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MOULD DESIGN PROCESS IN HIGH PRESSURE DIE CASTING SUPPORTED BY VIRTUAL PROTOTYPING

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ABSTRACT

High Pressure Die Casting is a widely used industrial process to manufacture complex-shaped product in light alloys. Virtual prototyping techniques, especially numeric based simulations of the casting process, evaluates the die filling process and helps faster optimization of the gating system. However, no formalised method to design an optimal gating system using virtual prototype tools is available yet and the majority of the studies aim to optimise existing geometries. The purpose of this work is focused on new approach to easily define the entire geometry of the mould without starting from an existing solution. The paper presents a four step approach which allows optimal mould and gating system to be designed taking advantage of simulation tools. Rather than optimizing the geometries of predefined designs by running attempt trials, the approach defines a procedure to position cavities, gating systems and determine the whole mould geometry. The design of a 6-cavity mould for gas cooking burners is reported as a test case for the validation of the method. The reached quality of the mould design has been assessed using metallographic analyses of the cast products.

KEYWORDS

High pressure die casting, numerical simulation, virtual prototyping, gating system.

1. INTRODUCTION

Light alloy components are commonly used in many sectors of industrial production. In particular, aluminium alloys have been greatly diffused in recent years due to limited production costs, mechanical performances, lightness and material recyclability. A strong push towards their use comes from improvements in casting processes, which allow the production to be increased, to reduce the cycle time, and to manufacture complex-shaped components [1].

In particular, High Pressure Die Casting (HPDC) is a metal casting process characterized by forcing molten metal under high pressure into a mould cavity (Fig. 1).

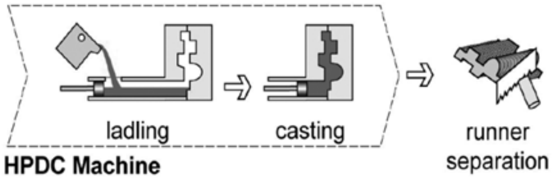


Figure 1: High Pressure Die Casting process.

HPDC is used to obtain a high volume of products and is widespread in the production context thanks to two main features: low costs and production efficiency. Furthermore, this process permits components with complex geometry, shape and good dimensional accuracy to be obtained [2]. Examples of obtainable components include electric motor housings, small parts of appliances, engine blocks, automotive parts, etc.

Product and mould design in die casting are strictly interdependent. The good quality of products is closely related to the geometry of the mould and in particular of the gating system, which refers to the channels through which the metal flows to fill the mould cavity (Fig. 2). Optimisation of the mould filling patterns through improving the gating system design becomes very important especially if the casting is produced by HPDC [2].

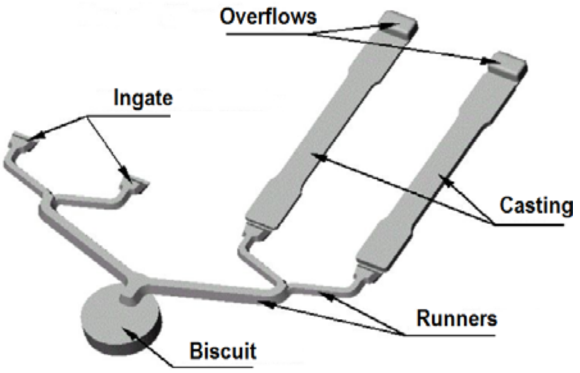


Figure 2: Example of gating systems and component naming

Efforts in the industrial departments are focused on the reduction of product defects and the maximization of productivity. Several defects are inherent to the HPDC process and play a key role in the mechanical performance and quality of die-castings. Macro-segregation of eutectic, intermetallic particles, porosity, oxide bi-films and confluence welds are typical HPDC defects [3].

The definition of the gating system geometry is mostly based on engineers' experiences, past solutions, knowledge acquired through the years and definitely a trial-and-error approach. [4]. Main problems which arise from the traditional methods are:

- obstacles to divulge know-how to other designers, especially novices;
- difficulty in applying established solutions for large varieties of products;
- time and cost waste

In recent years the main road in the product development has been characterized by the integration of simulation tools which permit casting processes to be virtually evaluated and critical aspects to be identified. The logical step to achieve an optimum gating design and overcome the expensive trial-and-error approaches is represented by Virtual Prototyping tools which are based on Numerical Simulation of thermo-fluid-dynamic laws.

The simulation of processes and systems needs to represent reality through the use of models. The models are usually formulated as governing equations and boundary conditions. For HPDC products, modelling the process becomes quite complex, as reviewed by Fu in [5] and summarised by figure 3, due to the sheer number of thermo-physical and chemical parameters to be considered.

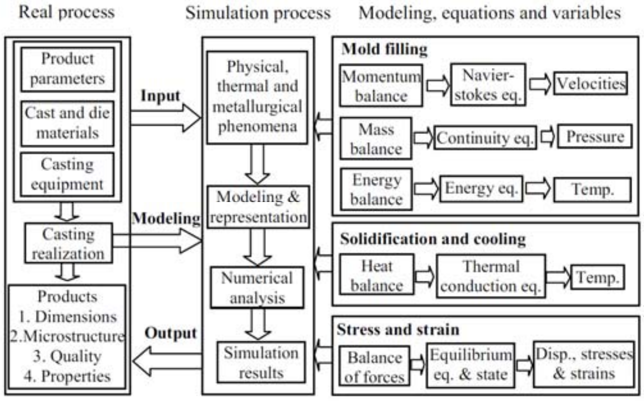


Figure 3 Associativity among process, modelling, simulation and output variables in HPDC virtual prototyping (from [5])

However, CAE tools offer a powerful and cost effective way to study the effectiveness of different die designs and filling processes [6]. The importance of these tools is related to the reduction of physical prototypes, costs and time to market.

