Investigation on the topological optimization of cooling channels for extrusion dies

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Abstract. During the extrusion process, high temperatures are generated, due to friction and deformation works, potentially leading to profile and die defects. Among the suggested solutions aimed at controlling the thermal field of the process, the most accredited one involves the manufacturing of cooling channels at the mating face between the die and a third plate. Despite the proven efficiency of well-designed channels, the main drawback lies in the managing of the many variables involved that strongly affect the cooling efficiency and balancing. In this frame, aim of the work is to investigate the applicability of the topological optimization tool, proposed by COMSOL Multiphysics software, for the design of cooling channels in extrusion dies. To validate the tool, an industrial case study has been selected and results compared between not optimized and optimized cooling solutions.

Introduction

Temperatures developed during the hot extrusion of industrial aluminum profiles are frequently nearby critical thresholds that can be detrimental for the profile quality, the die lifetime and the overall productivity [1]. To face the issue, one of the most efficient solution lies in the flowing of liquid nitrogen in a channel milled and drilled in the mating surface between the die and a third plate, the backer, incorporated in the tooling set as support to limit the die deflections [2]. Even if the use of nitrogen nowadays represents a consolidated industrial practice due to its proved efficiency [3,4], the channel design still represents a challenge due to the many variables involved, strongly affecting the fluid-dynamic and thermal performances of the nitrogen flow [5]. To date, nitrogen cooling channels are still designed based on die makers experience and their effectiveness judged merely by observing the out coming profile, a practice motivated by the complexity and cost of a continuous experimental monitoring of cooling efficiency: a glossy surface states a good design, a matt one a poor design. However, the surface appearance is mostly related to the gaseous nitrogen flowing from the channel' outlets that creates an inert atmosphere around the profile reducing oxidation, rather than to the overall channel performances. Nevertheless, this drawback can be overcome by the adoption of reliable numerical models at the process and channel design stage able to return continuous maps, in space and time, of all the parameters required to properly judge the selected solution. In addition, the level of complexity force not only through numerical approaches, but also demands for automated, robust and comprehensive methodologies.

If many works have been reported on aluminum extrusion FE (Finite Element) modelling [6,7], stating the robustness and reliability of the approach, only recently Reggiani and Donati [8], and Pelaccia et al. [9,10] proposed a comprehensive numerical model for the prediction of the thermal

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gradient during the extrusion process with nitrogen cooling. In addition, very promising results have already been achieved, by the same authors, by integrating the comprehensive FE model in an optimization platform able to change the channel sections iteratively and automatically along the path [11]. However, the main limitation of the procedure lies in leaving the optimizer free to vary only the cross-sections point by point, but not the path. More challenging and ambitious is the topological optimization applied to cooling channels that allows to attain any path within the design space, instead of dealing with a predefined configuration.

Currently, topological optimization is widely used in many engineering applications at the concept level of a design process, including the optimization of cooling channels in injection molds [12] and stamping tools [13]. However, to the best of the authors knowledge, a free-shape topological optimization has never been applied for the design of cooling channels in extrusion dies, thus motivating the proposed work.

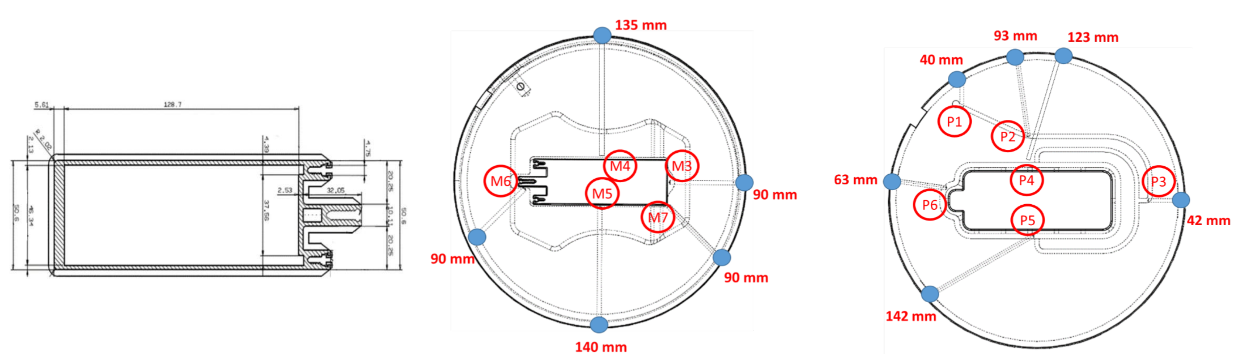
Therefore, in this context, an industrial case study previously investigated [10] has been selected to present and validate the approach. The process parameters and the experimental settings were selected as input for the subsequently numerical analysis. The original channel design, merely based on the die-maker expertise without the support of the simulation, was compared in terms of cooling efficiency with the new one designed using the numerical approach based on topological optimization.

