Additive manufacturing of H-13 inserts for optimal extrusion die cooling

Lorenzo Donati[1], Barbara Reggiani[2], Riccardo Pelaccia[2], Giuseppe Valli[1], Ivan Todaro[1], Rosario Squatrito[1], Luca Tomesani[1], Tommaso Pinter[3], Enea Mainetti[4], Yoram Rami[5]

[1]University of Bologna, Department of Industrial Engineering (DIN), giuseppe.valli2@unibo.it; ivan.todaro@unibo.it; l.donati@unibo.it ; luca.tomesani@unibo.it

[2]University of Modena and Reggio Emilia, Department of Sciences and Methods for Engineering, riccardo.pelaccia@unimore.it; barbara.reggiani@unimore.it

[3]Almax-Mori S.r.l., Via Matteotti 13, Mori (TN) 38065, Italy, tommaso.pinter@almax-mori.it

[4]A.t.i.e. Uno Informatica S.r.l., via Macon 30, 23900 Lecco, Italy, enea.mainetti@unoi.it

[5]S.h.l. ALUBIN, Kiryat Bialik (Il), yoram@alubin.com

ABSTRACT

The hot extrusion process is a widespread manufacturing technology selected to produce sound profiles of almost any complex section. Even assumed the consolidated state of the process, however many process related aspects need still to be completely solved such as those related to the high temperatures involved. Many defects can indeed arise consequently to the heat generated for the work spent to overcome friction at the tool/workpiece interfaces and to plastically deform the material as well as to the set pre-heating temperatures. These defects (hot cracks, tearings, pick-up, ..) can affects both the quality of the extrudate and the achievable productivity thus reducing the overall process efficiency. A solution adopted at industrial level is the use of liquid nitrogen cooling supplied by means of a channel manufactured on the mating face of the die with the backer. However, this has the main drawback to remove heat far from the regions where the highest temperature are reached, the bearing zones. In this context, the additive manufacturing technologies offer a valid turning key allowing integrating in the dies additionally functionalities such as conformal cooling channels. Aim of the present work was the design and the selective laser melting (SLM) manufacturing of an H-13 insert for extrusion dies with a conformal cooling channel. To support the design phase, numerical simulations have been carried out by including liquid nitrogen. Finally, experimental tests were successfully performed on ZM21 magnesium and AA6063 aluminium alloys confirming the efficiency of the achieved targeted cooling.

INTRODUCTION

The productivity of a well consolidated process such as the extrusion of aluminium profiles is strongly related the level of temperatures generated during the process itself [1]. Indeed, depending on the initial pre-heating temperatures of the billet and of the die, but especially depending on the level of deformation imposed to the forming profile, temperatures nearby the melting point of the material can be reached. An additional factor that contributes to the development of the high temperature field is the friction at the billet/tool interfaces that need to be overcome and that required a further amount of work at the press then converted into heat [1]. The detrimental consequences of these high temperatures are the decrease of the die lifetime and the many defects that could affect the outgoing profile such as hot cracks, tearings, pick-up. If the direct correlation between the extrusion speed and the generated temperature is accounted for, then it clearly emerges how the process efficiency and productivity are regulated by the thermal field.

Among the available options to control the extrusion temperature [1-3], the use of liquid nitrogen for die cooling is still widely increasing its diffusion in leading extrusion companies in order to improve the aesthetical quality of the extruded profiles and to increment the production rates. The benefits can be summarized at two levels: liquid nitrogen initially flow in the die thus globally reducing the temperature then it transforms into gas phase thus protecting aluminum profiles surface from oxidation at high temperatures [4]. Claimed benefits are clearly visible during experimental trials although today the liquid nitrogen cooling effect is applied not in proximity of the regions where the maximum temperatures are reached, the bearings, but in between the die and the backer through milled channels on backer face. In order to produce an optimal efficient die cooling, the nitrogen channels should be localized in the die, around the bearings, following the profile shape complexity. Those type of channels are named ‘conformal cooling channels’ and can be produced only by the expensive additive manufacturing (AM) technologies that offers the best solution for a free form design with almost no geometrical constraints, also with the H13 hot work tool steel that represents one of the most commonly used material to manufacture extrusion dies.

Among the additive technologies, the Selective Laser Melting (SLM) is known to be one the most handy for tool applications allowing to process a number of materials and to achieve high mechanical properties, in addition faster than other competitive technologies [5,6]. With the use of the AM in general, and specifically of the SLM, more complex shapes and tools with integrated functionalities like conformal cooling channels are made possible. If the use of the SLM technology for conformal cooling nowadays represents a standard in processes like plastic injection moulding, die casting and sheet metal forming [7,8], in the extrusion framework only a limited number of works have been presented in literature [9,10].

