



23rd International Conference on Material Forming (ESAFORM 2020)

Efficiency of Conformal Cooling Channels Inserts for Extrusion Dies

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Abstract

During aluminum extrusion process, critical temperatures can be reached both in the profile and in the tooling set due to the high pre-heating temperatures and to the work spent in overcoming friction at the workpiece/tool interfaces and in deforming the billet that is converted into heat. By considering that especially the rising of temperature in the profile can represent a critical aspect of the process strongly limiting the maximum achievable extrusion speed, liquid nitrogen die cooling is becoming a consolidated industrial practice in order to increase the process productivity. If cooling channels are traditionally manufactured by subtractive technologies on a third plate (the backer), a more flexible and efficient solution is offered by the selective laser melting (SLM) technology. SLM allows the design of free-form channels with the opportunity to efficiently remove the heat as near as possible to the bearing zones where the highest temperatures are reached. In the present work, the design approach and the manufacturing parameters of an SLM printed H13 die insert for the extrusion of a 10 mm round bar are presented. In addition, the extrusion process is simulated by means of the COMSOL code accounting for the nitrogen cooling effect. Experimental extrusion trials have been furthermore performed with ZM21 magnesium and 6063 aluminum alloys to assess the potentiality of the conformal cooling channel design and to validate the developed numerical model. As main result, a good experimental numerical matching has been achieved with peak errors of 7.5% and 14% in terms of temperature and extrusion load respectively.

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Keywords: Extrusion; SLM; nitrogen; FEM

1. Introduction

In the hot extrusion, high temperatures are reached due to the billet pre-heating used to improve the flow material, to the friction forces at the workpiece/tool interfaces and to the deformation energy converted into heat during the process [1]. The raising of the temperature also strongly depends on the extrusion speed thus limiting the process productivity, especially for complex profiles and die designs. Particularly critical is the exit temperature of the extruded profile that imposes a bond in the selection of the process parameters in order to avoid surface defects. In addition, high temperatures can also reduce the service life of the tools [2-3]. Among the different options offered to control and limit the developed temperatures, nowadays, the use of liquid nitrogen die cooling

is becoming a consolidated industrial practice to meet the targets of a quality improvement and of a productivity increase [4-5]. The liquid nitrogen enters in the cooling path, removing heat by the tooling set, and it exits through a number of transferring holes connected to the profile surface. In addition, the hot gas nitrogen on the way out surrounds the profile, creating a mixture of air and inert gas that partially reduces the oxidation of the extrudate. A proper cooling design should involve the positioning of the channel nearby the bearing zones, where the highest temperatures are generated, without significantly increase of the extrusion load. It is clear that the cooling efficiency depends on the overall channel design and on the many involved parameters, but a crucial role is played by the channel distance from the bearing zones that should be limited [6]. Conventionally, the channel is manufactured on the

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10.1016/j.promfg.2020.04.181

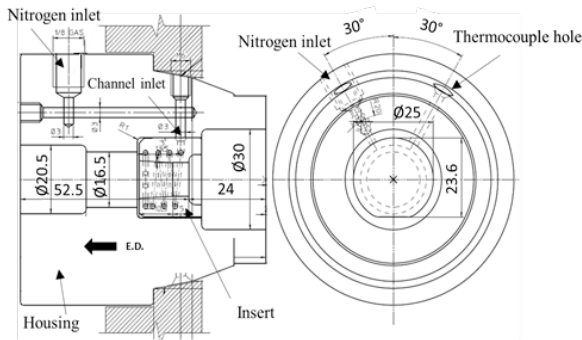


Fig. 1 The multi-die concept.

mating surface of a third plate, the backer, and the die by means of subtractive technologies such as milling and drilling, thus suffering of technical limits in terms of geometrical constraints and then of cooling performances. In contrast, additive manufacturing (AM) technologies could satisfy the free-form requirement for a targeted cooling due to the lack of design constraints as leading feature of these processes. Among the many AM technologies, Selective Laser Melting (SLM) allows producing 3D dense, high-strength components built-up layer-by-layer starting from a powder bed fused by means of a laser source [7, 8]. However, the main drawbacks of the SLM are the maximum achievable dimensions of the components as well as the high production costs. In this context, the aim of the work is to present a novel die design approach that contemplates an SLM insert with the conformal cooling channel and the bearing zones hosted in a conventional steel housing. Insert is designed, manufactured and experimental tested by means of extrusion trials with ZM21 magnesium and 6063 aluminum alloys in order to evaluate the overall performances. Furthermore, the extrusion process with liquid nitrogen is simulated by means of the COMSOL Multiphysics code to predict the process loads and the thermal gradients both in uncooled and cooled conditions.