Experimental Analysis

The Fig. 1 shows the tooling set composed by the mandrel, die and backer [10]. The mandrel with five portholes was designed to obtain the industrial hollow profile shown in Fig. 2a, while a planar cooling channel was manufactured in the backer surface in contact with the die (Fig. 1c).

a) b) c)

Fig. 1. The tooling set: a) mandrel; b) die; c) backer with the cooling channel [10].



a) b) c)

Fig. 2. a) Profile drawing, b) thermocouple locations in the die, c) thermocouple locations in the backer; dimensions in millimetres report the acquired depths of the thermocouple holes [10].

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Eleven thermocouples were positioned within the tooling set (Figs. 2b and 2c) in order to monitor the temperature field during the whole extrusion process. Five thermocouples were placed in the die around the bearings where the highest temperatures were generated (M7 was broken during the trials), six in the backer by following the nitrogen path with the aim to evaluate the cooling channel performances. The experimental campaign consisted in the extrusion of seventeen AA6060 billets in different conditions of extrusion speed and nitrogen flow rate. In detail, four different conditions were evaluated, excluding the first billet used to warm up the tooling set: the extrusion process without nitrogen cooling using the standard ram speed of 8 mm/s selected by the extruder (billets 2-4), the extrusion process with nitrogen valve opened at 40% maintaining the standard ram speed (billets 5-8), the extrusion process with nitrogen valve fully opened maintaining the standard ram speed (billets 9-12) and the extrusion process at increased ram speed of 50% (12 mm/s) by continuing to use the maximum nitrogen flow rate (billets 13-17). The thermal history of the tooling set recorded by the thermocouples is reported in Fig. 3. At first, it is worth nothing the temperature difference of about 200°C already in the uncooled condition between the cooling channel plane and the bearings, a trend that highlights the great distance between the cooling channel and the area where the highest amount of heat is developed. In the die, the thermal field showed a rapid rise in temperature in all thermocouples during the extrusion of each billet and a subsequent temperature decrease during the dwell time for the billet change. On the other hand, the heat exchange between the hot die and the less warm backer made more stable the temperatures in the backer, showing minimal differences between the extrusion phase and the billet phase change.

