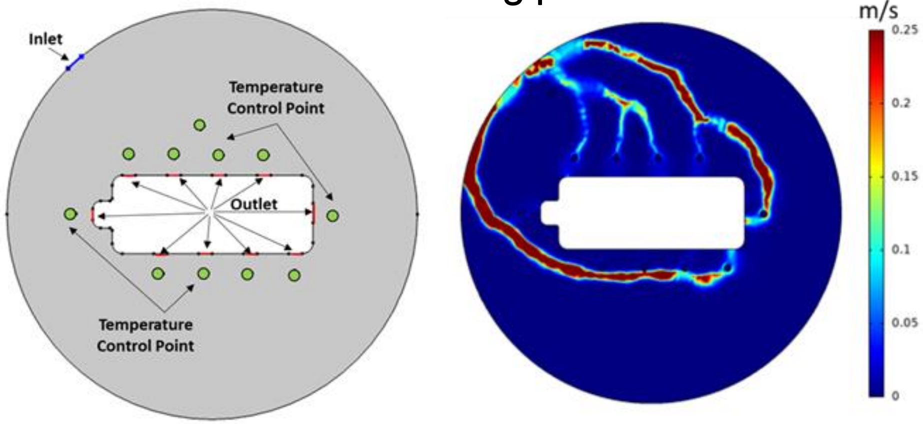
Model Implementation (Extrusion Process with Nitrogen Cooling)





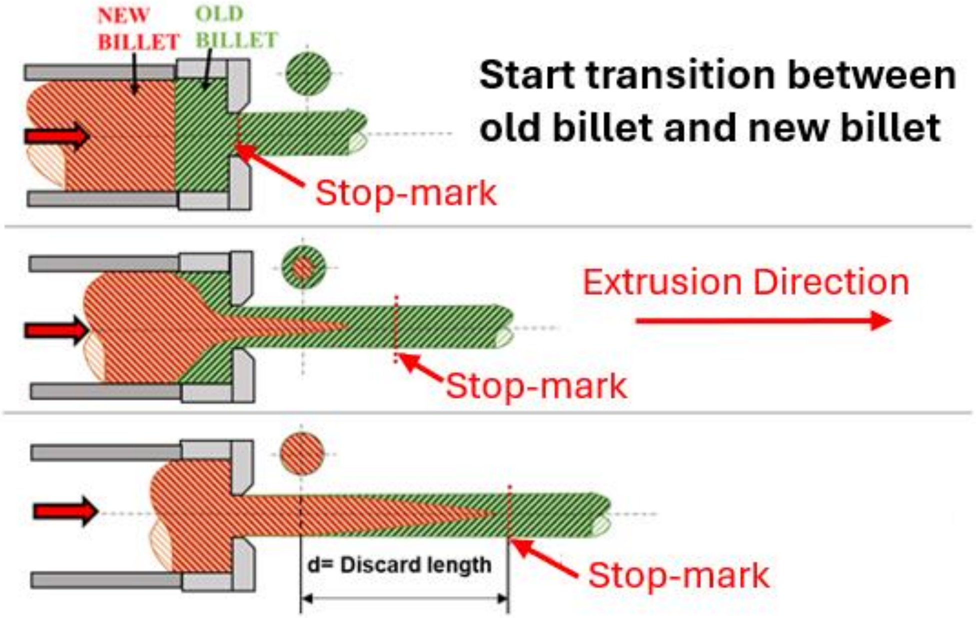
- The 3D model of extrusion process is coupled with 1D model of cooling channel
- Non-Isothermal Pipe Flow is added and coupled with the Heat Transfer interface
- If necessary, a preliminary evaluation of the channel design is possible with Topological Optimization interface (Density Model + Porous Media)

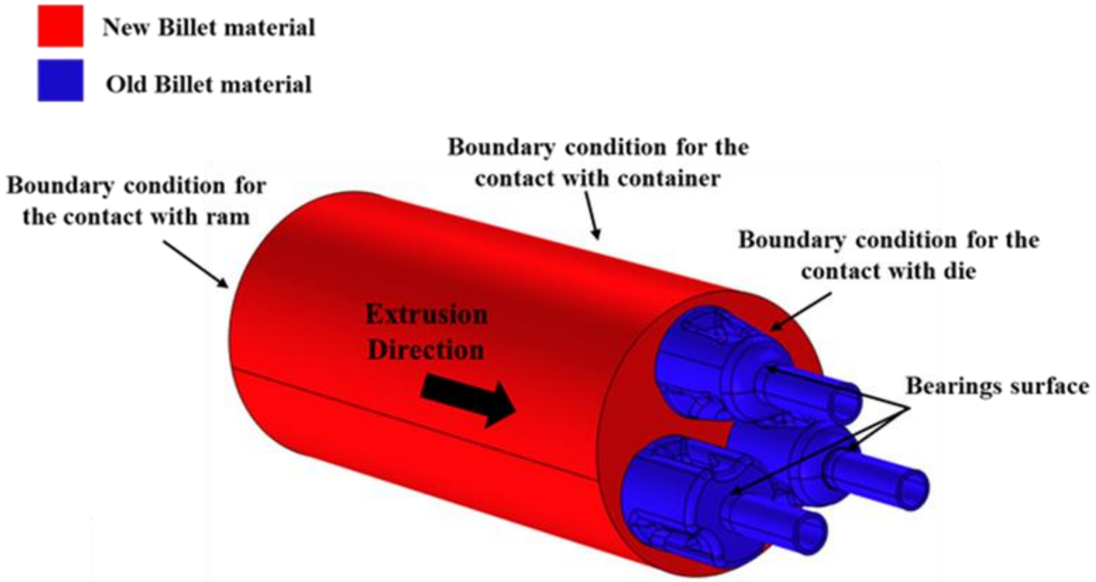
Backer is "virtually milled" to obtain the cooling path