Nowadays, CAE software are involved in the optimization phase of the HPDC design process and are only used to verify, validate and optimize the design solutions before they are practically implemented and physically fulfilled. The designers interpret the results of the numerical simulation and decide which changes need to be made on the product design. The numerical simulation can only verify a given casting design, thereby replacing a trial prototype. This is an iterative process until the last mould configuration minimizes the presence of defects and optimizes the mould filling process.

The major drawback in the current HPDC mould design process is an established methodology which allows the best configuration of gating system to be obtained starting from the product geometry and production constraints. Specifically, the majority of industrial or research practice pursue the optimization of the gating system among alternative solution or vary a restricted set of geometrical parameters for a given initial configuration. In other words, proposed approaches rely on the optimization of known solutions rather than systematically finding original configurations at the early phases of a new mould design.

In this context, the aim of this work is to present a four step design method for the definition of the geometry of gating systems in HPDC by means of Virtual Prototyping tools. In particular, CAE software is used as an integral means of the gating system geometry definition method and not only as optimization of a given predefined geometry. Therefore, virtual prototyping operates from the early design phase of the gating system for the sequential definition of the position of the cavities, the shape of the gating system and, finally, the whole mould geometry.

The paper is organised as follows. Section 2 describes the parts of a HPDC mould, the state of the art of the simulation tools and of the optimization methods in this field. The following section describes the proposed approach to incrementally define the optimal geometry of the mould. In section 4 the validity of the approach is demonstrated through an industrial application, a gas burner test case.

2. STATE OF THE ART

HPDC is an important process in the manufacturing of high volumes and low cost components for the automotive, household products and electronic industries. Liquid metal (generally aluminum, magnesium or zinc) is injected into the die at high speed (30–100 m/s) and under high pressure through complex gate and *runner* systems.

2.1. Die arrangement and typical cast defects

Figure 2 reports traditional geometrical arrangements for HPDC dies. Generally high components are produced using a multi-cavity die in order to increase production rate. The main parts of a gating system can be identified in:

- *Cavity (Casting)*: the void or empty space in the die which fills with metal to make the casting;

- *Biscuit*: the excess of ladled metal remaining in the shot sleeve of a cold chamber die casting machine;

- *Runner:* the die passage connecting the biscuit to the gate where molten metal enters the cavity or cavities;

- *Ingate*: a small restriction and passage for molten metal which connects the *runner* to the die cavity;

- *Overflows*: a small pocket for the first metal to flow through the cavity located around the edge of the casting. Vents (paths from the die cavity to its outer side) from *overflows* provide a path for the air to escape from the die.

The HPDC process is fairly complex. The phenomenon of casting solidification, accompanied by volumetric contraction, leads to several major defects in casting including shrinkage porosity, cracks and distortion. The location and extent of shrinkage porosity can be predicted by identifying regions of high temperature (hot spots) and low gradients (short feeding distances). Unfortunately, castings can be of complex shapes, and the heat transfer from all faces of the mould may not be uniform.

Moreover, the geometric complexity of the dies lead to a strong three dimensional fluid flow with significant free surface fragmentation and splashing. The order in which the various parts of the die fill and the positioning of the air vents are crucial for the formation of homogeneous cast components with minimal entrapped voids or porosity. This is influenced by the design of the gating system and the geometry of the die.

Other factors, such as air gap formation at the metal-mould interface, convection in liquid metal, application of feed aids, presence of cores, gating system design and pouring parameters also affect the location of shrinkage porosity, making its manual prediction difficult, if not impossible. Among these, the gate arrangement mostly determines how many incoming streams the fluid sub-divides into. The initial jets are fast and very fragmented. They rapidly reach the opposite sides of the die and then start filling back towards the gates. Fluid typically race tracks around the thicker structural rims of the components, blocking all the discharge vents early in the filling process and leading to large volumes of trapped air. This trapped air guarantees that there will be fine scale porosity. The timing of the blocking of the vents determines the extent of the gas porosity problem. The details of later flow patterns then determine the distribution of this gas porosity in the final casting. The topography of the thin-walled castings typically manufactured with HPDC determines how the incoming fluid streams distribute fluid within the die.

So overall, the HPDC flows are complex and are strongly affected by details of die cavity geometry, the metal flow and venting systems. The ultimate goal of a good die design relies on the predictions of the last locations to be filled and on the porosity to be expected due to the trapping of large volumes of air within the die cavities.

2.2. Virtual prototyping for High Pressure Die Casting

Numerical simulation offers a powerful and cost effective way to study the effectiveness of different die designs and filling processes. It ultimately leads to improvements in both product quality and process productivity, including more effective control of the die filling and die thermal performance. A significant number of real life case studies are also available in technical journals and proceedings of conferences related to casting.

Several grid or mesh based techniques have been used to simulate HPDC and other similar casting processes. Some software packages are available on the market and have been tested in research studies. Recent examples of these can be found in Yoshimura et al. [7] where Flow3D® was used to optimise the design of a die casting plunger tip. Kokot and Bernbeck [8] used MagmaSoft® to simulate the flow through a two cavity die to produce automotive head caps. The software is based on the finite difference method (FDM), which couples both the widely used Navier-Stokes and Fourier equations.

Kong et al. [9] used Fluent® to simulate the flow and heat transfer in the high pressure die casting of a representative component. However, among these recent examples, only Kokot and Bernbeck simulate HPDC geometries with any reasonable complexity in 3D. The regular finite difference mesh of MagmaSoft® however leads to stair-stepping artefacts in their flow simulation results.

Another simulation technique which is proving to be very effective at modelling these HPDC flows is Smoothed Particle Hydrodynamics (SPH). The SPH method is described in detail by Monaghan [10]. Materials are approximated by particles which are free to move around rather than by fixed grids, enabling a more accurate prediction of fluid flows involving complex free surface motion. Cleary et al. [11,12] demonstrate its usage in industrial applications, such as die casting.

2.3. Design of optimal gating systems

From an industrial point of view, only a handful of aluminum foundries are using these software tools today. This is due to several challenges posed by first-time users and the lack of strategies to effectively employ simulation tools in product design and optimization activities. For instance, Hu et Al. [13] investigate the effects of *runners* and gating systems in order to provide a homogenous mould filling pattern.