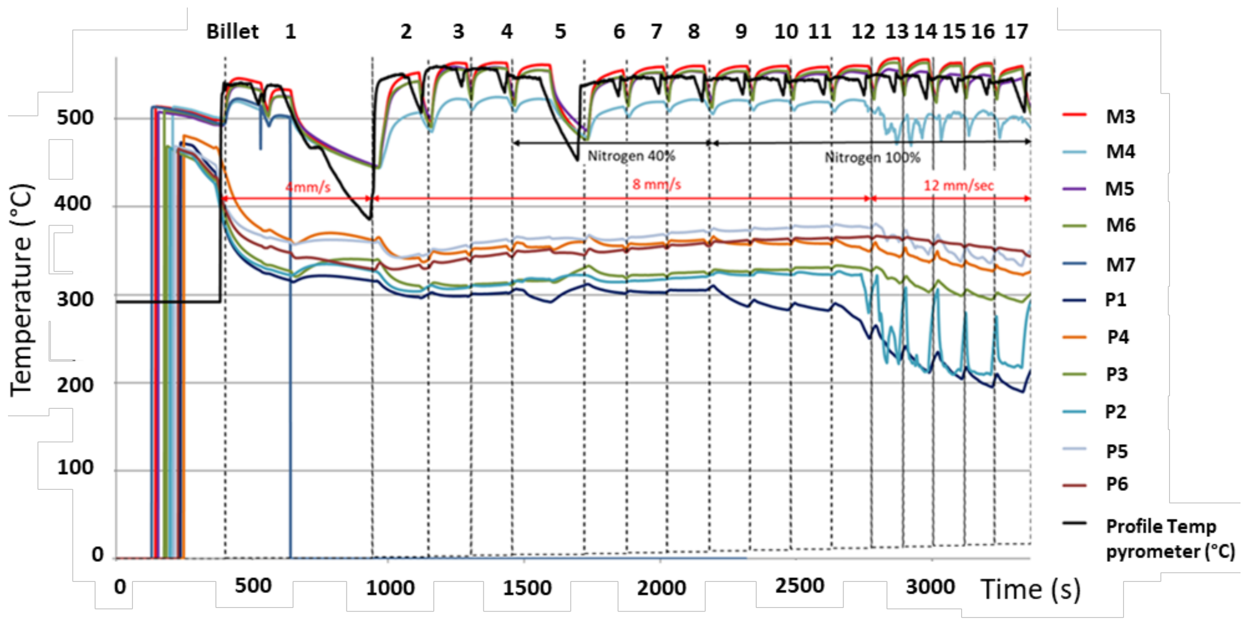


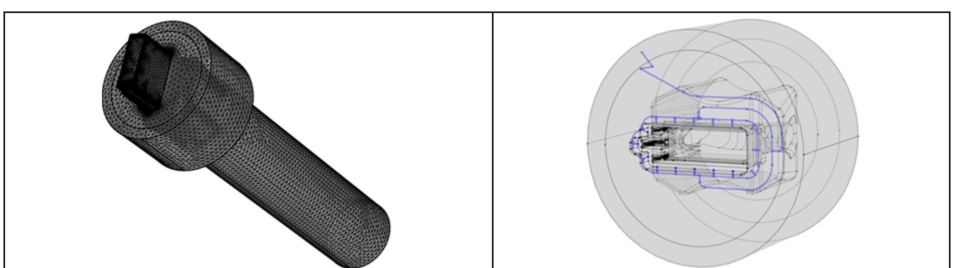
Fig. 3. Temperature history of the whole extrusion process [10].

By analyzing in detail the thermal history of the fourth billet (steady-state uncooled condition), it was detected the highest value of 565 °C in the bearings recorded by thermocouple M3, positioned closer to the short side of the profile without wings (Fig. 2b). Moreover, the thermocouples M6 and M5, positioned respectively near the wings and at the center of the lower side, acquired the same maximum temperature of 560 °C. The lowest temperature of 525°C was recorded by M4, located at the center of the upper side. In the backer, the lowest temperatures of 300°C and 311 °C were registered by the thermocouples P1 and P2 respectively, located along the initial portion of the cooling path. Thermocouples P3, P4, P5 and P6 were positioned in the die and recorded temperatures of 313 °C, 355 °C, 360 °C and 345 °C, respectively. Notably, the higher radial distance of thermocouples P1-P3 than thermocouples P4-P6 from the profile exit was the cause of their temperature' differences.

Starting from the thermal field of the fourth extrusion, it is immediately clear the inefficiency of the cooling channel design since not significant change in temperatures was found both in the backer and in the die when the nitrogen valve was opened at 40% (billets 5-8). The same trend was obtained in the die from the ninth to the twelfth extrusion when the maximum nitrogen valve was used. Also during the last extrusion, after eight billets extruded with nitrogen cooling, the heat removal in the die had a limited effect visible only in the thermocouple M4 (from 525 °C of the uncooled condition to 505°C). When the nitrogen valve was opened at 40%, the combination of high-pressure drops induced by the channel design and the high thermal gradient between the nitrogen and the tooling set caused a formation of a large amount of gas nitrogen that congested the nitrogen flow within the channel (an increase of volume of 177 times occurs during the phase change). In addition, the selected channel design did not promote the gas purging, thus limiting the liquid nitrogen flow with a long transitory also when the nitrogen valve was fully opened (effective cooling only in P1 and P2 nearby the nitrogen inlet). Therefore, the experimental campaigns showed the limits of the selected channel design and confirmed the issues that can occur using a design approach based only on the experience. In the next paragraphs, after the validation of the numerical model of the extrusion process with nitrogen cooling, a first attempt of new design approach based on the topological optimization of the cooling channel is proposed and deeply assessed.