2. Multi die concept design

For the development and design of the innovative die concept, the extrusion of a 10 mm round bar has been considered. In the novel design, the die is split into two parts (Fig.1): the SLM insert, which includes the conformal cooling channel that embrace the bearings, and the external steel housing made with conventional technologies.

The insert has an outer diameter and an axial height of 25 mm and 20 mm, respectively. The same are 75 mm and 76.5 mm for the external housing. The final round section of 10 mm diameter is obtained by bearings 5 mm long. After the bearings, a divergent exit angle of 3° is designed to avoid a further profile-insert contact. The housing has an inlet straight pipeline to provide a nitrogen path from the high-pressure tank to the conformal channel. In addition, it provides the support during the extrusion process in term of mechanical resistance. In order to achieve a targeted cooling where the highest temperatures are reached, a helicoidally channel is selected that surround the bearings (Fig. 2-3).

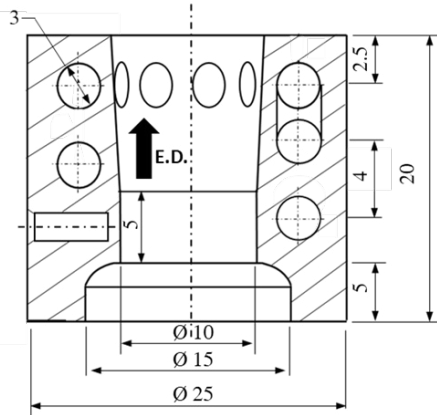


Fig. 2 Concept design of the insert in terms of printing constraints.

The helix pitch, the helix diameter and the channel diameter are chosen to meet the objective functions of cooling effectiveness and SLM printing requirements. Indeed, by decreasing the helix pitch and increasing the channel diameter, it is possible to get a higher cooling rate, but at the same time, the percentage of void in the insert grows, thus limiting its mechanical strength. In addition, if the helix diameter is reduced, the channel gets closer to the bearings, but problems can arise during the SLM printing process. As can be seen in Fig.2, the selected solution presents a helix pitch and diameter of 5 mm and 8 mm, respectively, and a channel diameter of 3 mm. The helicoidally channel is connected to a toroidal portion having eight radial nitrogen outlets towards the profile exit zone, thus supporting the protection against oxidation. A distance of 2.5 mm of the toroid axis from the bottom of the insert is left to guarantee the insert integrity during the printing phase. In order to monitor the insert temperature during the extrusion process, a thermocouple hole is provided in radial direction located nearby the bearings and angled of 60° clockwise with respect to the inlet of the helicoidally channel (Fig.1-3).

3. Insert manufacturing with SLM technology

After the design phase, both the insert and the housing were manufactured in the AISI H13, a chromium hot-work tool steel widely investigated and commercialized for forging, extrusion dies and die-casting applications due to its strength at high-temperature, to erosion and to thermal fatigue and due to its reasonable cost [7,8]. Concerning the SLM manufacturing of the insert, it is known that, in order to obtain a completely dense structure, a proper design of the component, as well as of the process parameters is required. For this, preliminary tests were carried out to find the optimal set of printing parameters by using a SISMA Industries MYSINT 100 LM Fusion Fiber laser (laser spot diameter 50µm) and a H13 powder with an average size of 30µm. In all the tests, the layer thickness was set to 20 µm and the hatch spacing to 60 µm while the laser power and speed were varied according to a two-factor-three-levels design of experiment thus producing nine combinations.

