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Recent Trends in Nitrogen Cooling Modelling of Extrusion Dies

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Abstract. Nitrogen cooling has been identified as a powerful industrial solution for the hot extrusion process to remove heat in the die and in the profile. The complexity involved in the design of cooling channels depends on many factors, including the cooling path, its position with respect to the hottest zones as well as the nitrogen phase-change that strongly affects the heat removal capacity. However, the industrial approach is still stuck in the empirical and based-experience practices that too often strongly limit the possibilities of obtaining a performing cooling solution. In this context, this work intends to summarize and discuss the advanced recent trends in the design of cooling channels for extrusion dies proposed by the authors based on the numerical approaches, with the final aim to propose possible solutions to fill the current gaps of the suboptimal industrial approaches.

Introduction

In the industrial framework of the hot extrusion process, nitrogen plants are increasingly present with the aim to improve the extrudate's quality and the production rate. Indeed, the proper use of liquid nitrogen allows to reduce both the die and the profile temperature [1-3], to increase the ram speed [4] and to improve of the surface quality of the final products acting against the hot oxidation [1,5]. In detail, the tooling set is provided with a cooling channel usually made on the backer surface in touch with the die, in an effort to surround the exit of the profile and to localize the cooling nearby the hottest bearings' regions. From the nitrogen plant, the liquid nitrogen is transported to the cooling system under pressure in the range of 3-6 bars at a temperature of -196°C, thus trying to have the nitrogen evaporation only at the outlets of the channels, where the gas inert atmosphere strongly reduces the profile oxidation [3, 5]. On the contrary, the phase change within the cooling path can lead to plug the channel (volume expansion of 177 times), drastically reducing the nitrogen flow rate and consequently the efficiency of the heat exchange [6]. For these reasons, the design of cooling channel involves many aspects (path design, channel geometry, distance from bearings, nitrogen parameters…) forcing the use of valid and robust criteria for the detection of the best efficient solution. On the contrary, the industrial approach is still stuck in empirical and experience-based practices that do not guarantee the achievement of optimized and efficient channel designs. Indeed, the efficiency of the cooling system is frequently evaluated only by analyzing the surface quality of the extrudate, erroneously merely correlating the higher "brilliant effect" with the cooling efficiency. However, as previously mentioned, the saving of the profile oxidation depends on the inert atmosphere generated by the gas nitrogen that invests the exit profile, and it is not a proper indication of the decrease in temperature within the die and in the profile. As a further limitation, the experimental evaluation of the cooling efficiency within the production line can be performed only by means of a monitoring temperature system using several thermocouples within the tooling set, an approach not always feasible for saving time and cost. Therefore, in this context,

the main purpose of the work is to present the recent trends in the design of cooling channels for extrusion die, showing in detail the potentiality of approaches based on the numerical simulation. Indeed, the numerical prediction of the cooling efficiency, taking into account all thermo-fluid dynamics aspects of the extrusion process, allows to overcome the current limits of industrial design practices by following robust methodologies. In literature, several works concern the simulation of the extrusion process [3] with the aim to capture all the aspects involved in the process optimization: loads and temperatures prediction [7-8], scrap assessment [9-11], evolution of the microstructure [12-13], optimization of the die design [7, 14] …

To the best of the authors' knowledge, the first attempts to simulate the efficiency of the cooling in the extrusion process were proposed in the work of Holker and Tekkaya [15], where the use of a conformal cooling channel manufactured with additive manufacturing technologies was deeply analyzed. Both numerical and experimental results showed the potentiality of the cooling to reduce the die and the profile temperatures. However, in these first studies, only compressed air was tested as coolant, furthermore, simulating the heat exchange in a simplified way by imposing a constant temperature on the channel walls. Inspired by Finite Element (FE) modeling of cooling channels for plastic injection molding [16], die casting applications [17], and cutting tools [18], an innovative approach was proposed in the works of Pelaccia et al. [4, 6], where the 1D modelling of nitrogen cooling was integrated into 3D model of extrusion process. The reliability of the model was demonstrated by comparing the numerical results with different experimental case studies, showing average errors below 10% in terms of temperature predictions. Starting from these works, Pelaccia and Santangelo [19] proposed the use of Homogenous Fluid Model (HFM) to capture the effect of the nitrogen phase change considering the liquid-gas mixture as a single fluid with pseudo properties. In addition, the potentiality of 1D approach, especially thanks to the low required computational time, was explored to implement an innovative generative digital twin based on genetic algorithms to design, in an automatic and iterative way, the best cooling channel in terms of drop of temperatures, balancing of the cooling around the bearings as well as saving of nitrogen consumption. Both size optimization and topological optimization approaches were proposed and discussed in the works of Pelaccia et al. [20-21].

From this basis, the aim of this work is to summarize and discuss the possible methodologies to model the extrusion process with nitrogen cooling proposed by the authors in the last years. The key achievements reached in the state of art were collected and summarized in the effort to fill the current gaps of the suboptimal industrial approaches.

Strategies for Nitrogen Die Cooling Modelling

The simulation of nitrogen cooling during the extrusion process can be modelled following different strategies (for both steady state and transient analysis) (Fig.1):

- by using an equivalent heat transfer coefficient (HTC) on the channel walls without considering the real nitrogen flow within the channel ①
- by modelling the nitrogen flow within the tooling set (1D or 3D modelling approach) and replacing the heat generated during the extrusion process with equivalent thermal boundary conditions ②
- by solving the thermo-fluid-dynamics problem that involves the nitrogen flow (1D ③ or 3D ④ modelling approach) coupled with the simulation of the extrusion process.