Also in [14] a study on thin-walled die casting of aluminum for notebook computer housing can be found. Authors simulate three predefined types of gating design and compare the virtual analyses with experimental results showing the agreement between the two procedures.

Recently, design optimization processes based on optimization tools permit a wide range of geometrical features to be modified, starting with a parametric CAD model of the entire casting (Figure 4). This is a powerful system for the optimization phase of a given geometry.

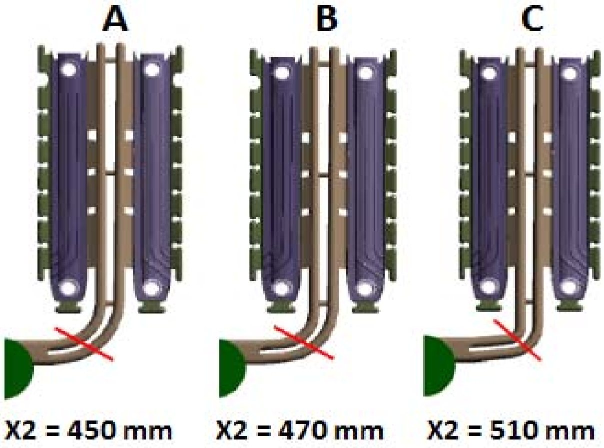


Figure 4: Parametric model of *runners* for aluminum radiator mould: three different bend radii (X2) are tested in order to optimize mould filling.

However, the necessity to start with a certain geometrical model is the major drawback of this method. The optimized geometry is selected among the possible alternative configurations which can be created by the combination of parameters in the 3D parametric model. Essentially, this approach involves the coupling of a process simulator which solves the flow problem with an optimization process, which iteratively finds a search direction to guarantee a better design. The procedure terminates with a design which is locally optimal with respect to the design variables [4]. Time consuming, needed for a large number of numerical simulations, is another problem related to this method.

In conclusion, the majority of these studies is restricted to particular test cases which do not require the application of any structure design procedure. Gating systems have rather been chosen in advance on the basis of designers' experience.

3. PROPOSED METHOD

The design procedure proposed in this work targets the geometric definition of gating systems for HPDC manufacturing. The use of Virtual Prototyping tools in the early design phase of product development allows the geometry to be created in an easy and standardized way. The design procedure is described in figure 5 by means of the IDEF0 formalism.

This approach is composed of four steps, following a reverse path to design the optimal configuration of gating system. The additional value compared with the other methods retrieved in literature is how the Virtual Prototyping tools are used to design the mould. In fact, the proposed approach uses the Virtual Prototyping tools and the numerical simulation results to define the optimal geometry of the gating system step by step and not to optimize a starting predefined configuration. The mould and the gating system geometry are defined in an incremental manner, starting with the optimal solution to fill the casting cavity (*inlet*) and subsequently to bring the molten metal, from the shot sleeve to the inlet, maintaining the same process conditions. The difficulties of this approach are inherent to the complex solution of 3D thermo-fluid dynamic equations. In this approach Virtual Prototyping tools help the designers to solve 3D thermo-fluid dynamic equations and to verify the adopted solutions rapidly and sequentially. Starting only with the cast geometry is an opportunity for the designers and not a constraint of this approach.

Virtual Prototyping tools are not used in an iterative manner such as a “black box” in which the possible alternative configurations are obtained as a linear combination of the parameters in the 3D parametric model. The forward step regarding to the current state of the art is the possibility to build the gating system using these tools and considering all the aspects which intervene in the HPDC process. In this way the process engineers are always conscious of their choices.

The *first step* (A1) is inherent in finding the correct filling solution of the casting. The shape and size of the *inlet* and how the liquid metal is injected into the casting is here defined. This is an essential phase because it determines the way through which the die is filled by the liquid metal and how to minimize the presence of defects. Furthermore, it is possible to design the *inlet* system in order to encourage the optimal filling of aesthetic parts of the casting or parts which require mechanical performances. In the same way, the *inlet* geometry can be designed to reduce the possibility of internal defects in the casting which needed other subsequently