If the freedom achieved with the SLM technology for the cooling channels design allows overcoming the manufacturing constraints of conventional machining, it also increases the number of parameters to be included in the die optimization such as the channel geometry, the cross section shape and the number and position of inlets/outlets. Since the experimental optimization is time and cost consuming, especially when additive technologies are involved, a valid alternative can be found in the numerical simulation that represents a well-consolidated and validated tool for the extrusion process [11-15].

In this work, a multi die concept for hot aluminum and magnesium extrusion process is proposed in which an H13 insert with forming zones and a conformal cooling channel was designed and manufactured by means of the SLM technology while the external die housing by conventional methods in order to keep the final die costs increase to a minimum level. Inserts were SLM printed and complex Finite Element simulations of the extrusion process with nitrogen cooling performed in order to predict the thermal field of the inserts. Dies were tested during aluminum and magnesium extrusion with different inserts design and the effect of the liquid nitrogen flow was recorded in term of thermal field, production rates and process load thus demonstrating greater potentialities respect to toady application.

DESIGN AND NUMERICAL MODELLING

In the present work, a profile extruded in a relevant amount has been selected consisting in a round bar of 10 mm diameter. The novel die concept was composed of two parts: the internal costly SLM insert with conformal cooling channels, thought to be made in AISI H13, and the external steel housing conventionally manufactured (Fig. 1a). This configuration has the great benefit of allowing each component to be separately manufactured, post processed and heat-treated according to the material’s specifications, thus achieving the best possible mechanical characteristics of material. The steel housing have been designed and manufactured by the die maker Almax Mori Srl (TN), Italy. The helix pitch, the channel diameter, the inlet position as well as the number and positions of outlets were considered in the insert design with the aim to achieve the best insert thermal functionality coupled with a high mechanical strength. The geometry optimization also considered the position of the thermocouple hole used for the temperature monitoring during experimental trials and the platform dimension of the SLM machine. To face with all these requirements, many insert designs have been evaluated resulting in the final solution with the cooling channel helicoidally wrapped around the bearing zone (Fig. 1b). A single nitrogen inlet was planned while a final toroidal portion with 8 radial outlets in the profile exit zone was designed. This portion was aimed at creating an inert gas covered zone where the profile exits at high temperature from the die, thus limiting oxidation. At the end of the design stage, two different geometries were selected for further investigations, with a channel cross section of 1.5 mm and 3 mm (Fig. 1c,d). Afterwards, a numerical campaign has been carried out in order to preliminary investigate the thermal and mechanical performances of the insert designs. The selected FE code was COMSOL® Multiphysics due to its potential in coupling the nitrogen cooling with the extrusion process. In addition, in previous works, the code was found able to resolve complex extrusion cases in a significantly low computational time [16].