Numerical Model of Extrusion Process with Nitrogen Cooling

A full comprehensive numerical model of the extrusion process was implemented in the COMSOL Multiphysics code by modelling the extrusion process with a pure Eulerian approach. Therefore, the geometry of the material flow was in the already deformed configuration (Fig. 4a), the tooling set was merged into one solid tool to avoid the contact analysis, while the ram and the container, required only for a Lagrangian approach, were replaced by proper thermal and frictional boundary conditions. The cooling channel was replaced with a 1D cooling path that follows the middle line path of the real 3D channel and integrated within the 3D model of the tooling set (Fig. 4b). The numerical approach based on the 1D modelling of the nitrogen cooling was tested and validated in different previous works of the authors [8-11], proving the good accuracy of the achieved results at very reduced computational time if compared to the approach based on a full 3D model of the nitrogen flow. In this work, the accuracy of the numerical model was demonstrated by analyzing, in terms of temperature prediction, the experimental-numerical differences in both uncooled and cooled conditions.



a) b)

Fig. 4. The 3D model for the simulations: a) the billet and the die set, b) the tooling set combined with the 1D cooling channel.

Table 1. Process Parameters set in the comprehensive stationary simulations of the extrusion process.

Process Parameters	**Billet 4**	**Billet 17**
Billet Temperature	480 [°C]	480 [°C]
Die Temperature	520 [°C]	Starts from steady state uncooled simulation
Container Temperature	430 °C	Starts from steady state uncooled simulation
Ram Temperature	440 °C	Starts from steady state uncooled simulation
Temperature of backer surfaces in contact with press	280 °C	280°C
Ram Speed	8 [mm/s]	12 [mm/s]
Inlet Nitrogen Pressure		4.5 [bar]
Inlet Nitrogen Temperature		-196 [°C]

The numerical uncooled condition was compared with the fourth extrusion, while the stationary numerical analysis of the cooled condition was compared with the last extrusion where it was experimentally found a visible cooling effect in the tooling set. In Table 1 are reported the main parameters required to prepare the steady state 3D simulations of the extrusion process integrated with the 1D model of the cooling channel. About the nitrogen cooling, a model based on the Homogenous Flow approach [14] was implemented that allows to predict the pressure drops and the cooling channel inefficiency caused by the gas formation however avoiding the effective simulation of the phase change. Indeed, the physical properties of nitrogen (dynamic viscosity, density, heat transfer coefficient etc.) were replaced with expressions that depends on the nitrogen vapor title ω_g, not set constant but as a function of the heat exchange within the channel. The details about the model were presented and deeply discussed elsewhere [14]. Figure 5 shows the numerical comparison of the thermal field between the uncooled (billet 4) and the cooled (billet 17) conditions in the die and in the mandrel, specifically in the planes where the thermocouples were positioned. It is immediately clear that the simulation properly predicted the inefficiency of the cooling channel designed by the die maker: not significantly differences in temperature were obtained in the die, while the small cooling effect in the backer was localized at the entrance of the cooling channel nearby the thermocouples P1 and P2, confirming the experimental evidence.

In detail, Table 2 reports the experimental-numerical comparison in terms of thermocouple's temperature in the backer. Except for P2 and P4, the average numerical errors were below the 5%, thus confirming the accuracy of the implemented model and its capability to predict the cooling efficiency induced by the channel design and the nitrogen gas formation. In this way, the numerical testing of the cooling channel designed with the support of the topological optimization can be considered as trustworthy even in absence of an experimental testing.

Table 2. Thermocouple temperatures in the backer: Experimental vs Numerical results (Billet 4 and Billet 17).

	Thermocouples Temperature [°C]					
Billet 4	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
Experimental	300	311	313	355	360	345
Numerical	313	357	327	366	366	341
Err%	+4.3%	+14.8%	+4.5%	+3.1%	+1.7%	-1.2%
Billet 17	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
Experimental	196	219	296	326	340	350
HFM numerical	205	210	298	260	355	335
%Err	+4.6%	-4.1%	-1%	-20.4%	+4.4%	-4.3%