Model Implementation (Extrusion defects)

- Since the extrusion is performed in continuous process, a certain length of the profile is contaminated by the interaction between the old and the new billet material for each run.
- This contaminated length is unavoidable scrap (low mechanical properties)





Phase field interface was chosen to describe the interaction between two immiscible fluids

Equations (Material Flow and Heat Exchange)

Navier-Stokes Equations for incompressible flow (Laminar Flow Interface)

$\underline{\rho(\mathbf{u}\cdot\nabla)\mathbf{u}=\nabla\cdot[-p\mathbf{I}+\mathbf{K}]}+\mathbf{F}$ → Conservation of momentum

$\underline{\rho\nabla\cdot\boxed{\mathbf{u}}}=0$ → Conservation of mass

$\mathbf{K}=\mu\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^{\mathrm{T}}\right)$ → Viscous term

$\eta=\boxed{\frac{\sigma(T,\dot{\varepsilon})}{3\dot{\varepsilon}}}$ → Perzyna viscoplastic model

$\sigma=\frac{1}{\alpha}sinh^{-1}\left[\frac{1}{A}\dot{\varepsilon}\exp\left(\frac{E_a}{RT}\right)\right]^{\frac{1}{n}}=\frac{1}{\alpha}sinh^{-1}\left[\left(\frac{Z}{A}\right)\right]^{\frac{1}{n}}$ → Zener-Hollomon Model of material flow stress

COUPLED SYSTEM

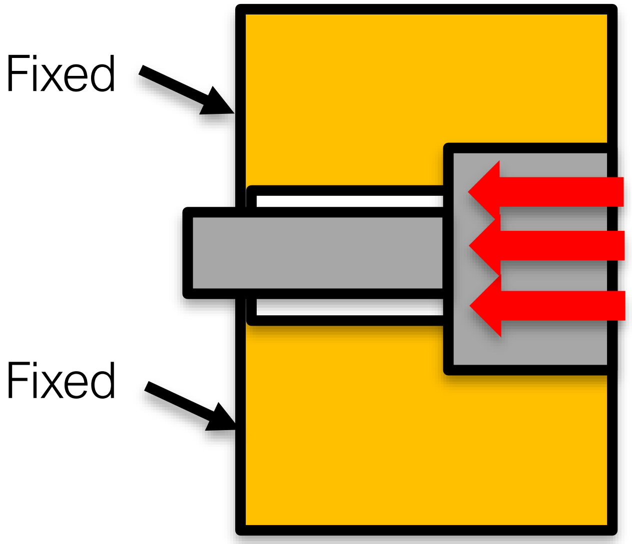
Fourier Equations for heat transfer in solid and fluid (Heat Transfer in Solid and Fluid Interface)

$$\rho C_p\boxed{\mathbf{u}}\cdot\nabla\boxed{T}+\nabla\cdot\mathbf{q}=Q+Q_{\mathrm{ted}}$$

$$\mathbf{q}=-k\nabla T$$

Equations (Die-stress analysis)

Tooling set subjected to compression state



Aluminum under deformation

Pressure on die-set from Laminar Flow Interface

Solid Mechanics Interface

$0 = \nabla \cdot S + \mathbf{F}_V$ → Momentum balance

$$S = S_{inel} + S_{el}, \quad \epsilon_{el} = \epsilon - \epsilon_{inel}$$

$$\epsilon_{inel} = \epsilon_0 + \epsilon_{ext} + \boxed{\epsilon_{th}} + \epsilon_{hs} + \epsilon_{pl} + \epsilon_{cr} + \epsilon_{vp} + \epsilon_{ve}$$

Thermal expansion from Heat Transfer Interface

$$S_{el} = \mathbf{C} : \epsilon_{el}$$

$$S_{inel} = S_0 + S_{ext} + S_q$$

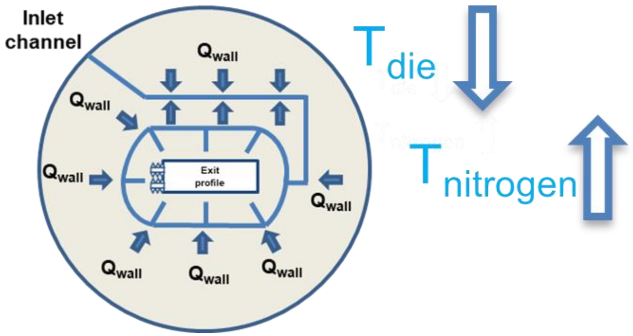
$$\epsilon = \frac{1}{2}\left[(\nabla \mathbf{u3})^T + \nabla \mathbf{u3}\right]$$

$$\mathbf{C} = \mathbf{C}(E, \nu)$$

Equations (Nitrogen Cooling)