In more detail, the first approach ① is the faster one because it is only necessary to add a thermal boundary condition without increasing the complexity of the model of the extrusion process. However, the experimental HTC is not constant along the cooling path and depends on the fluid-dynamic and the geometry of the cooling channel. Therefore, the use of this method is recommended only for fast preliminary analyses, but it cannot be used to predict the real cooling efficiency of the selected design, especially if the objective function is aimed at reducing the bearings' temperature uniformly.

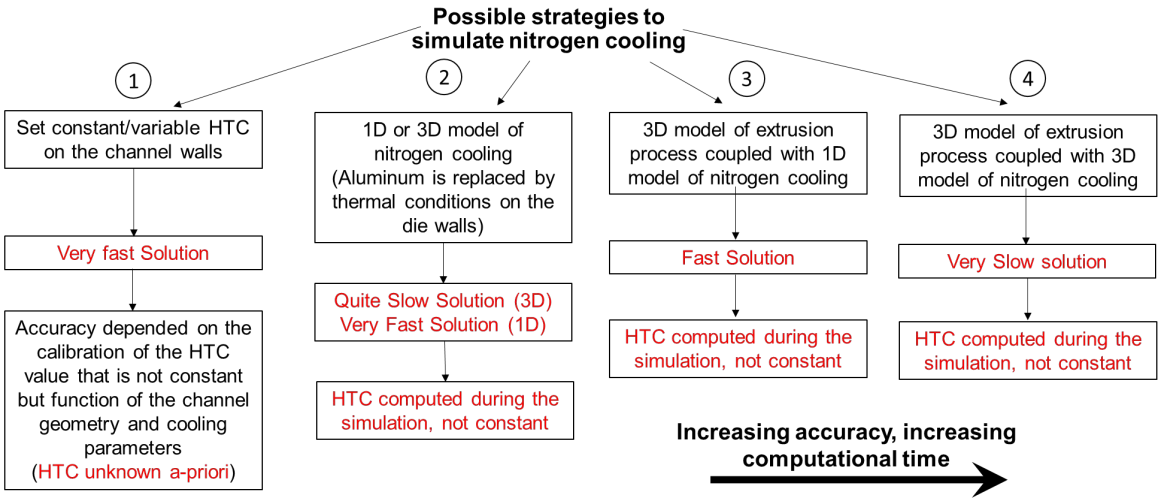

Fig. 1. Possible strategies for modelling the nitrogen cooling.

The coupled modelling of the extrusion process with the nitrogen cooling (③ and ④) is clearly the best approach to capture all the phenomena involved in the process and to accurately evaluate the efficiency of the selected channel design. In this case, the 3D model of the extrusion process can be combined with the 3D model of the channel or with the mono-dimensional (1D) one (Fig.2).

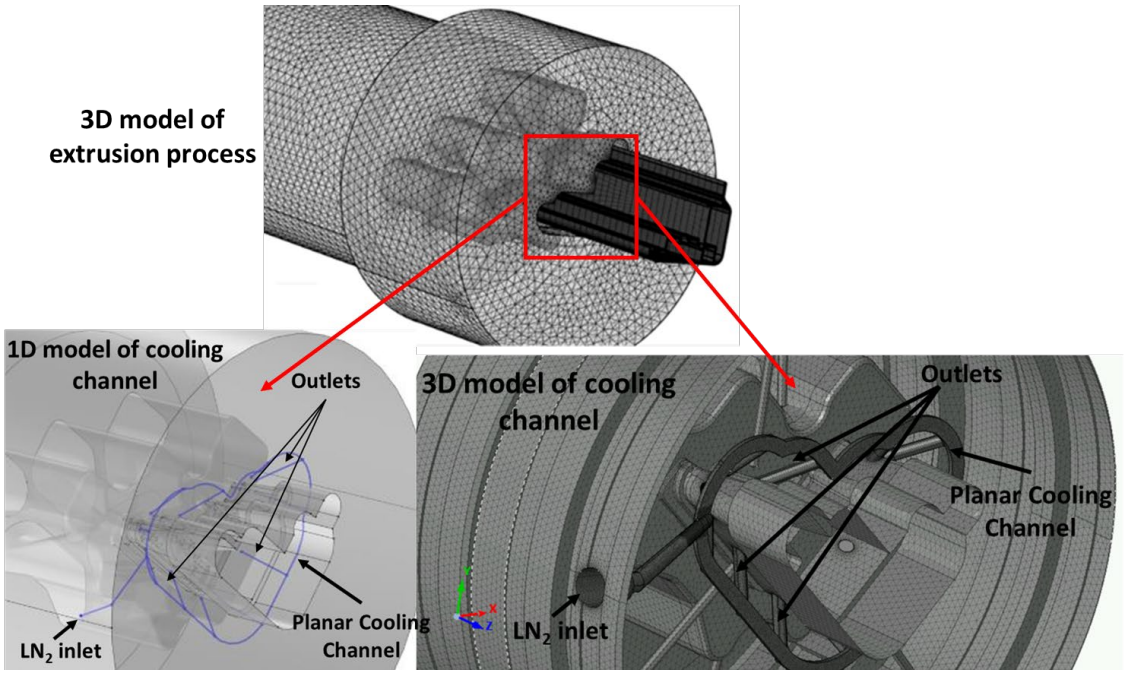

Fig. 2. Possible approaches to model the extrusion process coupled with nitrogen cooling (left 1D, right 3D model of the cooling channel).