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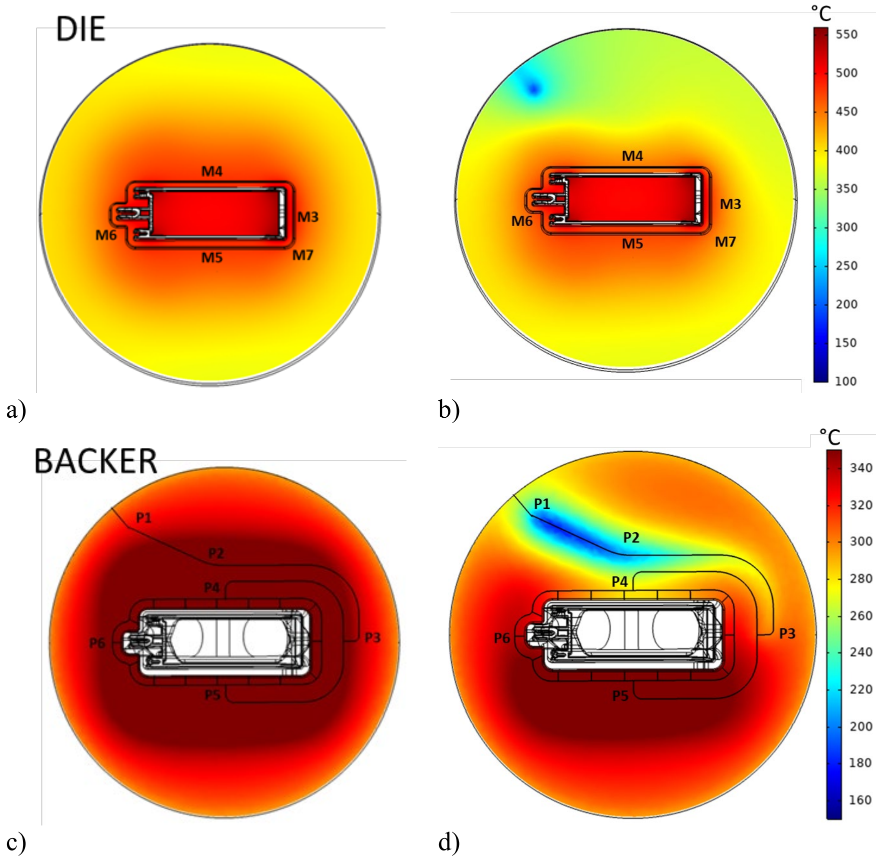


Fig. 5. Thermal maps in steady state condition: a) Uncooled Die (billet 4), b) Cooled Die (billet 17), c) Uncooled Backer, d) Cooled Backer.

Topological Optimization

For the topological optimization of the cooling channel, only the backer surface was modelled (Fig. 6a) allowing the tool to "virtually milled" it by the nitrogen flow in order to satisfy the selected objective functions. In the topological optimization approach based on the density method [15], the nitrogen flow was modelled using the Darcy flow model in order to treat the backer as a porous media with the porosity and the other physical properties controlled with penalization functions [15]. Following this approach, the elements of the mesh with the porosity equal to zero were considered as solid with the physical properties of the steel, while the elements with porosity equal to one were treated as liquid nitrogen. The density approach was controlled by the output material volume factor θ having the following expression:

$$\theta = \frac{(\tanh(\beta(\theta_f - \theta_\beta)) + \tanh(\beta\theta_\beta))}{(\tanh(\beta(\theta_f - \theta_\beta)) + \tanh(\beta\theta_\beta))} \tag{1}$$

where θ_f is the filtered material volume factor, β the slope and θ_β the projection point. When θ was equal to one the material was considered liquid; on the contrary, it was considered solid with a zero value. The slope and the projection point were calibrated to control the interpolation through intermediate values (set equal to 1 and 0.5, respectively). The interpolation was then constructed such that the physical governing equations of fluid flow were solved wherever the control variable was equal to one, while equations associated with the solid material were solved where the control variable was equal to zero. In details, the permeability, conductivity, density and specific heat capacity were expressed by the selected formulations [15]:

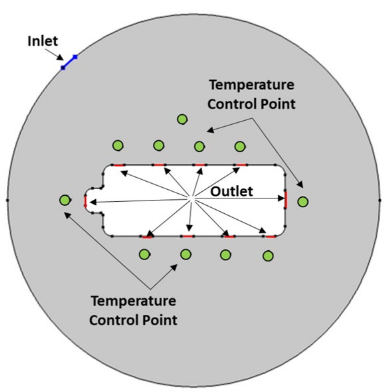
$$c = c_l + (1-\theta)^3 * (c_s - c_l) \tag{2}$$
$$k = k_s + (1-\theta) * (k_l - k_s) \tag{3}$$

$$\rho = \rho_s + (1-\theta) * (\rho_l - \rho_s) \tag{4}$$
$$c_p = c_{ps} + (1-\theta) * (c_{pl} - c_{ps}) \tag{5}$$