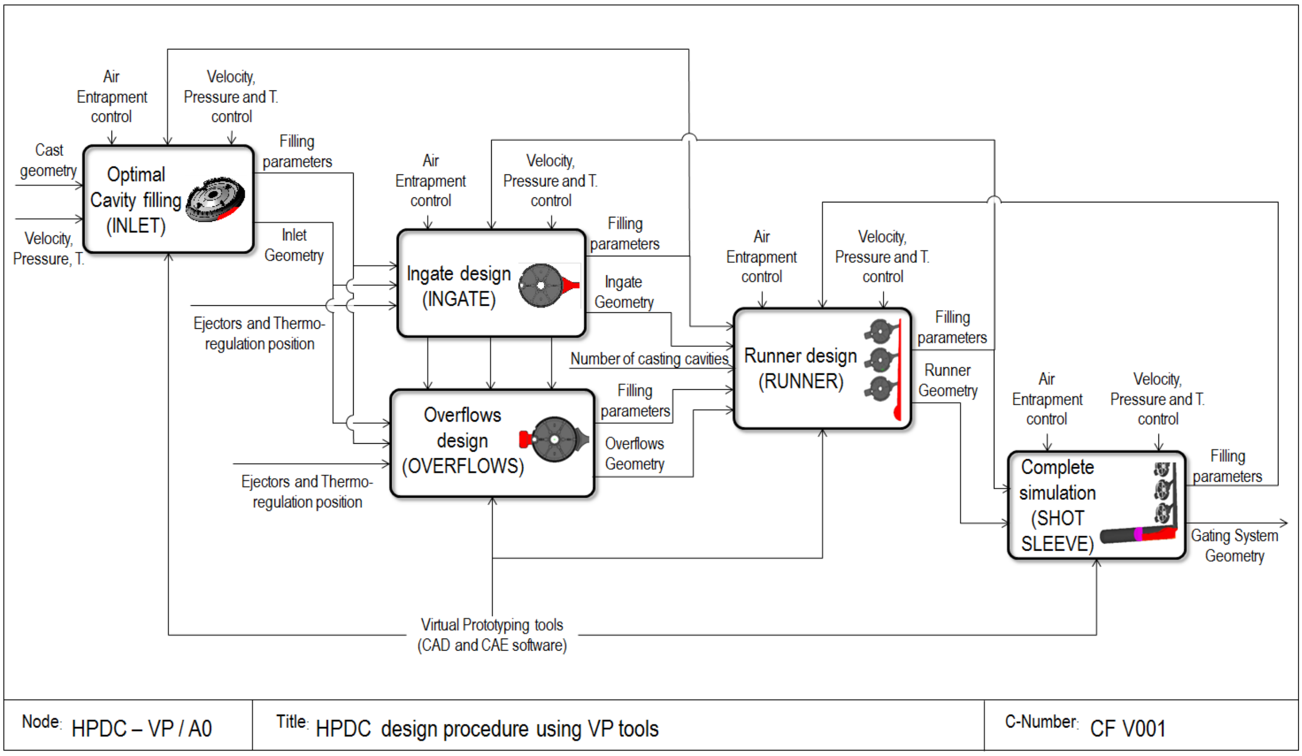


Figure 5: IDEF0 graph for the realization of HPDC design procedure using Virtual Prototyping tools.

manufacturing process. These aspects strongly affect the number of rejected components. The time required to simulate only one cast filling using Numerical Simulation tools is much lower compared to the time necessary to simulate the complete geometry of the gating system in the optimization process. Due to this consideration a large set of alternative solutions can be taken into account in the definition of the *inlet*.

The data necessary as input for the definition of *inlet* system by the use of numerical simulation is given by:

- Casting geometry (shape and dimensions)
- Filling parameters such as geometrical parameters (maximum length, thickness and width) and process parameters (maximum inlet velocity, pressure and temperature).

The main output is represented by the *inlet* geometry. To verify its optimal design, Virtual Prototyping tools allows the control of:

- The air entrapment in the casting and the presence of porosity (shrinkage porosity and voids)
- The HPDC process parameters such as pressure, velocity and temperature.

Input, output, constraints/controls and mechanisms/tools for the first step of the proposed method are shown in detail in figure 6.

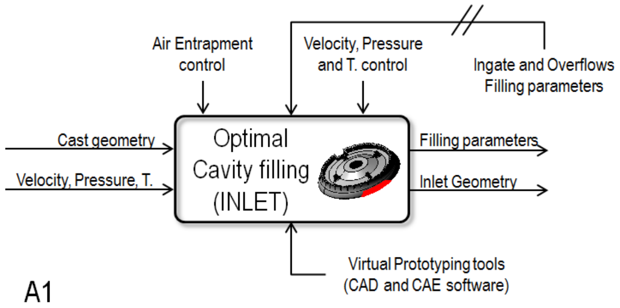


Figure 6: Magnification of the 1st step of IDEF0 design process.

The output results of the iterative design process, for this first step, is the spatial position of the *inlet* and its geometry. Process designers can easily identify the ideal inlet localization on the basis of their experience and intuition. The level of required expertise is very standard for the HPDC operators.

However, the simulation results provide guidance on geometrical and process parameters such as thickness, width, geometry, velocity. The optimal values of such parameters are hardly obtained without supporting tools. The resulting filling parameters become a constraint to be verified in the subsequent step.

The *second step* (A2) of the proposed approach is the definition of the *ingate* geometry. *Inlet* geometry and filling parameters are now input to this phase (Fig. 7). Moreover, the definition of the *ingate* geometry is influenced by the presence of mould mobile ejectors and thermo-regulation channels. The spatial positions of these items are usually fixed and limits the space available for the *ingate* system. In fact, moulds for different products usually share common supporting parts which impose fixed layouts. These modular solutions allow important savings for the company by reusing the supporting parts.

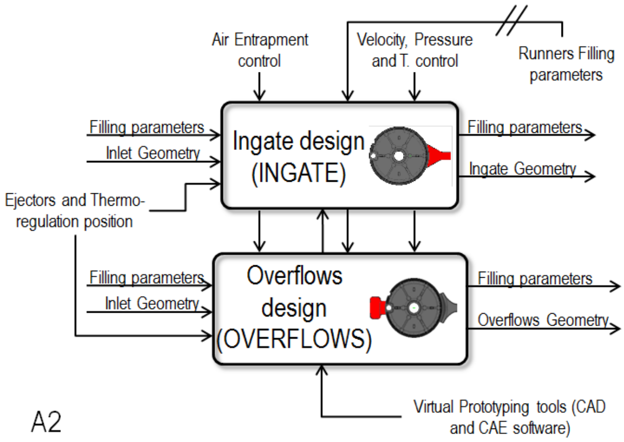


Figure 7: Magnification of the 2nd step of IDEF0 design process.

A second aspect of the second step concerns the definition of the geometry of the *overflows*. Their geometry must guarantee the ejection of the air entrapped in the mould and in the cavities to be filled. The *overflow* design phase shares the same input, constraints and controls of the *ingate* definition.

Virtual Prototyping tools (CAD and CAE software) are the mechanisms used to analyze the filling. The output is the geometry of the *ingate* and the geometry and spatial disposition of the *overflows*. As in the previous step, filling parameters (filling velocity, solidification time, casting temperature, etc.) to be respected by the *ingate* and *overflow* definition computed by Numerical Simulation become the input for the next phase.

The *third step* is to define the number of casting cavities in the mould and the design of the *runners*.