1. Conservation of the momentum $\rho \frac{\delta u}{\delta t} = -\nabla p - f_D \frac{\rho}{2 d_h} u|u|$ Hydraulic diameter variable along the path
2. Conservation of the mass $\frac{\delta A\rho}{\delta t} + \nabla(A\rho u) = 0$
3. Heat transfer equation $\rho A c_p \frac{\delta T}{\delta t} + \rho A c_p u \nabla T = \nabla A k \nabla T + f_D \frac{\rho A}{2 d_h} |u|^3 + Q_{wall}$

Non-Isothermal Pipe Flow Interface



4. Convective contribute with the die $\boldsymbol{Q_{wall} = hZ(T_{die} - T)}$ h is not constant

5. Heat transfer equation for the die $\rho_2 C_{p2} \frac{\partial T_{\text{die}}}{\delta t} = \nabla \cdot k \nabla T_{die} - Q_{wall}$

Heat Transfer in Solid and Fluid interface

Phase change of nitrogen is not simulated

C_p, ρ, k function of temperature to consider the effect of nitrogen phase change (**Homogenous fluid model**)

Topological Optimization interface

Density Approach

$$\theta = \frac{(\tanh(\beta(\theta_f - \theta_\beta)) + \tanh(\beta\theta_\beta))}{(\tanh(\beta(\theta_f - \theta_\beta)) + \tanh(\beta\theta_\beta))}$$

θ output material volume factor

0 solid

1 liquid

Penalization functions

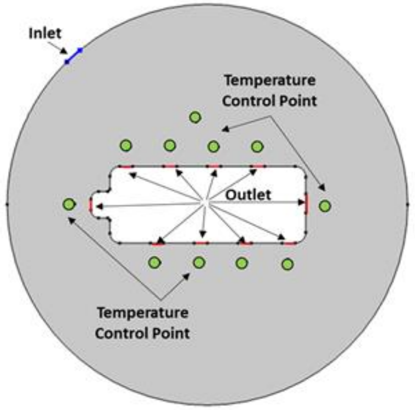
$c = c_l + (1-\theta)^3 * (c_s - c_l)$ *Permeability*

$k = k_s + (1-\theta) * (k_l - k_s)$ *Conductivity*

$\rho = \rho_s + (1-\theta) * (\rho_l - \rho_s)$ *Density*

$c_p = c_{ps} + (1-\theta) * (c_{pl} - c_{ps})$ *Specific Heat Capacity*

Porous domain virtually milled



Equations (Extrusion defects)

Velocity field from Laminar Flow interface

Chemical Potential

$$\frac{\delta\phi}{\delta t} + u \cdot \nabla\phi = \nabla \cdot \gamma \nabla G \longrightarrow$$

Cahn-Hilliard equation

$$\gamma = \chi \delta_i^2$$

Mobility tuning parameter

$$G = \lambda \left[-\nabla^2 \phi + \frac{\phi(\phi^2 - 1)}{\delta_i^2} \right]$$

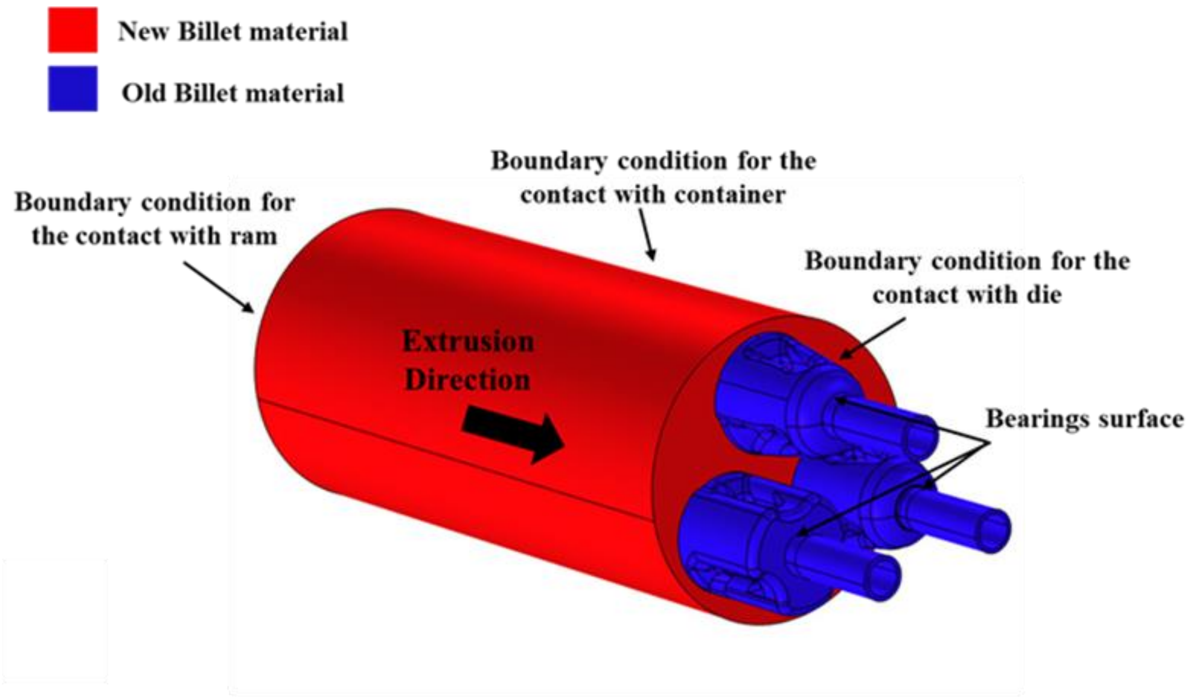
$$\lambda = \frac{3\sigma_{st}\delta_i}{2\sqrt{2}}$$