where the subscript l indicates the properties of the liquid nitrogen, while the subscript s the properties of the steel. The Fig. 6a shows the initial setting for the topological optimization: one nitrogen inlet was selected close to the original one, ten outlets were selected instead of the sixteen of the original design in order to reduce the excessive pressure drops. The number of outlets were selected as input; however, further investigations will be focused on the possibility to include the choice of outlets as objective function. Eleven temperature control points were used to implement an objective function related to the temperatures balance around the profile exits. The latter was imposed as the minimization of the standard deviation with respect to the temperature control value of 250°C combined to the minimization of the differences in temperature between the control points:

$$\Delta T_{min} = \sqrt{\frac{\sum_{i=1}^{n} (T_i - T_{ref})^2 + \sum_{i,j=1\, i\neq j}^{n} (T_i - T_j)^2}{n + \frac{n!}{2*(n-2)!}}} \tag{6}$$

The temperature reference of 250°C was selected reasonable to avoid thermal shocks in the tooling set as well as to guarantee an adequate cooling in the bearings located away from the cooling channel. A convective heat flux perpendicular to the backer plane was defined as boundary condition (heat transfer coefficient of 11000 W/m^{2}K at a temperature of 550°C) with the aim to replicate, in a simplified way, the heat exchange between the backer and the hot die. As constraints, a maximum θ_{avg} of 0.25 was imposed, to avoid an excessive volume of channels (not feasible from a technological point of view), together with maximum inlet pressure of 5 bars, the maximum available for the nitrogen plant used during the experimental trials. The optimization problem was solved using the Method of Moving Asymptotes (MMA) [15-16].



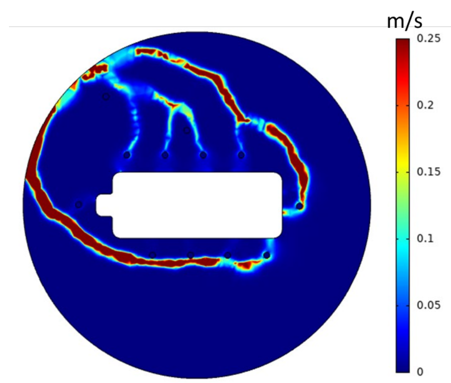


Fig. 6. Topological optimization: a) Problem setting, b) Velocity field of the nitrogen within the channel.

The Fig. 6b shows the velocity profile of the nitrogen flow after 280 iterations of the optimizer (computational time of 10h). The results obtained from the topological optimization was then used to design the new cooling channel. Fig 7 presents the comparison between the old and the new design. The L-shaped channel, that connected the external nitrogen pipeline with the backer surface, was imposed fixed in order to analyze the difference in terms of cooling efficiency of the sole planar path. The topological optimization suggested to split the channel in three different paths instead of just one with a lot of ramifications as in the original design. A rectangular cross-section was selected since the channel is commonly milled: the width of 8 mm was suggested by the results of the topological optimization, the depth was set variable in order to guarantee an adequate nitrogen flow rate also in locations far from the inlet (for longer route, higher hydraulic diameter to reduce the pressure drops).

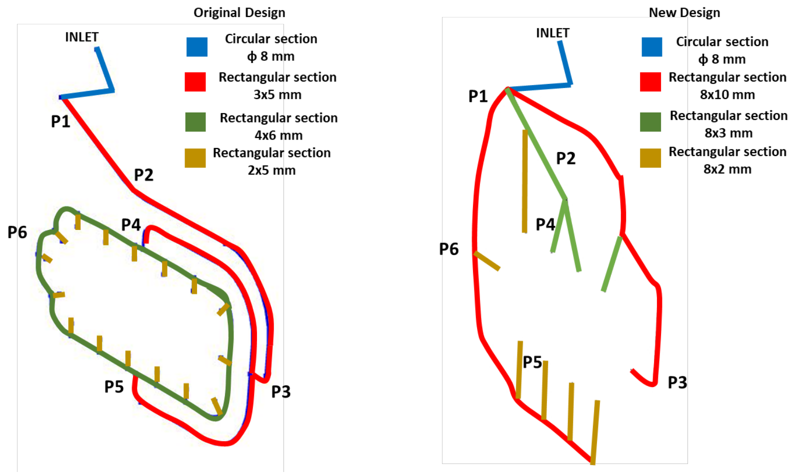


Fig. 7. The comparison between the old design and the new one.