The number of casting cavities is a design choice based on the maximum dimensions of the mould and the size of the HPDC machine which needs to withstand the pressure exerted by the casts. Besides this preliminary choice, other input to define the *runner* are the geometry of the *ingate* and *overflows* and the filling parameters given by the previous Numerical Simulation. The compliance of the *runner* with these design constraints is critical. In fact, damage (such as cracks, tears, distortion, wear and friction with the liquid metal) in the mould can occur if the velocity or pressure is too high. However, if the velocity and temperature are too low it can cause rapid solidification of the molten metal in the mould. This is a very critical aspect for the correct filling of the casting.

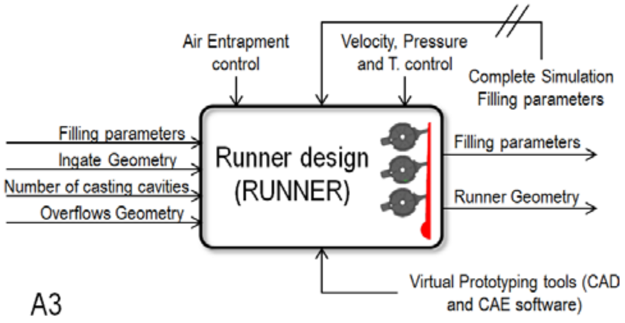


Figure 8: Magnification of the 3rd step of IDEF0 design process.

Once again, Virtual Prototyping tools are used to accomplish *runner* design and its analysis. The input, output, constraints/controls and mechanisms/tools for the third step of the proposed method are shown in detail in figure 8. In particular, outputs are:

- Number of casts obtained in one cycle
- Complete optimized gating system (*runner* + *ingate* + *inlet*)
- Filling parameters (velocity, pressure and temperature in each points of mould)

The *fourth step* consists of a simulation of the whole HPDC process (Fig. 9). The complete simulation is based on the geometry of the gating system obtained in the previous steps, the plug behavior considering the machine parameters (plunger diameter and length, maximum pressure, switching time for accelerated phase, etc.) and the process parameters (ladling time, ladling temperature, length and time for the first and second phase of acceleration).

The final simulation phase allows the HPDC process to be simulated as closely as is possible to reality. It verifies that the designed gating system is compliant with the initial specification. Moreover, it validates the intermediate results obtained by the proposed incremental approach.

Furthermore, the complete simulation of the filling process is necessary to identify the HPDC machine setting parameters, the solidification condition and the thermo-regulation aspects of the mould. This last step permits the total life time of the mould to be evaluated, as well as the cycle time for each cast. A number of considerations can arise from this last Numerical Simulation: the verification of the optimal design solution adopted for the gating system, costs, productivity, cycle time, etc.

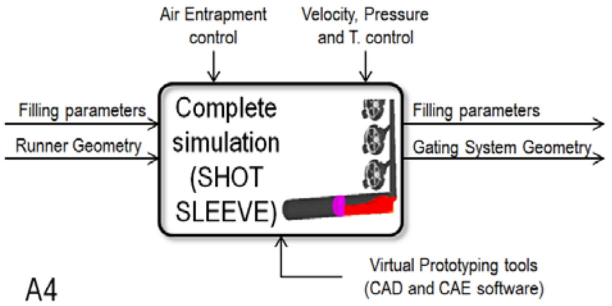


Figure 9: Magnification of the 4th step of IDEF0 design process.

4. METHOD VALIDATION THROUGH GAS BURNER COMPONENTS TEST CASE

The approach has been applied and validated through a large number of test cases. Here the re-design of the HPDC process of a flame-spreader component for gas burner products is reported. The results obtained for this component are highlighted as the pros and cons of this method.

4.1. Gating system re-design

The component is produced from a particular aluminum alloy called *Pyral N2* (Mn2-Ni2-Ti0.15). The key characteristic of this alloy is its high temperature resistance, necessary for this specific application. However, the lack of a Silicon element (Si) in this alloy makes the fluidity worse than a common casting Aluminum alloy. Therefore, using *Pyral N2* alloy in the HPDC process requires an increased temperature of the liquid metal in the cold injection chamber up to 720°C.

The re-design of the gating system has been necessary for two reasons: the first is a desired reduction of rejected castings for the presence of defects, while the second one is due to changes in the geometric features of the burner in order to increase its efficiency. A CAD model of this component is shown in figure 10.

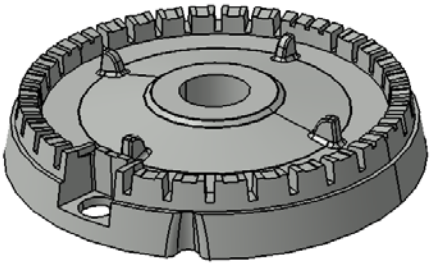


Figure 10: CAD model of flame-spreader component for gas burners.

A commercial CAE package (ProCast®) was used for numerical analysis. The software is based on the finite element method (FEM), which couples both the widely used Navier-Stokes and Fourier equations. Thermal and mechanical characteristics of Pyral N2 Aluminum alloy have been experimentally determined and included in the materials database of CAE package.

The design of the new gating system has followed the proposed approach. Starting from the *inlet* design, the first step of the method, the following constraints must be taken into account:

- inlet thickness < 3mm (to facilitate the cutting process while separating castings from *runners*)
- inlet width < 120°
- maximum inlet velocity < 50-60 m/s

Moreover, the filling process should foster the upper and circumferential part of the casting for aesthetic reasons and for the necessity of further machining operations (grinding process).

FLAME – SPREADER INLET

INPUT	*OUTPUT*	*MECHANISMS / TOOLS*	*CONSTRAINS / CONTROLS*
✓ 3D CAD model of casting ✓ Velocity = 50 m/s ✓ Temperature = 700°C	✓ Inlet Area = 146 mm^2 ✓ Inlet Position in casting model ✓ Inlet Geometry ✓ Numerical Simulation of filling process	✓ CAD software ✓ CAE software	✓ Thickness < 3mm ✓ Width < 120° ✓ Max. Velocity < 60 m/s ✓ Min. Temperature > 700°C

Table 1: Input, output, mechanisms and controls necessary for the definition of *inlet*.