Surface tension

ϕ phase field parameter:

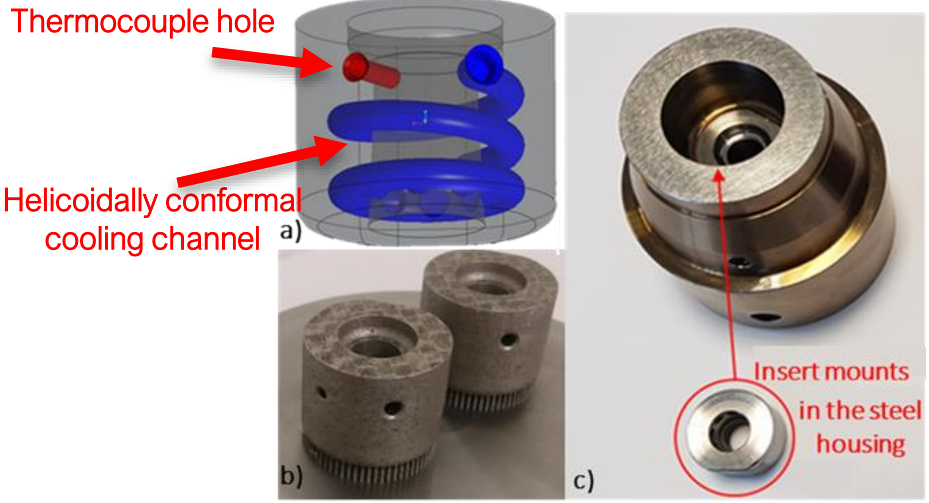
-Value 0 fluid 1

-Value 1 fluid 2



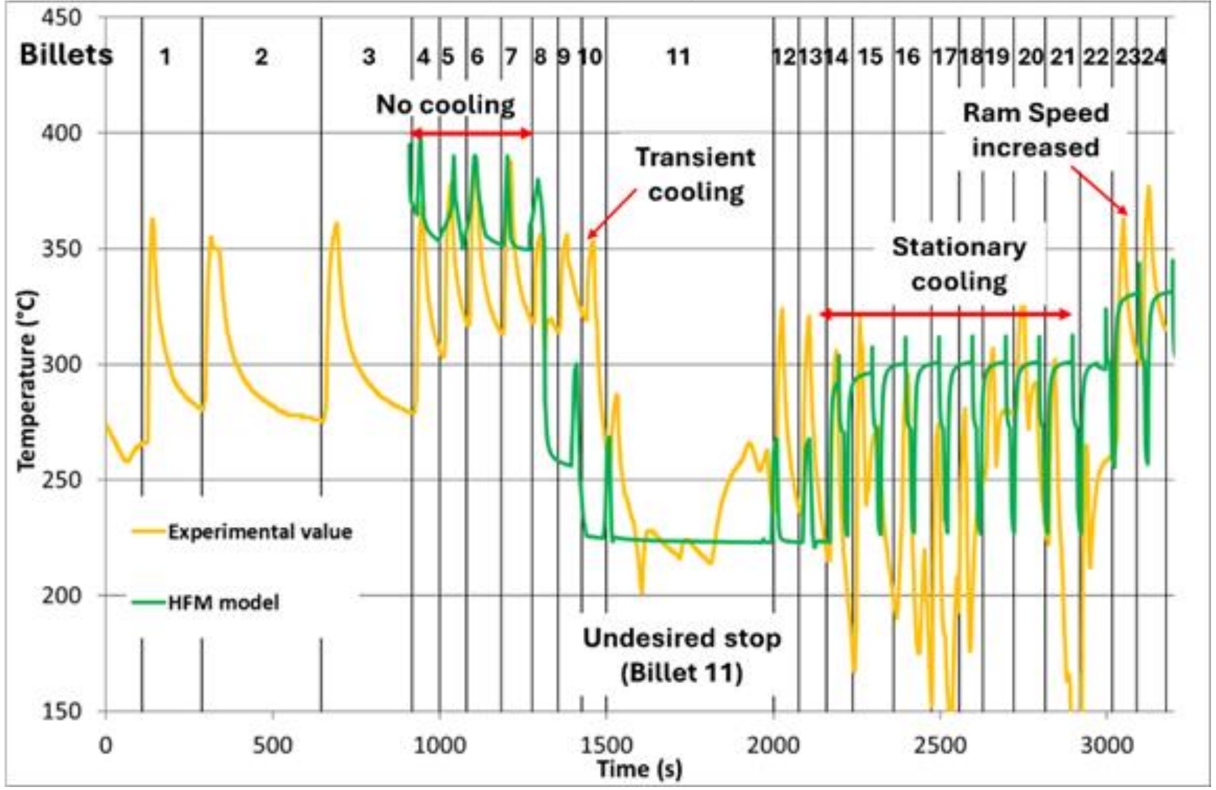
Case Study 1: Multi-die design with conformal cooling channel