Results and Discussion

The final step of the work was the testing of the new cooling channel design and the comparison with the old one in terms of cooling efficiency as predicted by the 3D model. The same process parameters and boundary conditions for the simulation of last extrusion were selected for both cooling channel designs (billet 17 in Fig. 3). In details, Fig. 8 evidences the differences in terms of cooling efficiency between the old design and the new one: a great cooling was achieved in the backer with the new design, highlighted by the large blue area around the profile exit, with a low cooling effect in the area near the right corner of the lower side, where the simulation properly predicted the gas formation. The great cooling effect obtained in the backer allowed to reduce the temperature around the bearings, detecting a minimum of 420°C in the thermocouple M4. The unbalance of the cooling in the backer caused the peak temperature difference of 45°C in the bearings (Table 4), thus suggesting the need for further investigation. Indeed, in this first optimization, the properties of the nitrogen within the Darcy fluid model were set constant and equal to those of liquid nitrogen, thus neglecting the effect of the phase change nearby the outlets of the longest cooling path. However, the achieved results clearly show the benefits of the proposed approach based on topological optimization of the cooling channel design, gaining a cooling efficiency significantly higher than that of the original design.

Table 3 Thermocouple temperatures in the Die: Old Design vs New Design (Billet 17).

Billet 17	Thermocouples Temperature [°C]				
	M3	M4	M5	M6	M7
Experimental Old Design	560	502	547	557	
Numerical Old Design	548	524	528	558	513
Numerical New Design	465	420	445	460	455

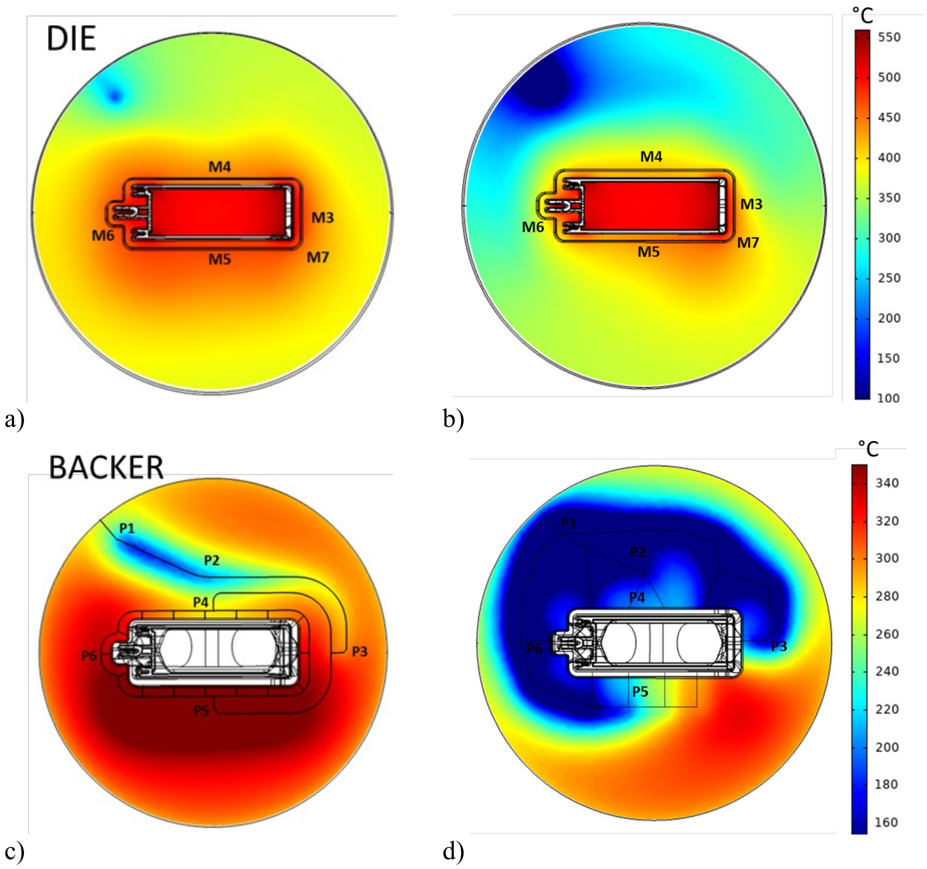


Fig. 8. Thermal map in steady state condition: a) Die Old Design, b) Die New Design, c) Backer Old Design, d) Backer New Design.