Different geometric configurations of the *inlet* system have been simulated by the Virtual Prototyping tool to come to the best filling solution. The optimal area of the *inlet* has been fixed in 146 mm^2.

Table 1 reports the input, output, controls and mechanisms necessary in the definition of the *inlet*. Important outputs of this first step are the velocity and temperature maps for the entire extension of the virtual casting. These maps are useful to identify possible filling problems and consequently modify the *inlet* geometry.

After the *inlet* definition, the second step pursues the design of the *ingate* and *overflows*. Table 2 summarizes input parameters, output, controls and mechanisms at this stage.

FLAME – SPREADER INGATE and OVERFLOWS

INPUT	*OUTPUT*	*MECHANISMS / TOOLS*	*CONSTRAINS / CONTROLS*
✓ 3D CAD model of casting ✓ 3D CAD model of mould with extractors and thermo-regulation cavity ✓ Inlet Area = 146 mm^2 ✓ Inlet Position in casting model ✓ Inlet Geometry ✓ Inlet Temperature = 700°C ✓ Inlet Velocity = 50 m/s	✓ Ingate Geometry ✓ Velocity at the Ingate = 5,2 m/s ✓ Temperature at the Ingate = 702°C ✓ Numbers of overflows ✓ Overflows geometry ✓ Overflows position ✓ Numerical Simulation of filling process	✓ CAD software ✓ CAE software	✓ Position of extractors ✓ Position of thermo-regulation cavities ✓ Max. Inlet Velocity < 60 m/s ✓ Min. Inlet Temperature > 700°C

Table 2: Input, output, mechanisms and controls necessary for the definition of the *ingate* and *overflows*.

Alternative configurations are designed and simulated to verify the correct die filling and the compliance with the constraints (figure 11). This figure also highlights the main types of problems which have occurred during the Numerical Simulation of the cavity filling for three alternative configurations of the *ingate*. It includes air entrapments in the *ingate* geometry (especially for configuration #1 and #6) and the possibility to create oxide bi-films and confluence welds (configuration #3). These casting defects are basically caused by a non-homogenous filling of the cavity by molten metal.

The best *ingate* configuration obtained for the production of this component using the HPDC process is reported in figure 12. Molten metal moves uniformly in the casting cavity and all the filling parameters are compliant with the specifications. The locations of the *overflows* are designed to eliminate the incidence of casting defects (air entrapments and confluence welds) which may be formed in the final phase of the filling process.

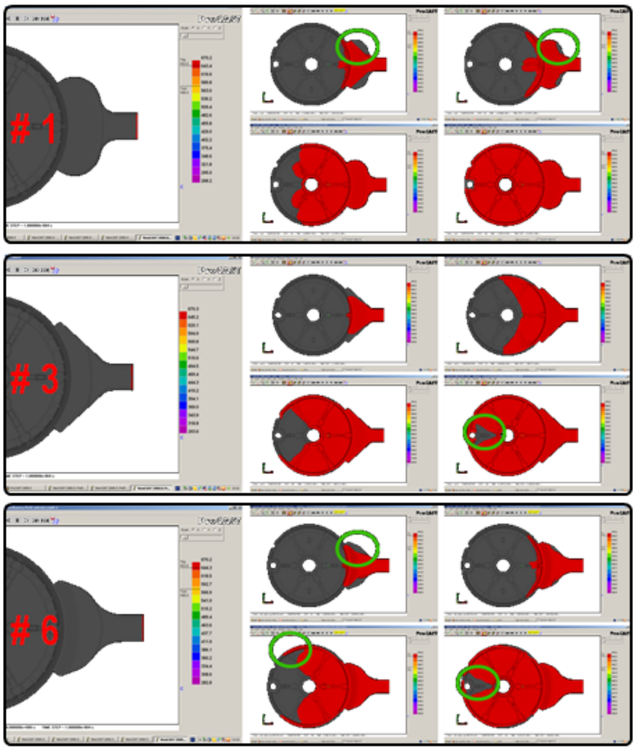


Figure 11: Alternative ingate geometry solution designed and simulated.

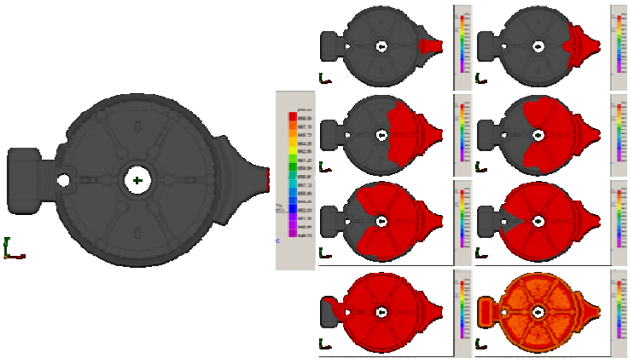


Figure 12: Optimal geometry solution for *ingate* and *overflows* designed and simulated.

After defining the optimal *ingate* system, the next step is the optimal design of *runners* and the choice of the number of castings to be made in one cycle. Multi-cavity die design relies on balanced solutions in such a way that all the components experience the same filling and cooling conditions. For these reasons it is important that the *runner* is designed to fill all the cavities at the same time. Six casting cavities are adopted in this specific case, according to the mould dimensions and the production machine. Table 3 presents input, output, controls and mechanisms necessary for the design definition of the *runner*.

FLAME – SPREADER RUNNER

INPUT	*OUTPUT*	*MECHANISMS / TOOLS*	*CONSTRAINS / CONTROLS*
✓ 3D CAD model of casting ✓ 3D CAD model of mould with extractors and thermo-regulation ✓ Ingate Geometry ✓ Velocity at the Ingate = 5,2 m/s ✓ Temperature at the Ingate = 702°C ✓ Numbers, Geometry and Position of overflows	✓ Runner Geometry ✓ Numbers of casting (6) ✓ Velocity in each point of Runner + Ingate + Casting ✓ Temperature in each point of Runner + Ingate + Casting ✓ Numerical Simulation of filling process ✓ Cavity filling time = 1446 msec	✓ CAD software ✓ CAE software	✓ Mould size and dimension ✓ Max. Inlet Velocity < 60 m/s ✓ Min. Inlet Temperature > 700°C

Table 3: Input, output, mechanisms and controls necessary for the definition of *runner*.