The 3D model of the channel allows for analyzing all the fluid-dynamic aspects of the nitrogen flow along the cooling path such as turbulences, pressure drops, presence of stagnation points, and so on. Nevertheless, the computational effort is very high even without considering the nitrogen phase change (even more days of calculation for complex case studies), making the 3D model of the extrusion combined with the 3D model of the channel not suitable for the standard industrial design time. On the other hand, the use of the 1D model of cooling channel drastically reduces the computational time, because the fluid-dynamic problem is reduced to the midline path of the channel, thus neglecting the turbulent effects and the velocity gradient along the 3D channel section. Despite this assumption, knowing the channel cross-section geometry – with potentially non-constant shape and dimensions through the cooling path – enables to calculate the variables involved (e.g., hydraulic diameter, Reynolds number, pressure drops…) with good accuracy [4, 6, 19-21].

The use of a 3D model of the cooling channel (approach ②) can be taken into account when the extrusion process is replaced with thermal boundary conditions where the material flow is in contact with the tooling set (feeder, portholes, bearings…). In such a way, the study is isolated to the die-set with a significant computational time saving. The accuracy of this approach depends on the applied thermal boundary conditions that should be obtained by a preliminary simulation of the extrusion process without cooling. Indeed, the cooling path must be designed to further reduce the temperature in the hottest surfaces and, to a lesser extent in the other areas, so that the thermal gradient on the die walls caused by the material flow must be well modelled.

This approach of studying only the heat transfer within the die can be also used with the 1D approach with the aim to bring the computational needed time to a few minutes or less. It becomes then reasonable that the integration of the model within optimization and generative tools able to test automatically and iteratively many different designs, pursuing specified constraints and objective functions. Indeed, the 1D approach permits to easily change the cooling path and/or the channel section geometry without re-design (at each iteration) the die with the new 3D cooling channels.

In summary, the simulation of the nitrogen cooling system using the 1D model guarantees good results despite the simplifications, gaining on the other hand a drastic reduction of the computational time and the possibility to fast re-design the cooling channel. However, the 3D model of cooling channel can be simulated with acceptable computational time if the extrusion process is replaced with thermal boundary conditions, making this approach competitive to analyze accurately all fluid-dynamics phenomena involved during the nitrogen cooling. For example, the 1D model can be used to fast select some good designs that may be tested with the 3D approach for a robust and reliable final check.

1D vs 3D Approach: an Industrial Case Study

A selected experimental case study was deeply analyzed in the work of Donati et al. [2] where an AA6060 industrial hollow profile (Fig. 3) was extruded in different conditions, varying the nitrogen flow rate (0% 20% 30% 100%).

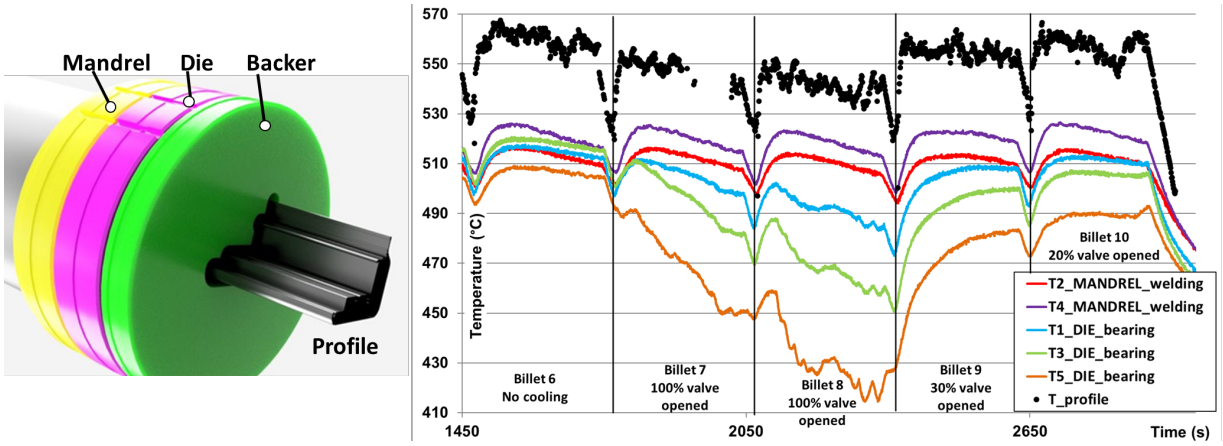

Fig. 3. Experimental case study analysed in the work of Donati et al. [2]: Rendering of the tools set up while forming the profile (left), Thermal history of the extrusion process (right).

The cooling channel was manufactured in the backer surface in contact with the die, while eleven outlets were made in the die to convey the nitrogen at the exit from the bearings: the 3D CAD and the dimensions of the channel are reported in Fig. 4. Remarkable results are the maximum decrease in temperature of 80 °C in the bearings (acquired by the thermocouple T5), of 20°C in the profile, and no significant temperature changes in the mandrel (thermocouples T2 and T4), where the cooling could backfire limiting the aluminum deformability. However, the cooling around the bearings was not homogenous since a maximum difference of 60°C was obtained between T5 and T1.