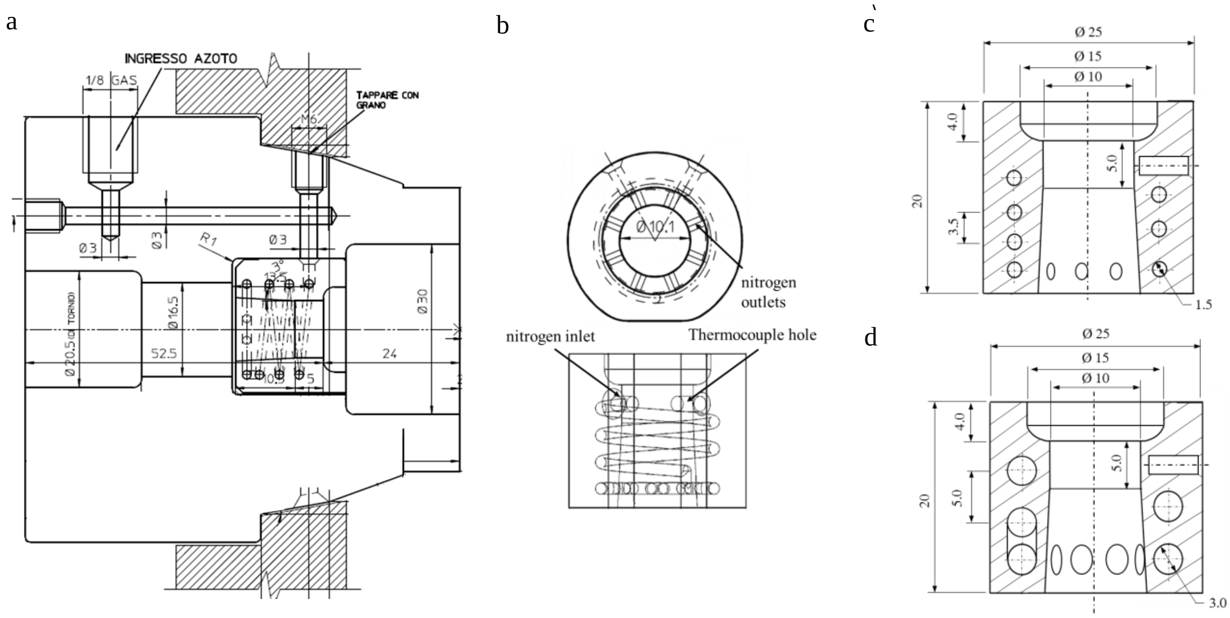

Fig. 1. (a) The novel die concept, (b) the insert final design with nitrogen inlet and outlets, (c) the insert design with 1.5 mm of cooling channel diameter, (d) the insert design with 3 mm of cooling channel diameter

The numerical model was required to face with the double aim of fast and reliable solutions, in order to be used as supporting-decision tool for die designers in extrusion industries. Thus, a simplified 1D model of the conformal cooling channel was integrated in the 3D model of the extrusion of the bar profile (Fig. 2). The parameters across the pipe were modelled as cross-section averaged quantities, which only varied along the length of the channels [16]. The equations describing the cooling channel are fully coupled by the code to those of the insert and the heat transfer coefficient is computed by means of the thermal conductivity of liquid nitrogen, the equivalent hydraulic diameter and the proper Nusselt number selected by the code depending on the flow state (laminar/turbulent) [17]. COMSOL uses a fluid-dynamic approach to model the material flow so that, in the initial CAD model, the billet copied the steady-state configuration with the material already filling the die. The container and the ram were not incorporated but their thermal effects were accounted for by applying proper boundary conditions to the interfacing billet surfaces. In order to have a more realistic distribution of the stresses, additional simulations have been also performed with the 3D geometry of the channel subtracted to the resistant volume of the inserts. For these, uncooled steady-state simulations were run and results compared in terms of peak and average Von Mises stress in the inserts as well as in terms of peak extrusion load. Uncooled and cooled temperature distributions for the two insert designs have been compared as well.

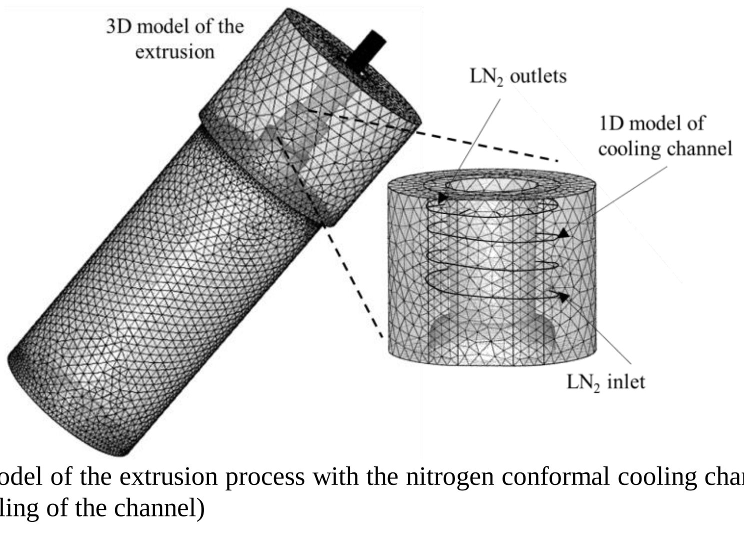

Fig. 2. The developed FE model of the extrusion process with the nitrogen conformal cooling channel for the 1.5 mm insert design (1D modelling of the channel)

At this stage of the work, conventional process conditions were selected to run the simulations. Specifically, the billet, die and container initial temperatures were set equal to 480°C, 490°C and 400°C respectively. At the billet/tools interfaces, a heat exchange coefficient of 11.00W/m2K was imposed with a sticking friction condition everywhere except in the bearings where a sliding (wall-no-slip) condition was assumed [14,18]. The outer die and convection with air were assumed at a constant temperature of 320°C and 25°C respectively. The billet length and diameter were considered equal to 180 mm and 90 mm. An extrusion ram speed of 5 mm/s was used. The billet material was modelled by means of the inverse sine hyperbolic law [19]:

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

where $\bar{\sigma}$ is the flow stress, $\dot{\varepsilon}$ is the strain rate, Q the activation energy, R the gas constant, T the temperature and n, A and α material constants. The coefficients used for AA6060 alloy (eq. 1) in the simulations were n=4.67, Q=161000/mol, A=0.76301·11s-1, R=8.314 J/(K°·mol), α=0.035 MPa-1 with T expressed in °K [20]. The insert and the steel housing were merged in a single solid element and the AISI H13 hot-work tool steel properties taken from the code database. Material data of liquid nitrogen were taken from literature [21] and a flow rate of 1lt/min was imposed in the simulations together with an initial nitrogen temperature of -196°C. Results are reported in Fig. 3 in terms of temperature distributions in uncooled (Fig. 3a,b) and cooled (Fig. 3c,d) conditions for the two insert designs.

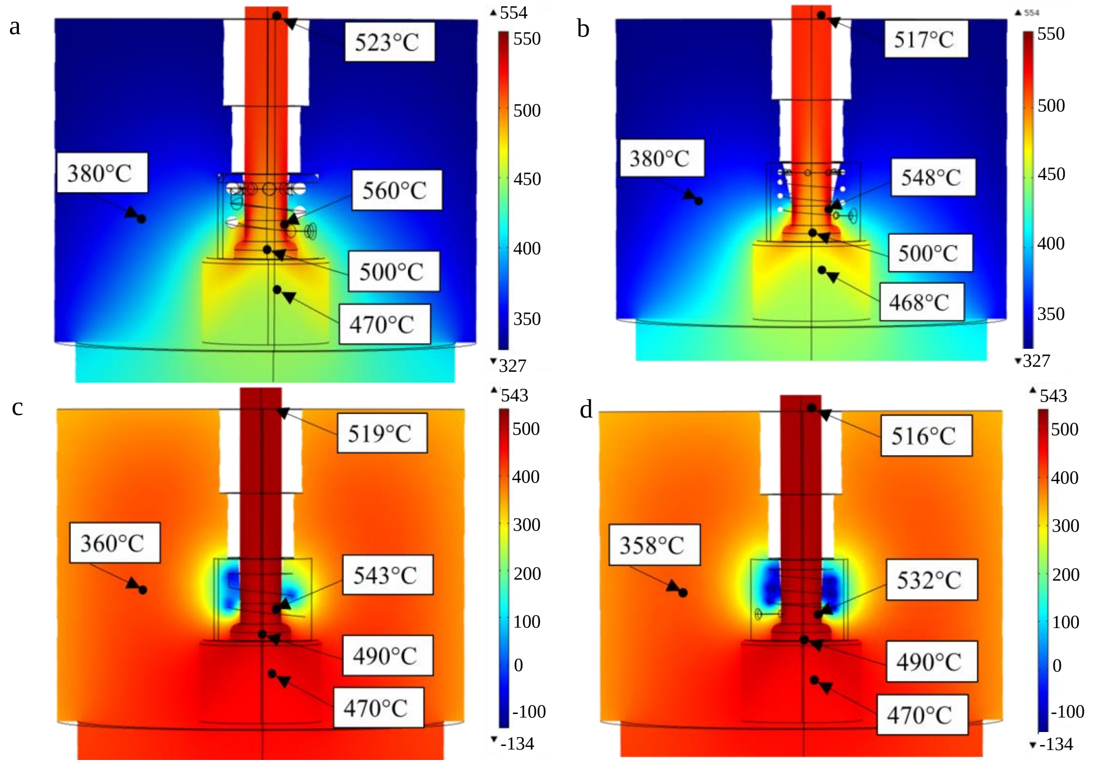

Fig. 3. Numerical predicted temperature in: uncooled condition for the (a) 1.5 mm and (b) 3 mm insert designs; cooled conditions for the (c) 1.5 mm and (d) 3 mm insert designs

The Fig. 3 clearly evidences the effect of the nitrogen cooling. In the simulations with liquid nitrogen (Fig. 3c,d), a colder (blue) region can be clearly seen that corresponds to the helical path of the channel. Nonetheless, the temperature remained unchanged and properly high in the forming zone of the inserts where the profile is generated (around 480°C). For the 3 mm of cooling channel diameter configuration, the average insert temperature dropped from 453°C of the uncooled condition to 210 °C of the cooled state thus suggesting an important effect of the forced cooling. The aluminum temperature in the bearings was decreased of 17°C (from 560°C to 543°C) reducing the risk of profile defect generation. A temperature drop of 20 °C (380°C-360°C) was achieved for the housing die during the process.