Some alternatives of *runner* geometry are presented in figure 13. In this case the difference among the three configurations is the disposition of castings with reference to the runner. The figure shows only one half of the complete gating system for the symmetry adopted in simulation.

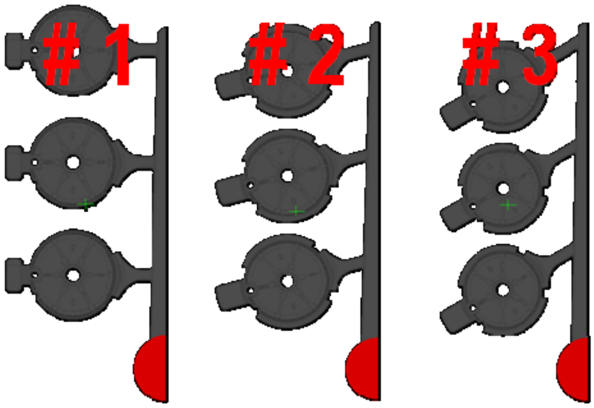


Figure 13: Different design alternatives of *runners*.

All the three different geometries of *runner* verify the filling conditions. In this specific case the most important parameters to verify are:

- inlet velocity < 60 m/s
- inlet temperature > 700°C

The main difference observed among the three configurations regards the simultaneity of filling of the 6 cavities as reported in figure 14. The best configuration of the *runner* is #2 in which the *ingates* form a 15° angle with the *runner*. Using this specific geometry the solidification process is homogeneous in all points of the mould.

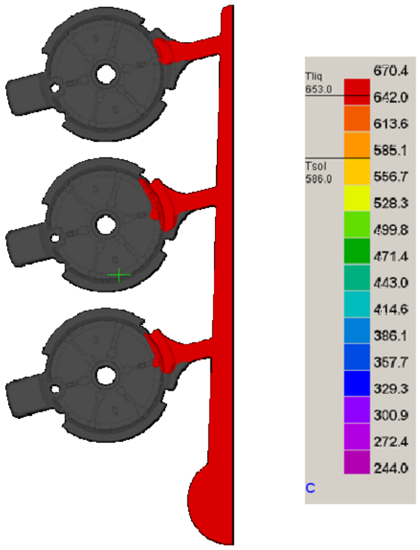
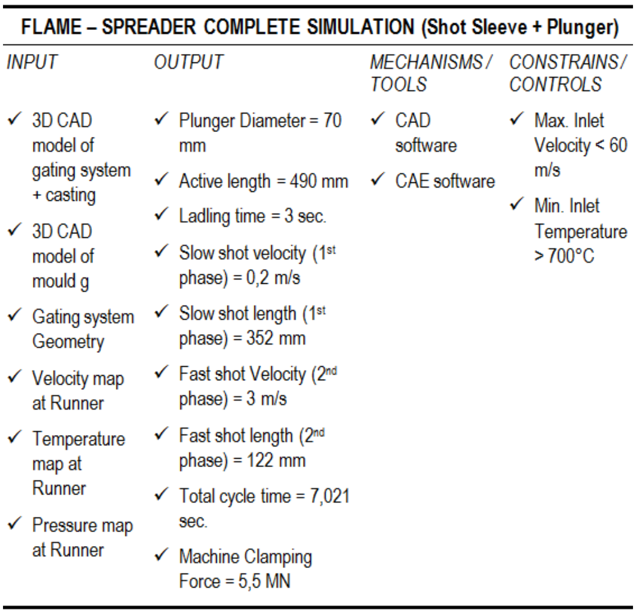


Figure 14: Particular time step of *runner* simulation which highlights the simultaneous filling of the 6 cavities (symmetry condition).



FLAME – SPREADER COMPLETE SIMULATION (Shot Sleeve + Plunger)

INPUT	*OUTPUT*	*MECHANISMS / TOOLS*	*CONSTRAINS / CONTROLS*
✓ 3D CAD model of gating system + casting ✓ 3D CAD model of mould g ✓ Gating system Geometry ✓ Velocity map at Runner ✓ Temperature map at Runner ✓ Pressure map at Runner	✓ Plunger Diameter = 70 mm ✓ Active length = 490 mm ✓ Ladling time = 3 sec. ✓ Slow shot velocity (1st phase) = 0,2 m/s ✓ Slow shot length (1st phase) = 352 mm ✓ Fast shot Velocity (2nd phase) = 3 m/s ✓ Fast shot length (2nd phase) = 122 mm ✓ Total cycle time = 7,021 sec. ✓ Machine Clamping Force = 5,5 MN	✓ CAD software ✓ CAE software	✓ Max. Inlet Velocity < 60 m/s ✓ Min. Inlet Temperature > 700°C

Table 4: Input, output, mechanisms and controls necessary for the complete simulation (sleeve filling).

Finally, in the last step, a complete simulation of the HPDC process (including molten metal ladling shot sleeve and plunger simulation) is run to:

- verify the whole process
- select the right HPDC machine (and the relative shot sleeve)
- retrieve data regarding the shot sleeve and plunger parameters (lengths and velocity)

The results (output) obtained by this final step are reported in table 4, as well as the input, the mechanisms and the tools. The complete simulation of the HPDC process also provides the cycle time necessary for the realization of the castings. Numerical Simulation reports a cycle time of 7,021 sec. for a complete HPDC cycle, and 0,490 sec. for mould cavity filling (gating system and casting cavities).

4.2. Results

In order to verify the quality of castings obtained by the new gating system, a metallographic analysis was conducted in a specific zone of the casting. As reported in figure 15, no defects (in particular air entrapments) are present in the casting, especially in the most critical upper part of the component.