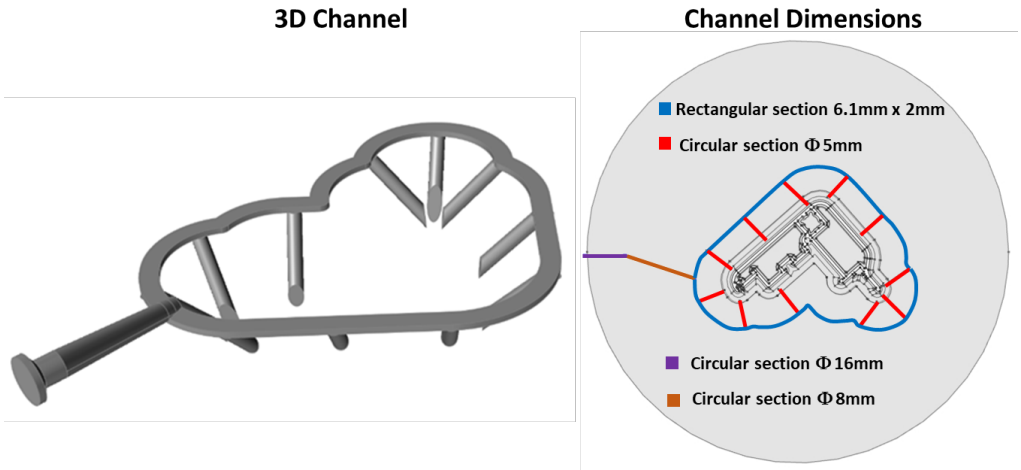

Fig. 4. The cooling channel designed by the die maker [2]: 3D rendering of the cooling path (left), Channel dimensions (right).

The case study was simulated testing both the 1D and 3D model of the cooling channel: the 3D model of the extrusion process was coupled with the 1D model of cooling channel in the first case (approach ③), while the 3D model of the die-set was coupled with the 3D model of the cooling channel in the second case (approach ②), replacing the aluminum flow with equivalent thermal boundary conditions. The latter was taken by the steady-state 3D simulation of the extrusion process without nitrogen cooling (billet 6 in Fig. 3).

The 1D nitrogen flow modeling was reported in detail in some works of Pelaccia et al. [4,6], while for the 3D approach, the Spalart–Allmaras turbulence model [22] was tested. The Multi-frontal Massively Parallel Solver (MUMPS) was used for both cases. In Tab. 1 are reported all the process parameters set for the steady state simulations of the 8th billet, experimental extruded with a 100% of nitrogen valve opening (Fig. 3).

Table 1. Process Parameters for the steady simulations: 1D model vs 3D model (Billet 8).

Process Parameters	1D model	3D model
Initial Billet Temperature	460°C	Not simulated
Initial Die Temperature	500 °C	500 °C
Container Boundary Condition	Convection 427°C 11000 W m^{-2} K^{-1}	Not simulated
Ram Boundary Condition	Convection 413°C 11000 W m^{-2} K^{-1}	Not simulated
Ram Speed	2.71 mm s^{-1}	Not simulated
Ports/aluminium interface	Real conduction with aluminium flow	Convection 510°C 11000 W m^{-2} K^{-1}
Welding chamber/aluminium interface	Real conduction with aluminium flow	Convection 540°C 11000 W m^{-2} K^{-1}
Bearings/billet interface	Real conduction with aluminium flow	Convection 565°C 25000 W m^{-2} K^{-1}
Inlet Nitrogen Pressure or Inlet nitrogen flow rate	2 bar (100%)	2 bar (100%)
Inlet Nitrogen Temperature	-196 °C	-196 °C
Liquid Nitrogen Density (-196 °C, room pressure)	806.59 kg m^{-3}	806.59 kg m^{-3}
Liquid Dynamic Viscosity (-196 °C, room pressure)	1.6137E-4 Pa s	1.6137E-4 Pa s
Liquid Nitrogen heat capacity at constant pressure (-196 °C, room pressure)	2.041 J g^{-1} K^{-1}	2.041 J g^{-1} K^{-1}
Liquid Nitrogen thermal conductivity (-196 °C, room pressure)	0.1465 W m^{-1} K^{-1}	0.1465 W m^{-1} K^{-1}

Figure 5 shows the thermal field around the bearings obtained with both numerical approaches: either way, the effect of nitrogen cooling was well captured as well as the inhomogeneity of the temperatures around the bearings caused by the selected channel design.

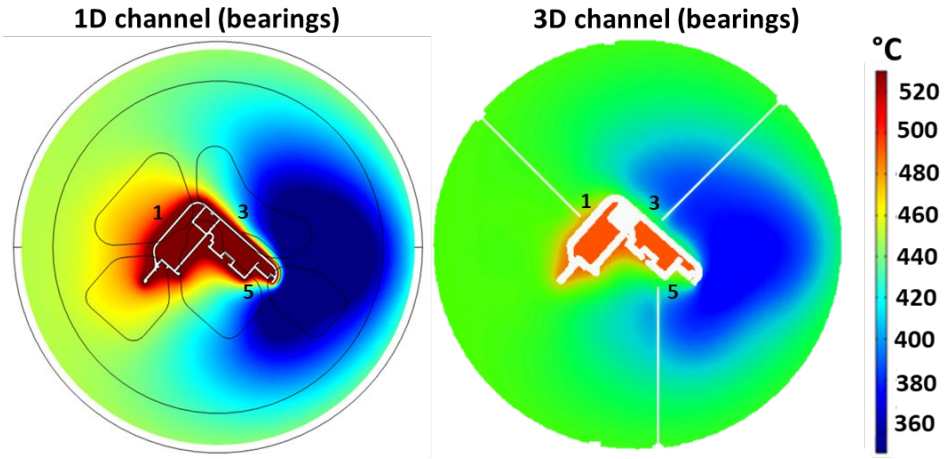

Fig. 5. The thermal fields obtained around the bearing zones: 1D (left) vs 3D (right) approach.