Insert for extrusion die realized with 3D manufacturing technology (SLM)

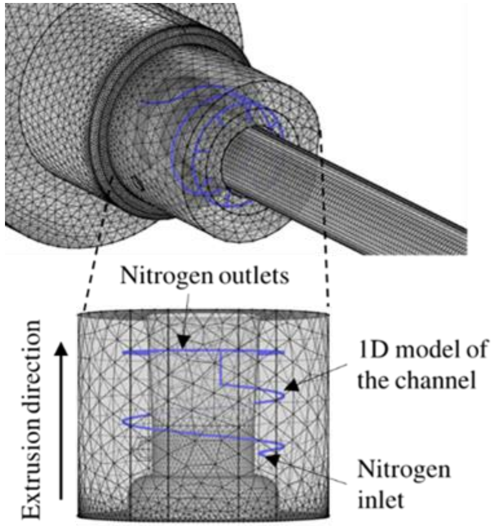


RESULTS

Thermal History recorded by the thermocouple

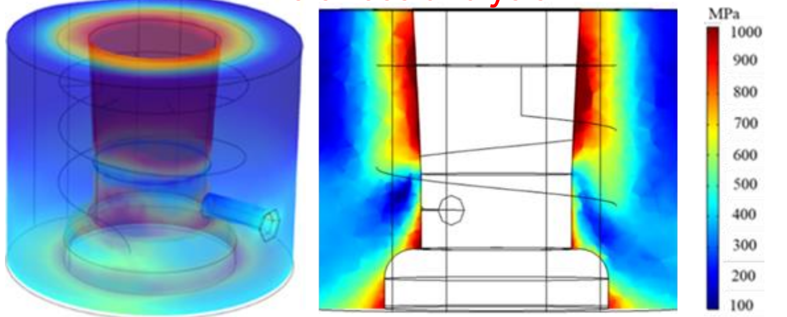


COMSOL Model and Process Parameters



Process Parameters	Value
Billet Temperature	450 °C
Die Temperature	450 °C
Container Temperature	376 °C
Ram Temperature	280 °C
Ram Speed	4.2/6.5 mm/s
Ram, Container/billet interface	No slip + Convection
Die/billet interface	No slip + Conduction
Bearings/billet interface	Slip + Conduction
Inlet Nitrogen Pressure	4 bar
Inlet Nitrogen Temperature	-196 °C
Nitrogen Properties	$f(T)$ [7]