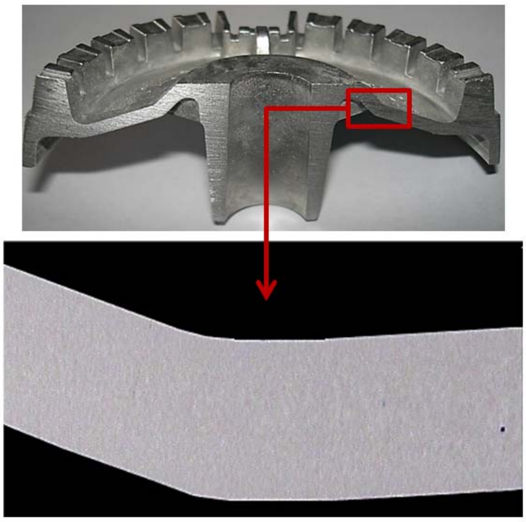


Figure 15: Optical magnification of casting to verify the presence of HPDC defects.

The six castings realized in the same cycle show the same characteristics, both in reference to product quality and the absence of defects.

Furthermore, an important improvement in the whole process can be underlined:

- an approximately 10% reduction in mould filling time compared to the previous gating system design.
- a 16% reduction in the gating system weight.

These outcomes are fundamental aspects for the assessment of the costs connected to the HPDC process. A consequence is a great reduction in terms of thermal energy necessary to maintain minor quantities of Aluminum alloy at fusion temperature.

The application of the proposed approach generates a great advantage in terms of the time needed for the complete design of the mould and gating systems. In particular, the incremental approach permit a reduction in the computational time necessary for the thermo-fluid dynamics simulations, especially in the early phase of this approach. In fact, the computational time to simulate the only one cast filling is much lower compared to the complete geometry of the mould. An important advantage gained by this aspect is the possibility to evaluate a large set of alternatives for the *inlet* system in order to optimize it.

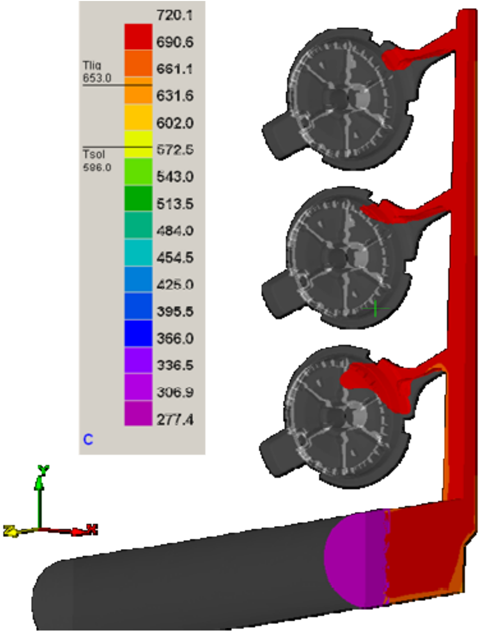


Figure 16: Complete simulation of flame-spreader casting with shot sleeve and plunger.

One drawback of the proposed approach is the fact that it is almost impossible to design a geometry which permits the inlet to be reached with the constant values of temperature and velocity imposed in the first step. Fluid dynamics wall effects and thermal exchange determine different inlet parameters in the final configuration. This mean that it is difficult to replicate the desired *inlet* definition as fixed in the step 1 when considering the whole geometry in the virtual simulation process. However, the approach continuously imposes the respect of the inlet parameters, and, for this reason, the differences between the cast filling (1st step) and the complete process simulation (4th step) are limited. Figure 16 shows an example of this described drawback. The complete simulation (considering the shot sleeve and plunger) is slightly different in terms of simultaneous filling of all the casts. The casts at the bottom of the mould start to fill before the others. The consequence in this specific case is negligible because the number of casting cavities is low (<10) and the filling delay is less than 0.5 msec.

For other types of products it is necessary to take into account these aspects and the results of the complete numerical simulation in order to refine the final geometry of the gating system. This can be accomplished by iteratively coming back to the runner design phase (3rd step) and making changes to its geometry.

5. CONCLUSION

In HPDC casting product development, the mould design is essential to ensure good product quality and production process efficiency. Traditionally, this goal can be accomplished via the tryout realization of design solutions in the workshop. Recently, virtual prototyping tools, especially CAD-CAE simulations, can provide the design information for casting product design reducing non-value added activities time and costs.

However, if used in mere substitution of physical trials, virtual prototyping is beneficial but hardly reach optimal performances. For this reason the paper proposes a four step approach for the design of optimal mould gating systems, aiming to maximise the quality of the casting in terms of absence of defects. Moreover, the approach represents a formalised and repeatable design procedure that makes use of CAE tools at multiple stages. Process designers, in industrial departments, can use the proposed method to reach these specific outcomes:

- Time reduction in the design of the optimal geometric configuration of the mould (approx. 20%).
- Reduction of rejected cast parts (approx. 5-8%).
- Reduction of energy costs (derived from less time and quantity of aluminium alloy to melt during a single cycle).

The reported gas burner test case shows the feasibility of the approach and improved design results compared to standard procedures. Indeed it shows how the separation in incremental design steps helps to control, optimise and progressively define the mould geometry and the process parameters. Some good results are obtained in this sense: a general reduction of product defects (such as the air entrapment) and a reduction of process time and costs (approx. 10% filling time and approx. 16% of gating system weight).

As future work, the approach could be extended to similar industrial fields, first of all plastic injection moulding. The rheological characteristics of the plastic materials pose different problems compared to the light alloys. For instance, gating system geometry is generally much less critical. On the contrary, inlet geometry and positions strongly determine the quality of the resulting product. The development of a general purpose method both for metals and plastics mould design are the next step of the presented research work.

The software automation of the proposed method is another important result which will be reach in future research activities. This future objective can be obtained with the development of a dedicated software tool which can be easily used by designers to find the best configuration of the gating system for a specific product cast geometry.

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