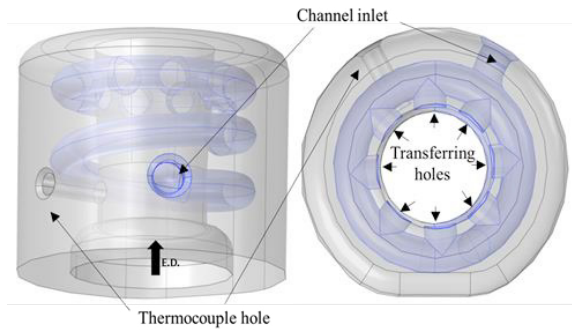


Fig. 3 The CAD model of the final insert design.

The investigated levels were 90-120-150 W and 700-950-1200 mm/s for the laser power and speed, respectively, coming to the higher density with a combination of 700 mm/s and 120 W. Then, the optimal printing parameters were used to prepare tensile specimen in 90° build-up configuration (perpendicular to the building platform). As main result it was found an ultimate tensile strength of 1600 ± 50 MPa, fulfilling the requirements for an extrusion die.

Then, the insert was SLM vertically printed using the selected parameters with the exit surface in the extrusion direction supported by pins. Conical pins have been designed with the purposes to support critical component' layers during the printing phase and to permit an easy separation of the component from the platform.

In the first attempt, four inserts were unsuccessfully printed on the same platform. All the inserts were cracked in relation to the high time required by the laser beam to melt the next powder layer causing harsh thermal gradients within the components and leading to severe internal stresses. To overcome this issue, only two inserts were printed on the platform reducing the time required for each layer generation as well as the heat gradient between adjacent layers. The X-ray analysis confirmed the integrity of the printed inserts and the absence of cracks, as well as the good quality of the cooling channel without yielding and plugged areas (Fig.4). The cooling channel was also specifically tested by verifying the nitrogen flowing with a portable nitrogen plant (Fig.4). In terms of surface quality, a standard roughness value for SLM process ($Ra= 7 \mu\text{m}$) was got. Then, the outer surface of the insert for the fitting in the die housing and the bearings surface were machined with the electrical discharge machining (EDM) process before putting the insert into service.

Accounting for this, during the design phase of the insert, the external diameter was increased of 1 mm (from 25 mm to 26 mm) and the bearings diameter decreased of the same amount (from 10 mm to 9 mm).

After the printing, inserts were annealed to reduce the residual stresses induced by thermal gradient and to avoid cracks during the removal by the platform. In more details, the annealing consisted in heating up at 90 °C/h until reaching 650 °C, then in holding for 4 hours at 650 °C and finally in oven cooling. Subsequently, the final heat treatment consisted in an austenitization at 1020 °C, gas quenching using forced pressure nitrogen, and two tempering (at 550 °C and 585 °C

respectively), achieving the required hardness for the extrusion process (45 HRC).

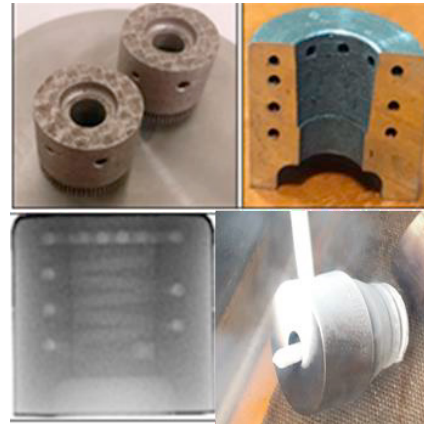


Fig. 4 The insert manufacturing and final quality assurance.

4. Experimental Setup and Trials

Experimental extrusion trials were performed with 6063 aluminum alloy and ZM21 magnesium alloy in order to evaluate the effectiveness of the designed cooling solution and the mechanical strength of the insert during the process.

The 6XXX series of aluminum alloy are widely used for the extrusion process [1-2, 9] due to the high deformability, ratio strength per density and corrosion resistance, finding applications in many fields. On the other side, magnesium alloys are subjected to a growing interest for the fabrication of lightweight components especially in automotive industry, due to their high strength on weight ratio, weldability, damping capacity and low density (one-third of aluminum density) [10]. However, magnesium alloys are less suitable to the extrusion process than aluminum alloys in relation to their lower ductility, thus offering a stimulating challenge [9].