Die stress analysis



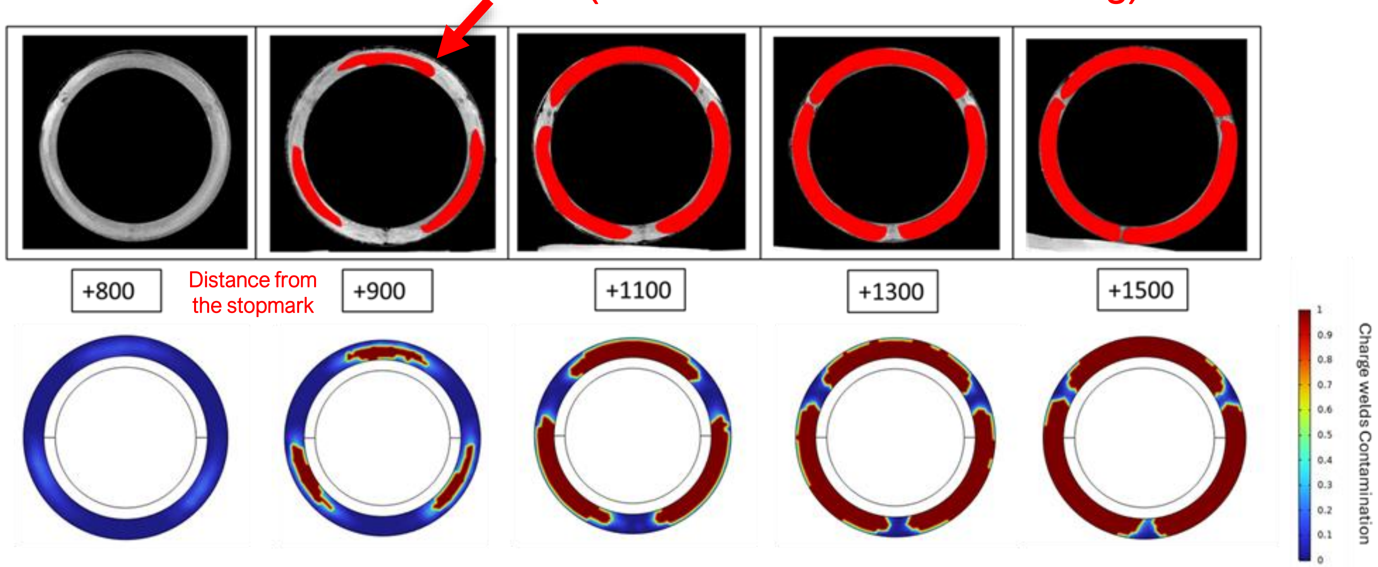
All points under the yield stress

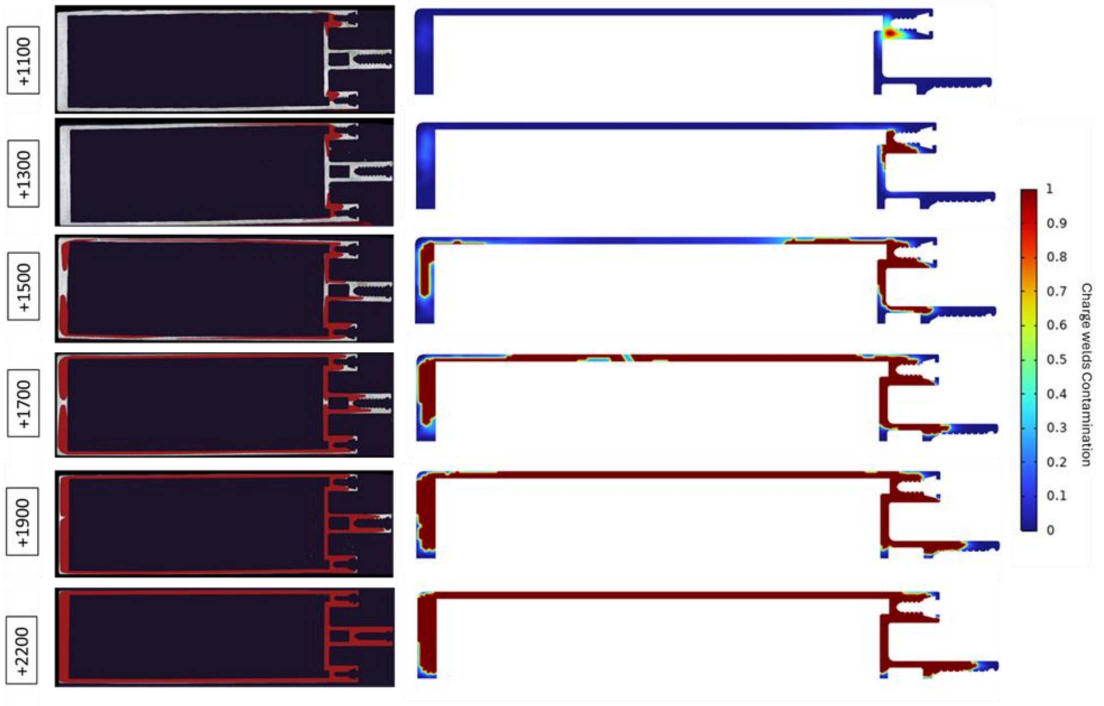
Insert resisted the whole campaign without defects

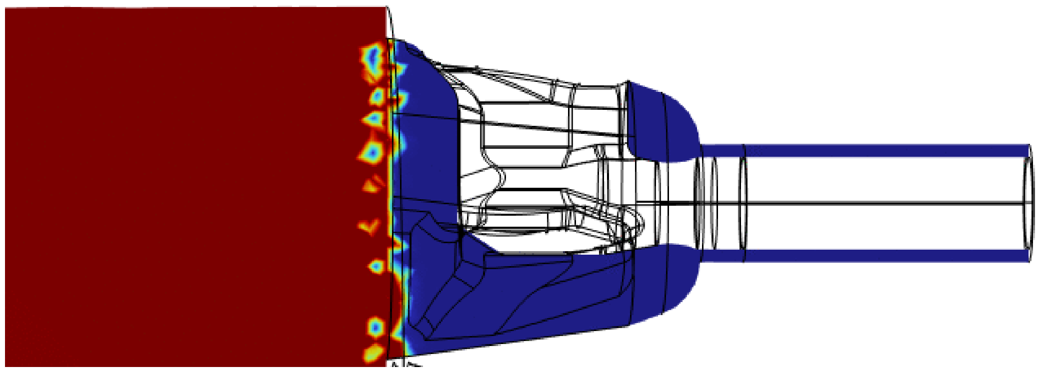
Billet 7	Value
Extrusion Load	0.98 MN
Num Extrusion Load	1.09 MN
%Err	11%

Case Study 2: Phase field method for the assessment of the new-old billet material interaction

New billet material (visible after chemical etching)