Summary

For the first time, an approach based on the topological optimization was implemented and tested for the design of the cooling channel in extrusion dies. The experimental campaign of the selected case study proved the limit of the design approach merely based on the experience without the support of numerical tools. The 1D model of the nitrogen cooling integrated with the 3D model of the extrusion process allowed to properly predict the cooling efficiency with an average experimental-numerical error of 6% in terms of temperatures, showing the poor performances of the original channel design. The new channel, designed on the basis of the topological optimization toolkit, guaranteed a great cooling in the backer and a significant decrease of temperature around the bearings (a maximum decrease of 104°C in the thermocouple M4). Further investigations will be focused on the integration of the nitrogen phase change in the topological analysis and on the testing of different objective functions in order to include, for example, technological constraints.

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References

[1] P.K. Saha, Aluminum extrusion technology, ASM International, Materials Park, OH, USA, 2000.

[2] L. Donati, et al, Effect of liquid nitrogen die cooling on extrusion process conditions, Key Eng. Mater. 491 (2012) 215-222. https://doi.org/10.4028/www.scientific.net/KEM.491.215

[3] P. Stratton, Raising productivity of aluminium extrusion with nitrogen, Int. Heat Treat. Surf. Eng. 2 (2008) 105-108. https://doi.org/10.1179/174951508X429221
[4] A.F. Ciuffini, et al., Surface Quality Improvement of AA6060 Aluminum Extruded Components through Liquid Nitrogen Mold Cooling, Metals 8(6) (2018) 409. https://doi.org/10.3390/met8060409
[5] A.J Norwood, et al., Analysis of cooling channels performance, Int. J. Comput. Integr. Manuf. 17(8) (2004) 669-678. https://doi.org/10.1080/0951192042000237528
[6] L. Donati, B. Reggiani, R. Pelaccia, M. Negozio, S. Di Donato, Advancements in extrusion and drawing: a review of the contributes by the ESAFORM community, Int. J. Mater. Form. 15 (2022) 41. https://doi.org/10.1007/s12289-022-01664-w
[7] N. Biba, et al., The Model for Coupled Simulation of Thin Profile Extrusion, Key Eng Mater 504-506 (2012) 505-510. https://doi.org/10.4028/www.scientific.net/KEM.504-506.505
[8] B. Reggiani, L. Donati, Prediction of liquid nitrogen die cooling effect on the extrusion process parameters by means of FE simulations and experimental validation, J. Manuf. Process 41 (2019) 231-241. https://doi.org/10.1016/j.jmapro.2019.04.002
[9] R. Pelaccia, M. Negozio, L. Donati, B. Reggiani, L. Tomesani, Extrusion of Light and Ultralight Alloys with Liquid Nitrogen Conformal Cooled Dies: Process Analysis and Simulation, J. Mater. Eng. Perform. 31 (2021) 1991-2001. https://doi.org/10.1007/s11665-021-06320-z
[10] R. Pelaccia, B. Reggiani, et al., Liquid nitrogen in the industrial practice of hot aluminium extrusion: experimental and numerical investigation, Int J Adv Manuf Technol. 119 (2022) 3141-3155. https://doi.org/10.1007/s00170-021-08422-3
[11] R. Pelaccia, M. Negozio, et al., Assessment of the Optimization Strategy for Nitrogen Cooling Channel Design in Extrusion Dies, Key Eng Mater. 926 (2022) 460-470. https://doi.org/10.4028/p-f7i0y2
[12] S. Kambampati, H.A. Kim, Level set topology optimization of cooling channels using the Darcy flow model, Struct. Multidisc. Optim. 61 (2020) 1345-1361. https://doi.org/10.1007/s00158-019-02482-6
[13] X. Zhao, M. Zhou, et al., Topology optimization of channel cooling structures considering thermomechanical behavior, Struct Multidisc Optim 59 (2019) 613-632. https://doi.org/10.1007/s00158-018-2087-z
[14] R. Pelaccia, P. E. Santangelo, A Homogeneous Flow Model for nitrogen cooling in the aluminum-alloy extrusion process, Int. J. Heat Mass Transf. 195 (2022) 123202. https://doi.org/10.1016/j.ijheatmasstransfer.2022.123202
[15] X. Zhao, M. Zhou, et al., A “poor man’s approach” to topology optimization of cooling channels based on a Darcy flow model, Int. J. Heat Mass Transf. 116 (2018) 1108-1123. https://doi.org/10.1016/j.ijheatmasstransfer.2017.09.090
[16] K. Svanberg, The method of moving asymptotes: a new method for structural optimization, Int J Numer Methods Eng 24 (1987) 359-397 https://doi.org/10.1002/nme.1620240207