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Added Value of Process Modelling in Development of Automotive Die Casting Parts

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Abstract
Porosity in high performance castings can reduce mechanical properties and consequently degrade both component life and durability. Automotive Market increasingly requests High Performance Castings with high structural integrity and good mechanical properties. These requirements are typically obtained with Gravity and Low Pressure Die Castings. High Pressure Die Castings, due to the process itself is not completely suitable to deliver such increasing requirements. However, because of the possibility of mass production with reduced shot times and hence costs, several innovations and technologies have kept evolving around this process, making it a competitive and lucrative process for industries to consider.
Process Modelling provides a wide scope to test several of these technological advancements virtually and be an integral part in the development of the die casting parts. This would then enable the casting engineers to be able to both predict defects in advance and take actions to improve the process/design.

Keywords: Die Casting, HPDC, part design, die design, casting development loop, digital tuning, die cycling, simulation, Porosity, Workflow, Macros, Automatization, Renault, ESI

1. Introduction

Automotive market is very competitive today. The time between the first draft of a car or associated powertrain and the first selling is about 3 years. Reduction of the time to market is a daily challenge for OEMs, Renault company included. The lesser the time one spends on designing and setting up the components, the sooner the market has a car that corresponds to its current needs, at a competitive price.

In the previous decade, only some happy fews were exploiting fully the usage of process simulation software. Graphical User Interfaces (GUI) were less user and process orientated not helping the cause, and simulations was more used for curative actions than for preventive actions.

With the continuously evolving computer hardware, know-how to connect the user requirements into the GUI to make them foundry oriented, and the ever-changing product designs and materials to develop light weight castings, simulations are more important to be embedded in the early product development stages to gain on lead time, optimize costs and deliver top quality castings.

2. Background

During designing and manufacturing of cast components, Renault Process Engineering participates to two main milestones/stages.

- First stage is dedicated to the Product (Part) Design shared between the Corporate Product Engineering and the Corporate Process Engineering, especially for High Pressure Die Casting parts that can't be designed without having included the process genes.
- Second stage is dedicated to Die Design that is mainly done by Foundry Localized Engineering.

To pass these stages, CAD software is obviously used. CAE software is also more and more in use in the recent years for both part life duration or dynamic crash validation and for process concerning manufacturability and validation.

This paper details below the process simulation aspects involved to pass these stages.

As an example, a 2011 AlSi9Cu3 Gearbox Housing which happened to be a new kind then, is considered. Those days the die design was developed once the product design was frozen and tuned by physical trial & error methodology at the Renault Cleon casting plant.
The delivery time and the costs were at the mercy of how successful these trials would end up being.

The question being answered in this paper, *what if one were to apply todays state of the art simulation methodology on this part and die and go for a digital tuning?* This would then give the readers a peek into Renault's simulation methodology, which is bringing an added value in the development of Automotive Die Casting Parts.

3. Method

To start with, let's go through the main assumption concerning the digital tuning of this 2011 gearbox housing. 4 different designs were physically tested during tuning loops then. The one considered for this paper is the very early development phase called DT1 that was not used for serial life of this gearbox.

4 main steps are used for the part & die digital study using ESI ProCAST 2018.0.

Step 1: Manufacturability Check
During the product design, manufacturability or the ability to manufacture the part must be checked to provide the product designers the right input. The main problem is that this check must be done quickly and iteratively since many iterations already exist in the product design without the consideration of manufacturability.

The part is assumed to be surrounded by a simple die. After a brief analysis of the wall thicknesses, drafts / under-cuts, parting line, feeding regions required during the filling of the part, ingate locations are identified to make a filling analysis. Depending on the part profile, it could also be decided on which die (mobile/fixed) should the ingates be positioned. Ideal gate velocities are assumed based on the theoretical cavity fill time as a boundary condition for this simulation.

The main goals to achieve from this step would be

- ingate position/dimension validation, keeping in mind the flow balancing, flow lengths and as much as possible lesser air entrapment at locations where the venting will not be possible.
- Last filling regions to determine the overflow positioning
- Hot spot identification in the casting, as these could be potential porosity locations

Step 2: Injection System Design
Once the die designer has the product design in front of him, he must first define the cluster size and position, in link to the HPDC filling rules available, and hence the HPDC press that is going to be used. Designing of the full die comes later. Design of the injection system including overflows must be validated (position & dimensions) in terms of air entrapment and shrinkage risks. Rules are also available for overflow dimensioning. An assumption of a simple die around continues in this step as well.

Step 3: Die Design
After having designed the injection system, die designer can now start to design his complete die shapes. This part allows a flat parting line, with the mobile and fixed dies able to form the entire casting part. The cooling system however, can only be dimensioned after having simulated some cycles (shots) to identify where the hot spots are in the die.