A total of 24 billets made of AA 6063 and 18 made of ZM21 were extruded replicating, on a laboratory scale, the production volume and the die stress of typical industrial standards. A 250-tons hydraulic press was used for the experimental trials. The nitrogen was stored in a portable tank pressurized to 5 bar and connected to the cooling channel with a pipe 4 m long. As stated, the extruded profile was a 10 mm round bar obtained by a billet with a length of 100 mm and a diameter of 45 mm. The container had the internal diameter of 50 mm, coming to an overall extrusion ratio of 25. The container temperature was pre-set at 376 °C for the extrusion of both alloys, while their differences in terms of mechanical and physical properties and of flow behavior required the selection of different billet and die temperatures.

Concerning the AA 6063, the preheated billet and die temperatures were set to 450 °C. Neglecting the extrusion of the first three billets used to homogenize the tooling-set temperature, 18 billets were extruded with a constant ram speed of 4.2 mm/s. From billet 4 to billet 7 the process was performed without cooling, whilst from billet 8 to 22 the nitrogen valve was completely opened (100% of flow rate).

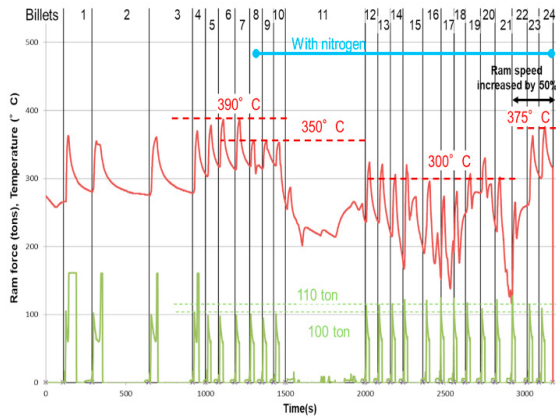


Fig. 5 Temperature and press load histories for the AA6063 alloy extrusion.

Billets 22 to 24 were processed again with nitrogen valve completely opened but with 50 percent higher ram speed (6.5mm/s) in order to evaluate the possibility to increase the productivity with nitrogen cooling but limiting the increase of exit profile temperature. Fig. 5 shows the temperature history, as recorded by the thermocouple placed in the insert nearby the bearings, and the extrusion load for the 24 billets. The process time of the billet 11 was longer than the standard, due to occurrence of some problems with the nitrogen flow. Data on the exit profile temperature acquired by a pyrometer placed out of the press were not reliable due to the profile fluctuation and the sun reflection during the trials. However, since the thermocouple always recorded values below 400 °C, it was reasonably assumed an exit profile temperature lower than the maximum bearings temperature.

During the uncooled process (billets 1-7), the thermocouple recorded a maximum temperature of 390 °C. The high thermal fluctuations during each ram stroke highlighted the influence of the cool components of the press in the heat exchange, contribution expected to be less relevant in an industrial standard due to the thermal inertia of bigger tools. When the nitrogen valve was opened, from billets 8 to 10, the thermocouple recorded a peak temperature of 350 °C. The low temperature decrease with respect to the uncooled condition was related to the gaseous state of the nitrogen flowing in the conformal channel caused by an excessive initial warm up of the first pipeline segment and of the channel.

However, after this transitory cooling regime, a peak temperature between 275 °C and 310 °C was recorded for billets 12 to 21, achieving a drop up to 90 °C with respect to the uncooled condition. In the cooled condition with the 50% increase of extrusion speed, the thermocouple acquired a temperature of 375°C, 15 °C lower than the uncooled condition with the original lower ram speed, showing the great possibility to increase the productivity. In order to avoid excessive thermal gradients in the die, the nitrogen valve was closed every time that temperature dropped below 200 °C. Although the high temperature decrease in the insert, the nitrogen flowed with some difficulties through the channel, obtaining a mixture of liquid-gaseous nitrogen. Even if a direct monitoring of the nitrogen phase change during the process was not feasible, when the pipe was iced the percentage of liquid nitrogen in the

channel was not negligible, while, with not iced pipe, only gas nitrogen was flowing. In terms of extrusion load, a peak of 110 tons was recorded during the cooled process, with only a 10% of increase with respect to the uncooled condition, proving that the designed targeted cooling nearby the bearings did not affect the billet deformability in the die.