Table 2 reports the comparisons between the experimental and the numerical results: in detail, the simulation performed using the 3D channel showed a lower difference between T3 and T5 with respect to the experimental data, while the mono-dimensional approach ensured more reliable results. However, both approaches achieved good results with numerical errors below 6% in terms of temperature prediction.

The fully 3D approach gained little less accurate results because a constant thermal boundary condition was adopted both on the ports, on the welding chamber, and on the bearing surface, while the 1D approach allowed simulating the 3D aluminum flow coupled with the nitrogen cooling, offering a more detailed modeling of the process [3]. For example, around the bearings, a difference in temperature of about 10 °C was observed between T3 (the hottest) and T5 in uncooled conditions; the difference increased to 30 °C when the nitrogen valve was fully opened (Fig. 3). Therefore, the thermal field generated by the aluminum flow around the bearings was not homogeneous and, in this case, the approximation with constant boundary conditions resulted in higher numerical errors, overestimating the temperatures around T5 and consequently underestimating the cooling efficiency in this region.

Table 2. Thermocouple temperatures in the die: Experimental vs Numerical results (Billet 8).

	Thermocouples Temperature [°C]			**Computational time**
	T1	**T3**	**T5**	
Exp.	490	460	430	
1D Num.	509	450	430	15 min
Err%	3,9	-2.2	0	
3D Num.	498	447	453	4 h
Err%	1.6	-2.8	-5.3	

Even if the numerical results obtained with the two presented approaches are comparable, the main difference emerged in terms of required computational time, which evidences the potentiality of the mono-dimensional model: 15 minutes using the 1D model coupled with the 3D model of the extrusion process against about 4 hours using the fully 3D model without the simulation of the aluminum flow (Intel® core™ processor i7-7700HQ and Ram 16GB). The computational time depends on many factors (mesh, solver, computational power of the computer…); however, it is clear how the 1D approach allows to drastically reduce the computational effort without losing in accuracy.

Automatic Design of Cooling Channel Using the 1D Approach: Size and Topological Optimization

The decrease of the computational time ensured by the mono-dimensional approach can be exploited within the framework of the multi-objective optimization, where the best channel design is automatically searched and selected. Basically, these methods use algorithms (adaptive, evolutionary, heuristic…) to find the solution that better fits with the objective functions and the constraints, iteratively changing the input variables, that, in this context, are correlated to the geometry of the cooling channel. Therefore, it becomes clear how the low computational effort is fundamental for testing a large number of designs in a reasonable time.

In this paragraph, the most remarkable results of the works of Pelaccia et al. [20-21] are summarized, showing two different approaches for the optimization of the cooling channel design for the extrusion process.

The first work [20] involved the size optimization of the cooling channel (designed by the die maker without the use of numerical tools) tested in the work of Donati et al. [2], where, as previously shown, the nitrogen cooling was effective but not homogeneous around the bearings. The size optimization consists of changing the cross-channel section along the cooling path without modifying the latter. In this case, the 1D cooling path was divided into ten parts (Fig. 6), for each of which the hydraulic diameter was set as the input variable of the optimization. In addition, the nitrogen inlet pressure was selected as a further input variable in order to control the nitrogen flow rate with both the channel design and the valve opening.

The objective functions were the minimization of the temperature difference between the three thermocouples around the bearings (imposing an absolute target value of 450°C), and the minimization of the nitrogen consumption. The algorithm used to solve the optimization problem was the Non-dominated Sorting Genetic Algorithm (NSGA-II). A total of 100 designs (10*10 initial population*number of generations) were evaluated, starting from an initial population of 10 configurations generated using a Pseudo-Random Sobol DOE strategy: the FE model was launched by the optimizer, the results stored in a table, and, at each subsequent run, the input variables were changed by the algorithm with the aim to satisfy the objective functions. The FE model was simplified to reduce the computational time: the aluminum flow was replaced by the equivalent thermal boundary condition, thus reducing the simulation time from 15 minutes (see Tab. 2) to 5 minutes (Intel® core™ processor i7-7700HQ and Ram 16GB). Therefore, a total computational time of about 9 hours was spent to evaluate 100 designs, perfectly in line with the demands of today's industrial framework.

Figure 7 shows the optimal design proposed by the optimizer: the thermal field around the bearings is more homogenous, obtaining a temperature of 458 °C, 453°C and 460°C for T1, T3, and T5 respectively, also reducing the nitrogen consumption of about 60%.