In general, similar effects were observed for the 1.5 mm insert design that reached the same level of peak temperature in the forming zone and almost the same profile exit temperature of the 3 mm configuration. However, a lower average insert temperature was measured for the cooled 1.5 mm design, justified by a reduced helical pitch and then by a longer cooling path. In addition, it was numerically predicted a very high inlet pressure required to guarantee a nitrogen flow rate of 1 l/min for the 1.5 mm insert design (4 bar), while a more reasonable data was attained for the 3 mm design (1.1 bar).

Concerning the structural analysis, the level of the predicted Von Mises stresses remained under the yielding point, that suggesting a proper resistance of the inserts to the in-service loads, at least in uncooled conditions. In details, a peak and an average Von Mises stress of 818 MPa and 302 MPa were numerically achieved for the 3 mm insert design while the corresponding values for the insert with a diameter of 1.5 mm were 450 MPa and 158 MPa. No a significant difference was found between the two insert configurations in terms of peak extrusion load (2.17 MN and 2.15 MN for the 3 mm and the 1.5 mm insert designs).

In order to find the limit of the cooling capacity, three different ram speeds, 2.5 mm/s, 5 mm/s and 10 mm/s with and without liquid nitrogen supply have been numerically tested for the 3 mm insert design. Results are reported in Fig. 4 in terms of peak temperature history in the forming zone. The same level of temperature reached at 5 mm/s was achieved by doubling the ram speed (10 mm/s) if the nitrogen cooling was used. Obviously, the numerically tested condition at 10 mm/s without cooling is unrealistic generating a profile exit temperature of 610°C, next to the aluminum melting point. However, it was included in order to quantitatively assess the gain achievable with the use of nitrogen cooling in terms of production rate. The same was for the lower ram speed of 2.5 mm/s with the final value of temperature in uncooled conditions approaching that of the cooled insert at 5 mm/s.

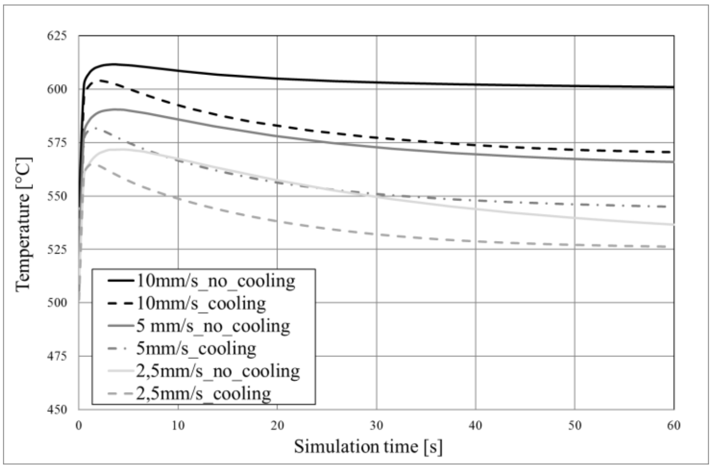

Fig. 4. Comparison of the 3 mm insert design thermal performances

SLM MANUFACTURING

Due to the encouraging results, at the end of the numerical campaign, the two insert designs have been additively manufactured by means of the SLM technology on a SISMA Industries MYSINT 100 LM Fusion Fiber laser (laser spot diameter 50 microns). Preliminary experimental tests were performed in order to select the optimal printing parameters for the AISI H13 powder (average size 30µm) in terms of density. In all the tests, the layer thickness was set to 20 µm and the hatch spacing to 60 µm while the laser powder and speed were varied according to a two-factor-three-levels design of experiment thus producing nine combinations. The investigated levels were 90-120-150 W and 700-950-1200 mm/s for the laser powder and speed, respectively. As a result, Fig. 5 reports the measured density over fluence. It can be seen that the higher density was found for a fluence of 143 J/mm3 achieved with a laser speed of 700 mm/s and a laser power of 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.