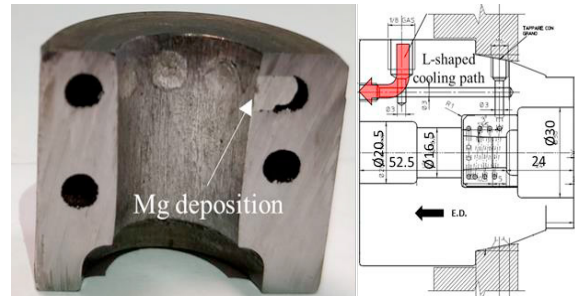


Fig. 6 Magnesium deposit in the exit holes of the cooling channel (left); new cooling channel path (right).

Coming to the extrusion trials of the ZM21 alloy, the billet and the die were preheated at a temperature of 300 °C, while the container temperature was set to 376 °C as in the trials with aluminum billets. During preliminary extrusion tests, the cooling channel was plugged by a magnesium deposition (pick-up) at the exit of the bearings preventing the nitrogen flow (Fig. 6-left). The pick-up defect was related to the too small divergent angle at the end of the bearings (3°) that caused an undesired profile-insert contact. Since the channel holes could not be cleared, an alternative cooling L-shaped path made in the housing was used (Fig. 6-right).

An extrusion speed of 4 mm/s was selected for the processing of the 18 billets. The first three billets were extruded without cooling to homogenize the tooling set temperatures, while the subsequent seven billets were extruded with a 100% of nitrogen flow rate in the reduced cooling path. During the billet change, the cooling system was not shut down, but the nitrogen flow rate was reduced to 50%. The last eight billets were extruded without cooling to reach the steady-state uncooled condition. As shown in Fig. 7, the peak average temperature recorded by the thermocouple in uncooled condition was 353 °C, while a temperature of 310 °C was detected with nitrogen cooling, showing a not negligible effect also with the reduced cooling path. The extrusion load increased of 20% with nitrogen cooling if compared to the uncooled condition, from 100 tons to 120 tons. At the end of the experimental trials, a positive remark was that no evident fail-marks or cracks were observed in the inserts, even after trials that recorded temperatures below 200 °C.

On the other side, trials suggested a way to further optimise the design of the conformal cooling channel in order to guarantee a liquid nitrogen flow without excessive pressure drops. It is indeed expected that a higher channel diameter could result in a higher cooling effect with a reduced nitrogen flow rate.

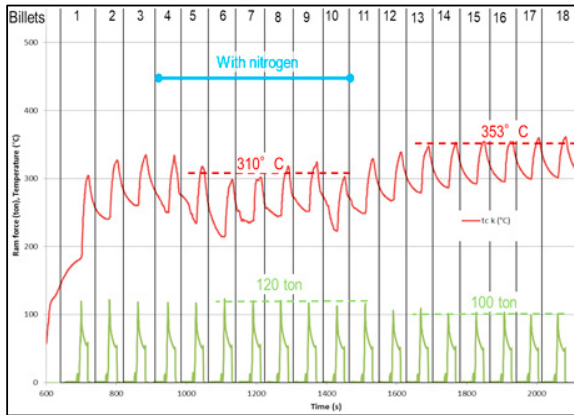


Fig. 7 Temperature and press load histories for the ZM21 alloy extrusion.

In this redesign direction, numerical simulations could offer a valid support for an easy and fast assessment of the insert performances. Then, the next step of the work consisted in the development of an FE model of the extrusion process coupled with nitrogen cooling.

5. Numerical model of the extrusion process

A numerical FE model was set in the commercial code COMSOL Multiphysics, which allows coupling different physics in order to simulate complex problems [11].