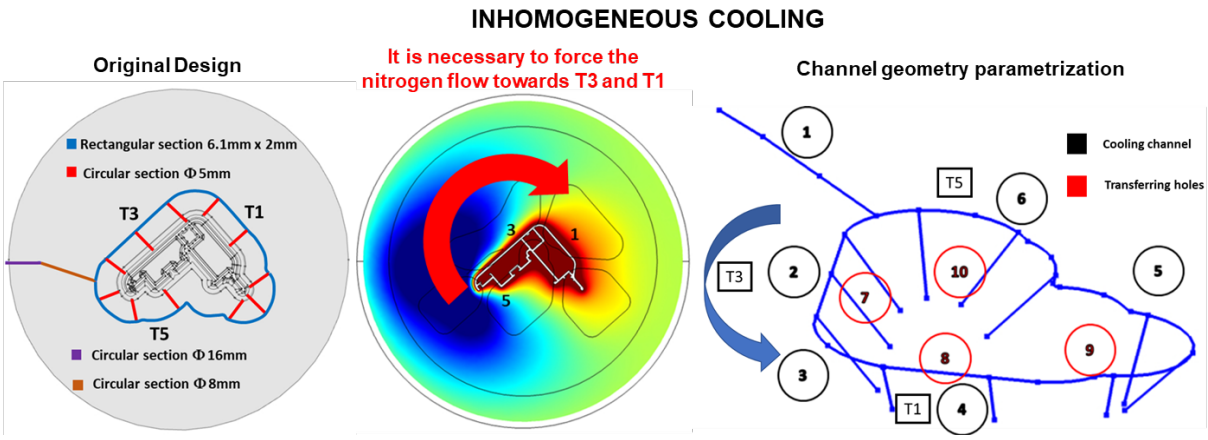

Fig. 6. Selection of the input variable for the optimization problem: Channel geometry parametrization.

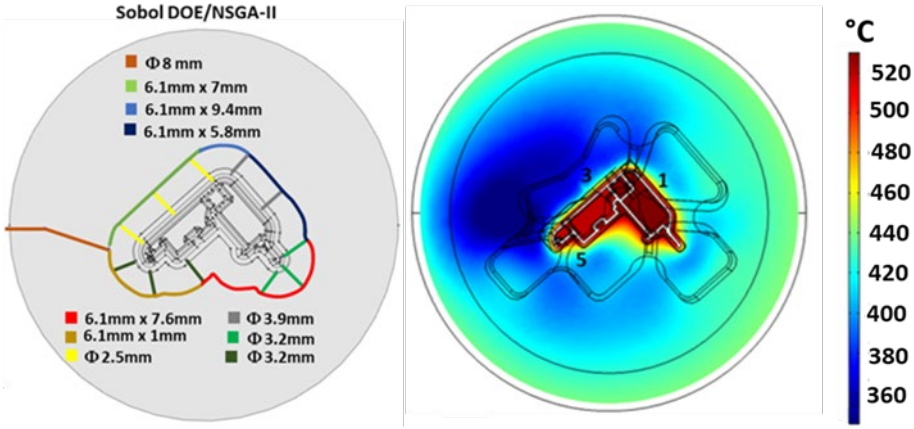

Fig. 7. The optimal channel design: Channel dimensions (left) and thermal field around the bearings (right).

The second proposed approach is the topological optimization, in which different cooling paths were created and tested by the optimizer, thus trying to satisfy the objective functions and the constraints. The cooling channel tested in this work [21], always designed by the die maker without the use of numerical tools, presented great limits in terms of cooling efficiency (Fig. 8 [6]). Indeed, the drops in temperature were negligible when the nitrogen valve was opened at 40%, and, also after nine billets extruded with the nitrogen valve fully opened, the cooling around the bearings was not effective.

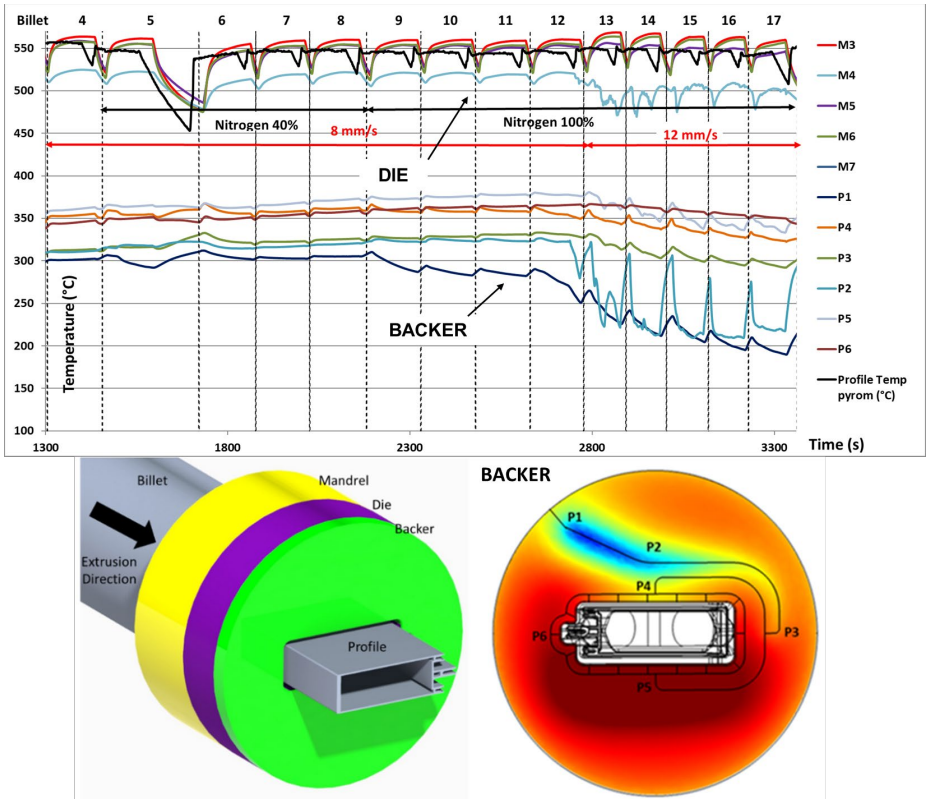

Fig. 8. Experimental case study analysed in the work of Pelaccia et al. [6]: Thermal history of the extrusion process (top), rendering of the tools set up while forming the profile and numerical thermal field along the cooling path (bottom).