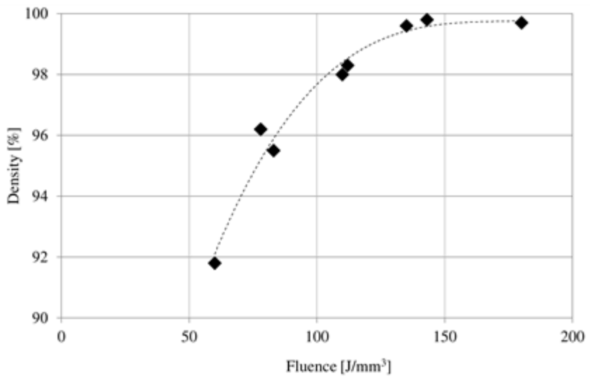

Fig. 5. Density over fluence distribution for the AISI H13

Then the two insert designs were vertically printed in the growth direction opposite to the extrusion flow by using the optimal set of parameters identified in the preliminary tests (Fig. 6a). Eight inserts (four for each design) were produced, two at a time on the platform. The outer insert and the bearing surface were initially oversized to grant following optimal dimension for next EDM process. After printing, each insert was visual inspected by X-ray analyses, resulting completely crack-free (Fig. 6b). An additional insert was also longitudinal sectioned (Fig. 6c). The surface roughness was acquired in order to check the “as-printed” quality of the outer surface of the insert and to evaluate the continuity of the individual layers. A standard surface quality for SLM printing was measured (Ra =12±3 µm).

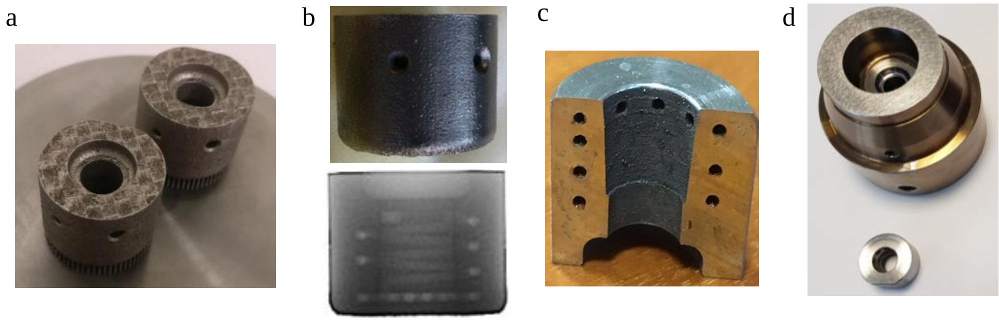

Figure 6. a) two SLM inserts with cooling channels of 3 mm diameter; b) picture (left) and X-ray analysis (right) of the printed insert of 1.5 mm diameter; c) longitudinal section of the insert without evident cracks, holding die (top) and insert (bottom) before final assembly

Inserts were then heat-treated (quenched and tempered) achieving the required mechanical properties (≈ 45 HRC) and surface finished to remove the allowance by means of EDM for the bearings zones and of turning for the outer diameter for the shrink fit with the steel housing. In figure 6d the holding die and the insert are showed before the final assembly. Internal cooling channels presented a surface quality comparable to that of the outer surface of the insert, verified by means of a sample sectioning and a microscopic observation and by testing the successful passage of compressed air.

EXPERIMENTAL TRIALS

AA 6063 ALUMINUM TESTS

Experimental trials were performed on a 2.5 MN laboratory press at Alubin plant, Haifa, Israel. A total of 24 billets made of AA6063 were consecutively extruded with and without the use of liquid nitrogen. Billets length and diameters were 100 mm and 45 mm respectively with a container diameter of 50 mm. Billets and die were pre-heated at a temperature of 450°C while the container had a temperature of 375°C. The liquid nitrogen was stored at about 5 bar in a tank of 230 l and supplied by a 4 m length pipe. The first 7 billets were extruded at a lower ram speed (from 2 to 4 mm/s) ad without nitrogen cooling in order to homogenize the temperatures. Then, nitrogen valve was completely opened (100% of flow rate) and the extrusion speed increased to 4.2 mm/s.

Figure 7. Experimental trials at Alubin: (a) nitrogen tank and extrusion press, (b) 3 mm design after trials, (c) 1.5 mm design after trials, (d) profile at the die exit

The press forces were recorded throughout the experiments and a K-type thermocouple was used to monitor the temperature of the insert in the location reported in figure 1c and d.

Fig. 8 shows the temperature development in the insert during the extrusion of the 24 billets. The trials started with the nitrogen valve closed and billets from 1 to 5 were used to warm-up the system, being billets 6 and 7 the repetition of not-cooled conditions. From billet 4, the temperature started to increase of 10°C during each extrusion reaching a steady-state value of 390°C for billets 6 and 7. With the valve nitrogen opening for billet 8, a decrease in temperature can be immediately observed. Billets 8,9 and 10 showed a peak insert temperature of 350°C thus resulting in a temperature drop of 40°C. Specifically, from billet 8 the nitrogen valve was fully opened but initially gaseous nitrogen –instead of liquid- reached the bearings, as experimentally observed by connecting pipes that were not covered by ice. With advancing of extrusion, ice started moving forward along the pipes and, from billet 12, liquid nitrogen reached the die inlet and the die temperature evidenced a drop of 90°C. Billet 11 required the change of the dummy block as evidenced by the long cycle time and globally the system cooled down. In trials from 12 to 24, the nitrogen valve was closed during billet change in order to limit the decrease of temperature of the die. Billets 22 to 24 were processed with 50% higher ram speed (6,5mm/sec) and a rise of temperature to 375°C as stead-state condition was found.