In details, the thermal and fluid-dynamic modules used to simulate the extrusion process without cooling were coupled with the “Non Isothermal Pipe Flow” module, which enables the simulation of the nitrogen cooling by means of a simplified 1D model of the channel (Fig.8). The physical properties of the fluid, the boundary conditions, as well as the flow rate, pressure drops and heat transfer coefficient (HTC) are evaluated in the mid-line path of the channel. Results then do not change within the cross section that is reduced to a single node. However, the geometrical features of the channel, such as the hydraulic diameter and the section changes, are taken into account in the fluid-dynamics equations for the calculation of the HTC. In the set of equations that govern the coupled problem, reported in detail in [11], the following term accounts for the heat exchange between the insert and the channel:

$$Q = hZ(T_{insert} - T) \quad (1)$$

where T_{insert} is the temperature of the insert in the nodes around the channel, Z is the perimeter of the cross section of the channel and h is the HTC. The latter is calculated as [6, 11]:

$$h = Nu \frac{k}{d_h} \quad (2)$$

As can be seen, the h coefficient depends on the hydraulic diameter of the channel d_h , on the thermal conductivity k and on the Nusselt number that takes account of the flow regime (laminar/turbulent). The 1D model provides low computational time without limiting the accuracy and reliability of the achieved results. Indeed, the aim of the developed model is to

evaluate the macroscopic effect of the nitrogen cooling on die and profile temperatures and on press load. The 1D model also allows to rapidly modify the cooling channel design for the achievement of an optimal solution.

COMSOL Multiphysics uses a pure Eulerian approach [11] so that the billet was in the already-extruded configuration (Fig.9). The insert and the housing were CAD modelled and treated as different domains while the other tools in contact with the billet (container and ram) were replaced by equivalent boundary conditions, thus further reducing the element of the mesh and the required computational time.

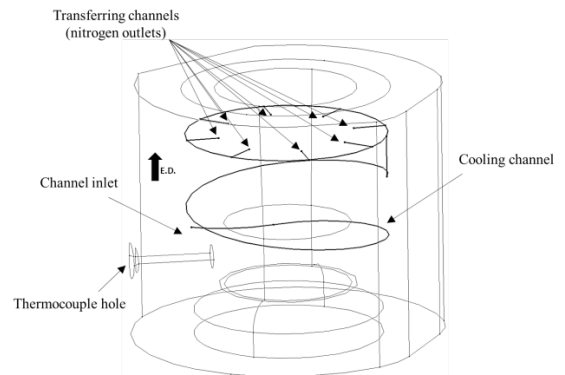


Fig. 8 Model of the 1D conformal cooling channel.

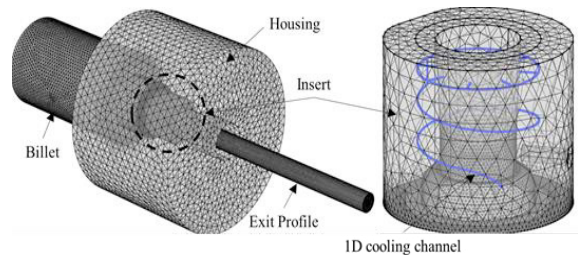


Fig. 9 The FE model of the workpiece (left) and of the insert/housing (right).

Concerning the flow stress, the Sellars-Tegart inverse sine hyperbolic model was used, treating the hot metal as a fluid with a high viscosity [12,13]. In the contact areas between the billet and the tooling set, a sticking friction condition was generally imposed, while in the bearings the slip friction condition was used. The process parameters and the boundary conditions applied to the model were selected to replicate the experimental settings (Tab. 1 and 2 for AA 6063 and ZM21 alloys, respectively).

The nitrogen properties are known to be pressure and temperature dependent, but with the aim to keep the computational time reasonable for an industrial application, the phase change was not simulated in the model.

Both for uncooled and cooled conditions, steady-state simulations were performed to be compared with the steady-state conditions reached in the experimental trials.