In this case, the excessive pressure drops, caused by too many ramifications and outlets, resulted in a great gas formation within the cooling path that strongly limited the heat exchange. Therefore, a simple size optimization could be not enough to obtain a good channel design. The 2D model of the backer without the channels was selected for the topological optimization: a convective heat flux perpendicular to the backer plane was defined as a boundary condition to replicate, in a simplified way, the heat exchange between the backer and the hot die; the minimization of the temperature

differences between eleven control points (Fig. 9) was chosen as an objective function; one inlet, 10 outlets, and a maximum available volume (25%) to create the cooling path was defined as constraints to avoid excessive voids in the backer (not feasible from a technological point of view). The nitrogen flow was modelled using the Darcy flow model, thus considering the backer as a porous media with porosity and the other physical properties controlled with penalization functions. Following this approach, the backer was "virtually milled" to create the cooling path: the elements of the mesh with a porosity equal to zero were considered solid with the physical properties of the steel, while the elements with porosity equal to one were treated as liquid nitrogen [21].

Figure 9 shows the nitrogen velocity field resulting from the topological optimization and the final design of the cooling channel inspired by the obtained results. In detail, the topological optimization suggested splitting the channel into three different paths instead of just one with a lot of ramifications as in the original design. The improved cooling efficiency of the new cooling path is highlighted in Fig. 10, where the thermal field in the backer generated by the original design was compared with the new one.

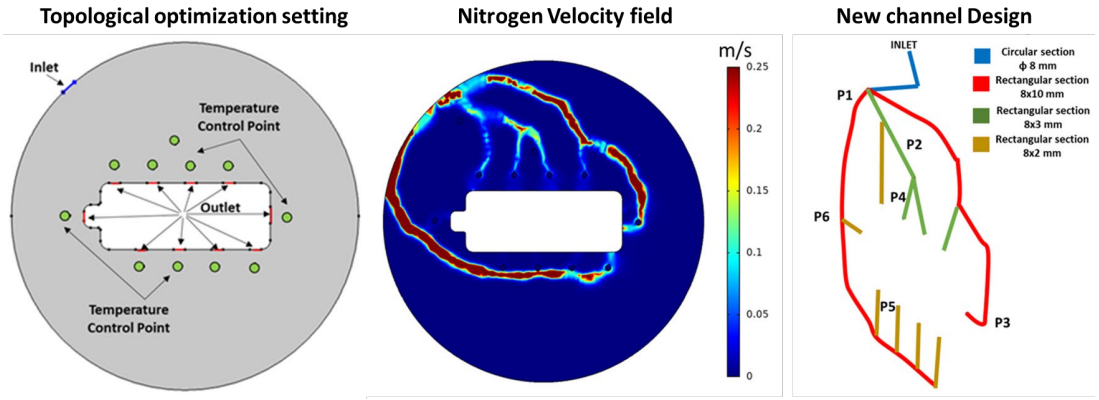

Fig. 9. The topological optimization: from the problem setting (left) to the design of the new cooling channel (right).

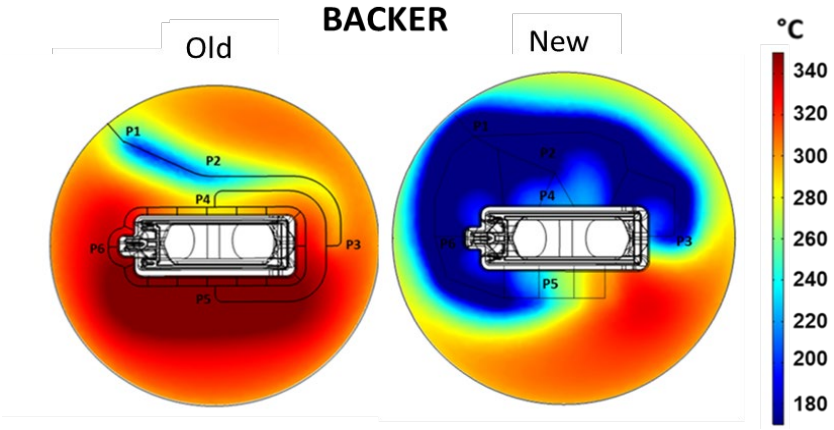

Fig. 10. The thermal field in the backer: Original design (left) vs New optimized design (right).

Homogenous Fluid Model (HFM) as a Simplified Approach to Capture the Effect of the Phase Change within the Cooling Path

One of the main drawbacks of a poorly designed cooling channel can be the formation of a high quote of gaseous nitrogen along the cooling path that strongly reduces the heat exchange with the tooling set. In this context, the use of a model (1D or 3D) with a fully liquid nitrogen can lead to a great overestimation of the cooling effect, while the fully gaseous model can cause the opposite effect. Therefore, it is required a numerical model able to capture the gas formation with the final aim to better understand the phenomena that affect the cooling efficiency. However, the computational effort to simulate the nitrogen phase change during the heat exchange with the tooling set can be extremely high, also without the coupling with the extrusion process.

In the work of Pelaccia and Santangelo [19] the 1D homogenous fluid model (HFM) was proposed as a simplified approach to take into account the gas formation without the real simulation of the phase change. The HFM approach considers the liquid-gas mixture as a single fluid with pseudo properties. Therefore, the physical properties of the nitrogen (dynamic viscosity, density, heat transfer coefficient etc.) were replaced with expressions that depend on the nitrogen vapor title ω_g, not set constant but as a function of the heat exchange within the channel [19].