Figure 9 reports the press load evolution during the trials. During warm-up (billets 1 to 4) the maximum press load of 1,6 MN was reached at the end of the stroke (too short billet rest) then an average value of 1,0 MN was achieved during not-cooled trials. In billets 8 to 10 no change of press load is evidenced although some cooling effect was already recorded by the thermocouple; actually nitrogen was opened but the die was reached by gaseous state only. Trials from billet 12 to 24 showed a limited increase of the press load to 1,15MN as combined effect of low ram speed/lower profile exit temperature (billets 12 to 21) and increased ram speed/higher exit temperatures (billets 22-24).

After the trials the die was dismantled and the insert didn't evidenced any trace of cracks or wear as expected by a conventional die. The die with 1,5mm channels was not tested at the press but only connected to the nitrogen pipes in order to verify if the liquid nitrogen was able to flow within the die heated up at 450°C. It was clearly visible that the nitrogen always changed its phase into gaseous being thus impossible to reach a liquid nitrogen cooling condition.

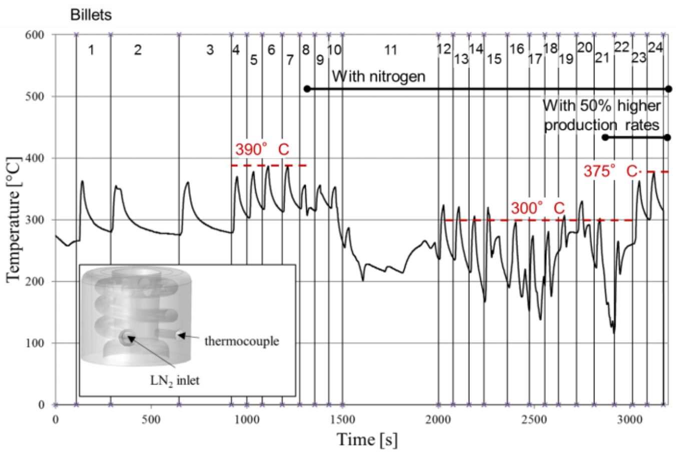

Figure 8: Temperature of the insert as acquired with a K-type thermocouple

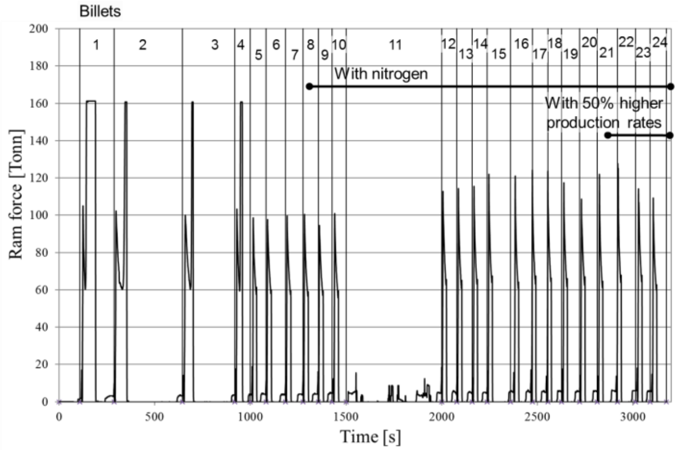

Figure 9: Time-history of the press loads over the 24 extruded billets

ZM21 MAGNESIUM TESTS

The same experimental setting used for the aluminum billets was adopted for extrusion of the 18 billets made of ZM21 magnesium alloy. Billets length and diameters were unchanged (100 mm and 45 mm respectively) while the billets and die pre-heating temperature was 300°C while the container had a temperature of 374°C. As for the aluminum trials, the first 3 billets were extruded at 4 mm/s without nitrogen cooling in order to homogenize the temperatures. Then, nitrogen valve was completely opened (100% of flow rate) for the next 7 billets and then closed again for the remaining billets.

In Fig. 11 are shown the load (pressure, bar) and the temperature development in the insert during the extrusion of the 18 billets.