Table 1. Process parameters for AA 6063

Process Parameters	Value
Preheated Billet Temperature	450 °C
Container Temperature	376 °C
Preheated Die Temperature	450 °C
Ram Temperature	430 °C
Ram speed	4.2 mm/s
Aluminum-steel heat exchange coefficient	11000 W/(m ² K)
Steel-Steel Heat Exchange Coefficient	3000 W/(m ² K)
Q parameter of Sellars-Tegart model	203.399 KJ/mol
A parameter of Sellars-Tegart model	6.063*10 ¹² 1/s
n parameter of Sellars-Tegart model	5.108
α parameter of Sellars-Tegart model	0.0456 1/MPa

Table 2. Process parameters for ZM21

Process Parameters	Value
Preheated Billet Temperature	300 °C
Container Temperature	376 °C
Preheated Die Temperature	300 °C
Ram Temperature	280 °C
Ram speed	4.2 mm/s
Magnesium-steel heat exchange coefficient	5000 W/(m ² K)
Steel-Steel Heat Exchange Coefficient	3000 W/(m ² K)
Q parameter of Sellars-Tegart model	141.441 KJ/mol
A parameter of Sellars-Tegart model	1.35*10 ¹² 1/s
n parameter of Sellars-Tegart model	3.6
α parameter of Sellars-Tegart model	0.0238 1/MPa

For a further insight, two different simulations in cooled condition were carried out, one with only liquid nitrogen flow through the channel and one with only gas nitrogen. The real HTC should have a value between the two boundary conditions.

Fig. 10 shows the relation between the boiling point of the nitrogen and the operating pressure. Accounting for this, experimentally the nitrogen temperature in the pressured tank was set to -200°C with a pressure of 5 bar in order to have the highest possible rate of liquid nitrogen in the cooling channel. In the numerical model, an inlet pressure of 4 bar was set in the cooling channel, assuming a pressure drop of about 1 bar in the first pipeline, while a negligible decrease of temperature was supposed from the tank to the cooling channel in the steady-state condition.

6. Experimental-Numerical comparison

The steady-state simulations highlight the critical conditions of the extrusion process in terms of thermal map and extrusion load. Therefore, the numerical-experimental comparison was made in terms of peak load and temperature as recorded by the thermocouple nearby the bearings.

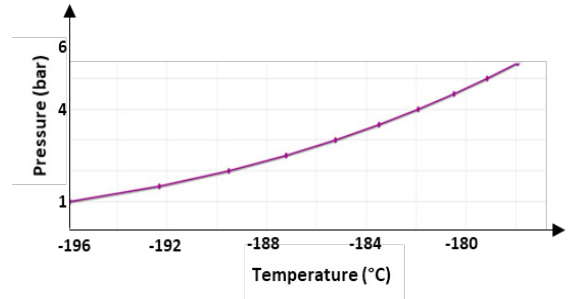


Fig. 10 Boiling point of liquid nitrogen according to the operating pressure.

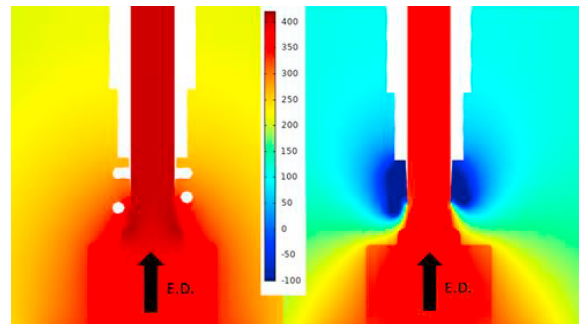


Fig. 11 Thermal map of the extrusion process in uncooled (left) and cooled (right) conditions for AA 6063 alloy.

Regarding the extrusion process with AA 6063 billets, Fig. 11 shows the thermal map of the die and the billet both in uncooled and cooled conditions by supposing only a liquid nitrogen flow through the channel. It comes clear the strong cooling effect of the liquid nitrogen with the proposed design. Indeed, the blue color along the cooling path underlined the decrease of the die temperature, while in the workpiece, the temperature remained around 400 °C so preserving a high deformability where required.