An example of application of the HFM approach can be presented analyzing the experimental case study discussed in the work about the topological optimization [21], where, as previously mentioned, the cooling efficiency was very low (Fig. 8). Two steady-state simulations of the last extrusion (17^{th} billet) were performed: the numerical prediction with the fully liquid model was compared with the one obtained with the HFM approach. Table 3 reports the process parameters set in both simulations.

Table 3. Process Parameters for the steady simulations: fully liquid model vs HFM model (Billet 17 in Fig. 8).

Process Parameters	**Fully Liquid**	**HFM model**
Billet Temperature	480 °C	480 °C
Die Temperature	520 °C	520 °C
Container boundary condition	Convection 430 °C 11000 W m^{-2} K^{-1}	Convection 430 °C 11000 W m^{-2} K^{-1}
Ram boundary condition	Convection 440 °C 11000 W m^{-2} K^{-1}	Convection 440 °C 11000 W m^{-2} K^{-}
Backer surfaces in contact with press	Convection 280 °C 3000 W m^{-2} K^{-}	Convection 280 °C 3000 W m^{-2} K^{-}
Ram Speed	12 mm/s	12 mm/s
Inlet Nitrogen Pressure	4 bar (100%)	4 bar (100%)
Inlet Nitrogen Temperature	-196 °C	-196 °C
Nitrogen Density	806.59 kg m^{-3}	$\rho(\omega_g)$ [19]
Dynamic Viscosity	1.6137E-4 Pa s	μ (ω_g) [19]
Nitrogen heat capacity at constant pressure	2.041 J g^{-1} K^{-1}	c_p (ω_g) [19]
Nitrogen thermal conductivity	0.1465 W m^{-1} K^{-1}	k(ω_g) [19]

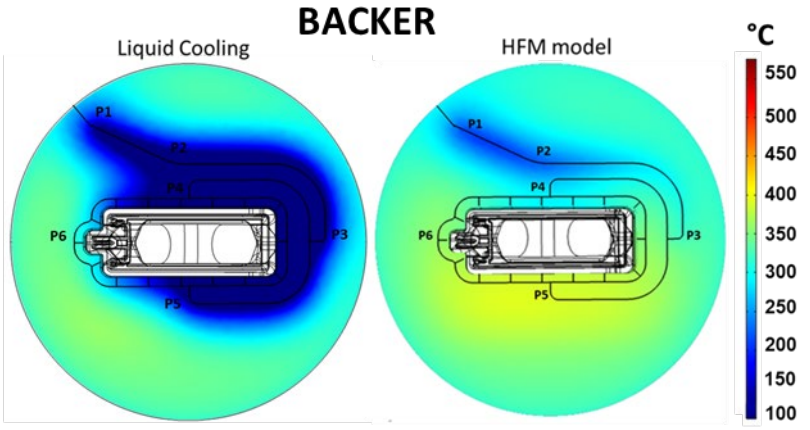

Fig. 11. The thermal field in the backer: fully liquid model (left) vs HFM approach (right).

Figure 11 shows the thermal field in the backer plane where the thermocouples were positioned: it is immediately clear how the fully liquid model overestimated the drop of temperature along the cooling path, while the HFM one well captured the drastic reduction of the heat exchange caused by the gas formation, that restricted the cooling only nearby the nitrogen inlet. In detail, Tab 4 reports the comparison of the two numerical models with the experimental data: the average errors in terms of temperature prediction were about the 7% and 38% for the HFM and the fully liquid model, respectively.

Table 4. Thermocouple temperatures in the backer: Experimental vs Numerical results (Billet 17).

17th extrusion	Thermocouples Temperature [°C]					
	P1	P2	P3	P4	P5	P6
Experimental	196	219	296	326	340	350
Fully Liquid	155	160	170	120	145	285
%Err Fully Liquid	-20.9%	-26.9%	-42.6%	-63.2%	-57.4%	-18.6%
HFM numerical	205	210	298	260	355	335
%Err HFM	+4.6%	-4.1%	-1%	-20.4%	+4.4%	-4.3%

Conclusions

This work summarized the state of art about the recent trends in the design of cooling channels for extrusion dies proposed by the authors and based on the numerical simulation. The discussed experimental case studies showed the possible limits (low cooling efficiency, inhomogeneous cooling) of the cooling channels designed based on the current industrial practices. The analyzed works evidenced the potentiality of the numerical modelling for the prediction of the cooling efficiency: the 3D model of the cooling channel should be used only with appropriate simplifications to reduce the high computational effort, while the mono-dimensional approach demonstrated a good accuracy (average errors below 10%) despite the simplifications, thus achieving a saving CPU time of about 90%. The advantage in terms of computational time allowed to integrate the 1D approach within an optimizer to automatically design/re-design the cooling path with the final aim of achieving the best cooling performances: the size optimization can be used to improve a quite good cooling path only changing the channel dimensions, while the topological optimization allow to create a new cooling path pursuing the selected objective functions. Among the most remarkable results, recently, a new 1D nitrogen model based on the homogenous fluid (HFM) approach was proposed and validated. The HFM makes it possible to capture the thermal effects of the nitrogen phase change, simulating a single fluid with pseudo properties that depend on the nitrogen vapor title which, in turn, is a function of the heat exchange within the channel.

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