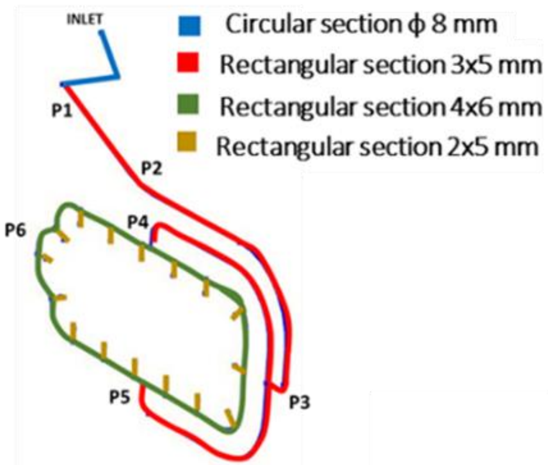
Experimental Analysis is a time and cost consuming activity

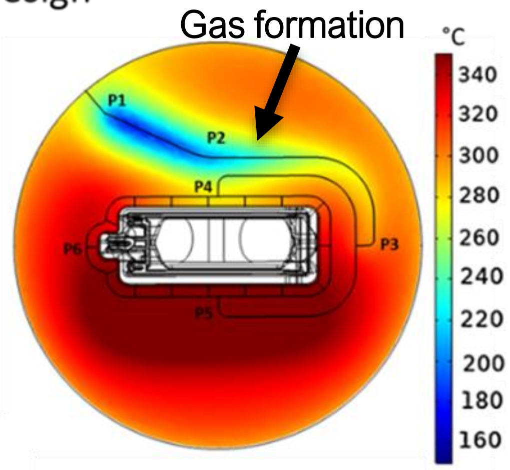
Empirical and analytical approach not accurate

Excessive scrap
or
Not Enough Scrap

Case Study 3: Cooling Channel re-design by means of topological optimization interface

Original Design

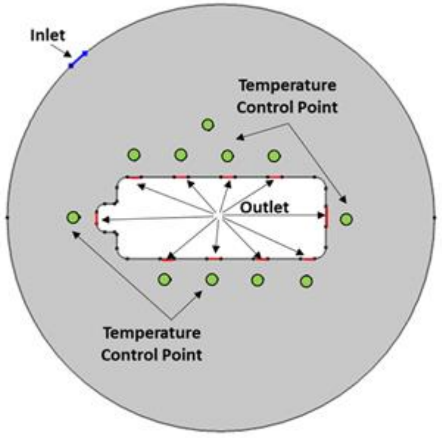




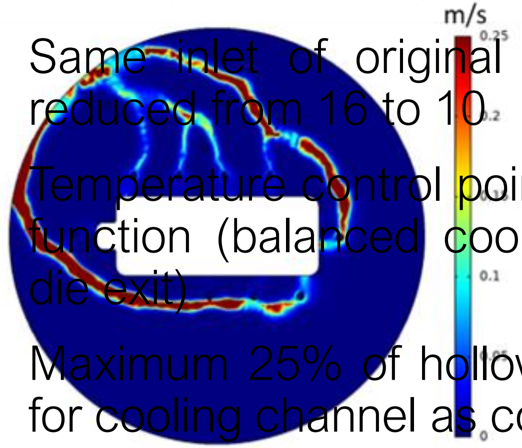
- Channel designed by the die maker without numerical tools
- Experimental results evidenced not efficient cooling
- Numerical error below 10%

Same process parameters of the experimental trial

Topological optimization

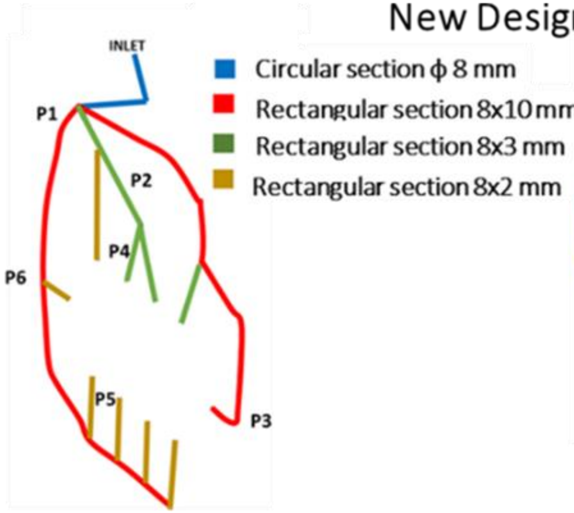


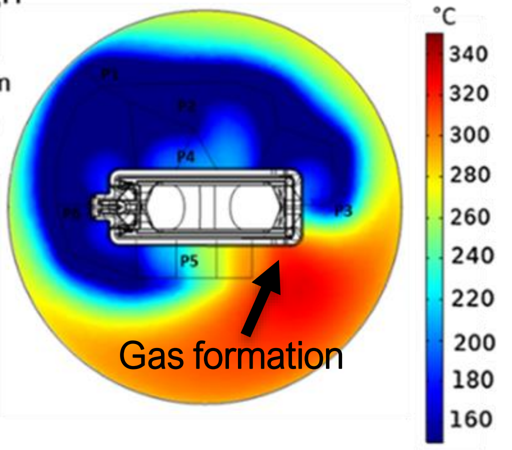
Velocity field of nitrogen



- Same inlet of original design, outlets reduced from 16 to 10
- Temperature control points for objective function (balanced cooling around the die exit)
- Maximum 25% of hollowed-out volume for cooling channel as constraint