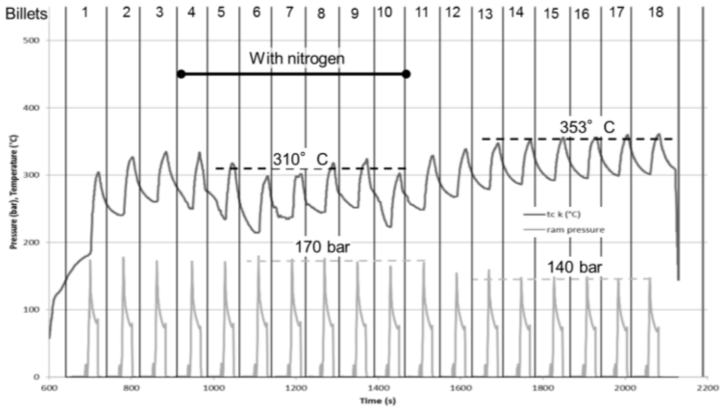

Figure 11: Time-history of the pressure and of the temperature over the 18 extruded ZM21 billets

As for the aluminum trials, the effect of the nitrogen flow was clearly visible leading to an average temperature decrease of more than 40°C. However, the cooling effect was reduced with respect to what achieved during the aluminum extrusion tests (drop of 90°C). It was also observed that the ZM21 created material deposits after bearing that closed the nitrogen outcome holes thus suggesting for the requirement of a further die design optimization.

However, as positive remarks, the die with the novel insert with a conformal cooling channel resisted also at this second stage of experimental tests without any evident failure. The ram load did not increase significantly during cooling moving from 140 bar in uncooled conditions to 170 bar with a 100% of valve opening (+21%). With respect to the aluminum trials, a better exit profile quality was achieved both with and without nitrogen, this representing an important outcome also in consideration of the selected extrusion temperatures not far from industrial standards.

CONCLUSIONS

In the present work, a novel concept for extrusion dies with conformal cooling for liquid nitrogen has been presented and developed. The novel concept involves the use of the SLM technology for an insert manufacturing with an optimized design of nitrogen cooling channels, that is then assembled in an external steel-housing conventionally manufactured in order to limit final die costs. After the design stage, two insert designs have been selected with a helical cooling channel development wrapped around the bearings, both with a circular channel cross section but two different diameters, 1.5 and 3 mm. In order to investigate the inserts thermal and mechanical performances, a comprehensive numerical analysis has been performed by means of an FE model of the extrusion process and a specific 1D model for liquid nitrogen cooling prediction was innovatively applied. Then, experimental trails of the inserts were carried out on a laboratory press with and without the use of liquid nitrogen.

As main conclusions, it can be stated that the developed numerical model was able to model the cooling effect of liquid nitrogen in the conformal channels, predicting an average insert temperature drop of more than 250°C for the 3 mm of channel diameter design and thus suggesting an important effect of the forced cooling. In addition, the numerically predicted temperatures in the forming zone of the inserts remained almost unchanged in cooled conditions confirming the proper channel design and positioning that allowed to remove heat merely where required. As a further important result, numerically, the cooled inserts with liquid nitrogen were proved to allow a doubling of the production rate if compared to the uncooled condition reaching the same level of peak temperature nearby the bearings.

Coming to the manufacturing step of the work, inserts with 1.5 mm and 3 mm of cooling channel diameter have been successfully SLM printed with a H13 tool steel powder by selecting the following parameters: layer thickness of 20 µm, hatch spacing of 60 µm, laser speed 700 mm/s, laser power 120 W (fluence 143 J/mm3).

In the experimental trials, the cooling effect with conformal cooling channel configuration was remarkable nearby the bearing with a profile temperature decrease up to 90°C for the aluminum trials for the 3 mm insert design thus allowing an increment of more of the 50% of the ram speed at the same exit profile temperature. This also confirmed the goodness of the developed numerical model that predicted the same behaviour. Experimentally, the process load, as well as the temperature in the entrance side of the insert, were not affected by nitrogen cooling. For the magnesium tests, the cooling efficiency was less pronounced, even if still remarkable, achieving a temperature drop of 40°C. However, a better profile surface quality was obtained than that of the aluminum, both in cooled and uncooled conditions.

The performed experimental tests highlighted the critical behaviour of nitrogen phase change due to the significant volume increase when it transforms from liquid to gas becoming problematic for the cooling effect. In particular, the 1.5 mm insert design was not able to evacuate the gaseous phase fast enough and consequently the liquid nitrogen never reached the die inlet. The experimental campaign showed also the importance of controlling the nitrogen flow during ‘on’ and ‘off’ phases of the extrusion cycle in order to avoid an excessive cooling of the die assembly.

The achieved results, in particular the increase in production rates, the lack of cracks or wear on the inserts and the development of a FEM tool for the generalization of the results to different profile geometries, promote the extension of the activities in future to more complex industrial cases

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