The numerical predictions for the uncooled condition of the AA 6063 alloy were compared to the experimental results of billet 7, representing the steady-state uncooled condition. The extrusion of the billet 10 was instead selected for the comparison with the numerical model where only gas nitrogen cooling was accounted for. The numerical data achieved with a liquid nitrogen cooling were compared with the experimental outcomes of billet 17 since it generated the lowest thermocouple temperature, probably just in relation to the highest percentage of liquid phase in the channel.

As regards to the ZM21 alloy, billet 18 and 10 were used for the comparison with the numerical uncooled and cooled conditions, respectively. Fig. 12 shows the cooling effect of the L-shaped path as predicted by the FE model assuming, in the steady-state condition, low-pressure drop and so an high percentage of liquid nitrogen in the channel. Tab. 3 and 4 show the detail of the experimental-numerical comparison in terms of peak press load and thermocouple temperature for the AA 6063 and ZM21 alloys, respectively. The simulations showed a good matching with the experimental results in terms of temperature in the thermocouple location with a peak percentage error of 7.5% in the cooled condition for the ZM21 alloy.

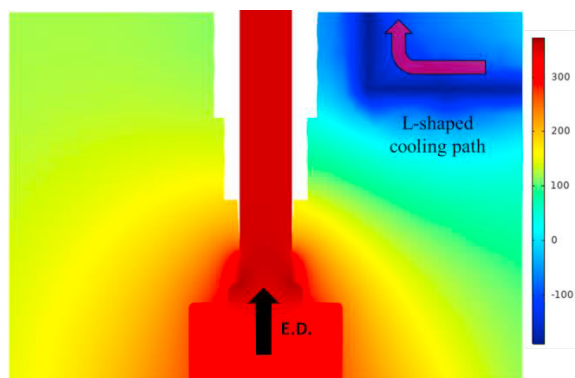


Fig. 12 Thermal map of the extrusion process in cooled condition for ZM21 alloy.

Furthermore, the performed simulations properly captured the important temperature drop moving from the uncooled to the cooled condition, as experimentally observed, even if with a less amount.

Table 3. Experimental-Numerical comparison for the AA 6063 alloy

	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%

Table 4. Experimental-Numerical comparison for the ZM21 alloy

	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%

In terms of extrusion load, a peak error of 14 % was achieved in the extrusion simulation with the AA 6063 alloy and with gas nitrogen cooling, thus coming again to a good overall experimental-numerical matching. As further important result it must be mentioned that the maximum computational time was in the order of 30 minutes with the cooling process using a laptop with medium computing power (Intel® core™ processor i7-7700HQ, Ram 16GB), a time fully compatible with the industrial requirements.

7. Conclusions

In the present work, a multi-die design has been presented consisting in a SLM printed insert with a conformal cooling channel and an external steel housing conventional machined.

The insert has been experimentally tested at laboratory scale for the extrusion of both AA6063 aluminum and ZM21 magnesium alloys and subsequently numerically modelled with the COMSOL Multiphysics code in cooled and uncooled conditions.

The main achieved results can be summarized as in the following:

- The insert has been successfully SLM printed without any internal cracks and defects with the optimal detected set of parameters (700 mm/s and 120 W of laser speed and power).
- During the experimental trials, the press load did not increase excessively in cooled condition, showing a maximum of 20% with the ZM21 alloy.
- The cooling efficiency was very high, especially for AA 6063 that showed a temperature drop of more than 90°C from the uncooled to the cooled condition, thus allowing an increment of more than 50 percent of the ram speed at the same exit profile temperature.
- Reasonable, nitrogen was partially in a gaseous state thus reducing the cooling capacity, especially if the system is thought to work at real industrial standards.
- The selected insert design led to the pick-up defect generation at the insert exit with ZM21 alloy, in relation to the selected low divergent angle (3°).
- Insert did not fail or crack during the whole experimental trials suggesting the proper mechanical performances under the tested extrusion condition.
- The numerical simulations showed an overall good matching with the experimental results both in cooled and uncooled conditions with peak percentage errors of 7.5% and 14% in terms of temperature and load, respectively.

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