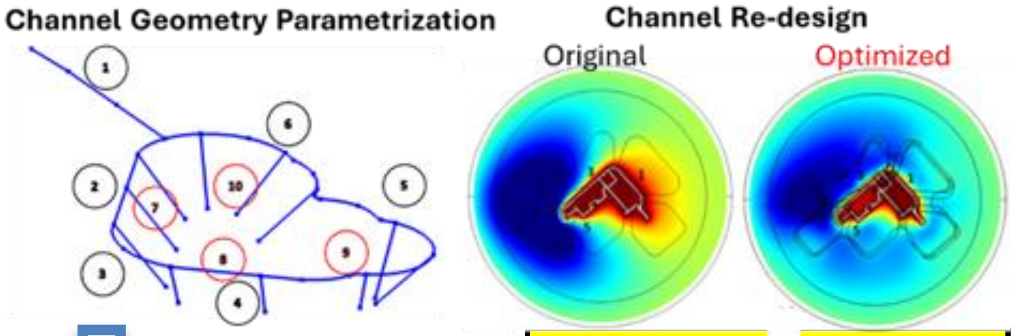
New Design





Case Study 4: Multi-objective optimization of extrusion die

MULTI-OBJECTIVE OPTIMIZATION OF COOLING CHANNEL



- Balanced cooling with the optimized design (max temperature difference from 36°C to 6°C)
- Nitrogen consumption reduced of 60%

Initial Population

Define new design

COMSOL with Matlab

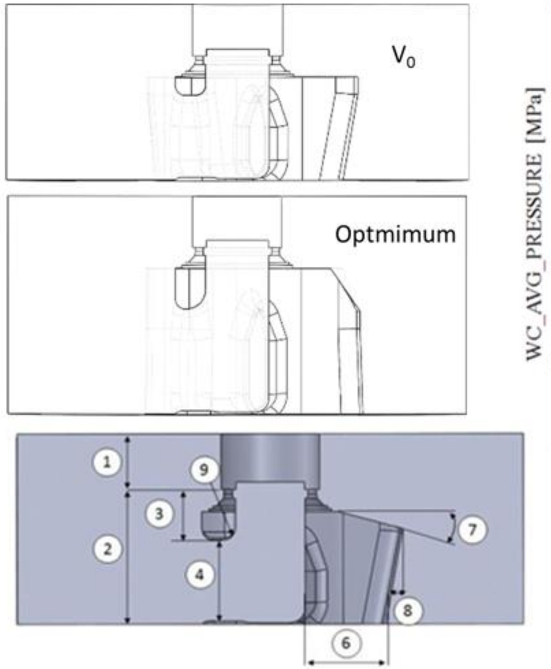
Test automatically all initial configuration

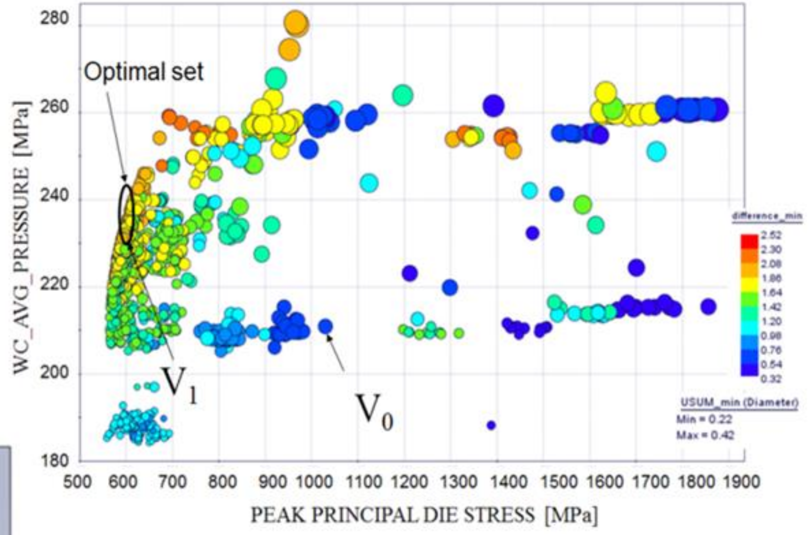
Test the new design

Optimization Platform (Modefrontier)

- Objective Functions
- Constraints
- Genetic Algorithm to optimize the problem

MULTI-OJECTIVE OPTIMIZATION OF DIE DESIGN





PARAMETRIC DIE

- In the original die design a break occurred after 64 extrusion.
- The optimal design showed a peak principal die stress reduced of 46%
- Ram speed doubled
- Mechanical properties of profile improved

Conclusions

- Different interfaces were coupled to generate advanced models able to assess the hot extrusion process from different points of view.
- The accuracy of numerical predictions was demonstrated in terms of extrusion load, thermal field, scrap assessment, cooling efficiency, and die stress analysis.
- The experimental-numerical comparisons also showed the limits of industrial practices, sometimes based on experience and/or empirical approaches.
- An advanced iterative procedures based on the use of genetic algorithms evidenced the concrete possibility of automatically optimizing the die design as well as the entire process concerning the objectives to be achieved.

References

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