Step 4: Die Design & Process Validation
Die design is now developed completely, including cooling system and it's time to go for a comprehensive validation of the part quality on this full die design. This stage is also important, as it allows early (pre) definition of what will be the process conditions in terms of cycling times, casting temperature, cooling management, sleeve fill ratio, slow shot, slow to fast switch, fast shot, 3rd stage pressure, …

First thermal cycling is run till a steady state die temperature is reached (operating die temperatures on the shop floor), and then the full filling & solidification results are run on this die.

4. Simulation Results and Analysis

Step 1: Manufacturability Check (Bare Casting)

The cavity fill time in Fig 1a, shows the last regions to fill. An overflow in these last filling regions, opposite of the ingates and the encircled area will normally function well to transport the air out of the cavity. No high risk of any major air entrapment can be seen at this stage.

Fig 1b, highlights massive hot spots in the casting, which may lead to porosity. The porosity in the highlighted region is the main area of concern, as indicated in Fig 5a showing the quality requirements for this part. It must be noted here that an intensification pressure of 900 bars, appropriate with the HPDC press was considered. The physics behind the Advance Porosity Model (APM) of ProCAST allows to compute shrinkage porosity risks considering the effect of intensification pressure which helps in force feeding regions connected to the gates through liquid metal, thereby compressing porosity levels.

Atleast 3 possibilities can already be thought about at this stage to reduce the possible porosity risk

- The locations of hot spots outside of the indicated region in Fig 1b, are mostly allowed as no specific mechanical characteristics are requested, and hot sealing post machining could be an acceptable solution.
- The cooling system which will evolve later in the die design, could be an option to extract heat out of these regions and reduce the probability of porosity formation. However, on careful observation, the bosses and rib network around these hotspots are too thick, giving it a low chance to change drastically the defects in these areas.
- Change in product design seems to be the best way. However, this solution was not considered during the 1st physical test loop in 2011, as the design was frozen before the die design started. But finally, it was understood and redesigned much later. For our further analysis in this paper however, we shall continue with this unchanged product design.

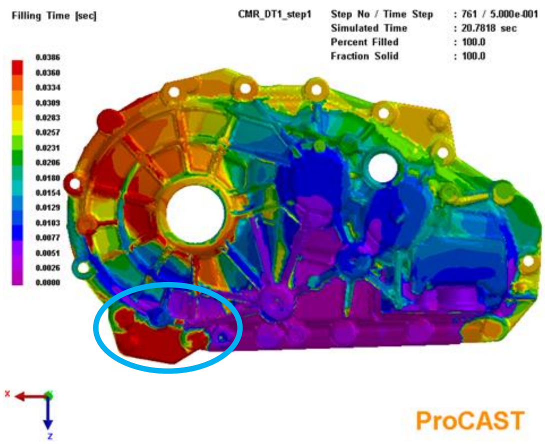


Fig1a: Cavity Filling Time

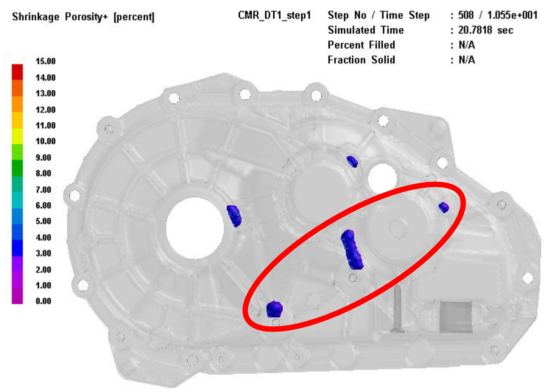


Fig1b: Shrinkage Porosity plot highlighting the main hot spots in the casting

Step 2: Injection System Design (Biscuit/Runner/Ingate/Overflows)

Filling through an injection system biscuit (means without a shot piston) helps a quick analysis of the runner design and the overflow validation. The progressive filling in Fig 2a confirms good positioning of the initial overflows as the flow pushes the air in the cavity into these and no major air entrapment. The plot indicates the fraction of element that is filled. The filling time plot in Fig 2b (left) confirms the overflow location validation, confirming the Step 1 analysis. Shrinkage Porosity plot in Fig 2b (right) shows mostly similar risks than what was observed in Step 1. We do notice some additional regions of porosity than what was noticed before. This could be because of the change in thermal gradients and filling profile we create by adding the biscuit and runner into the simulation, as opposed to the ideal gate velocities in Step 1. If these regions, don't request strong mechanical characteristics, and hot sealing can cover them up (if) post machining, this is an acceptable solution.

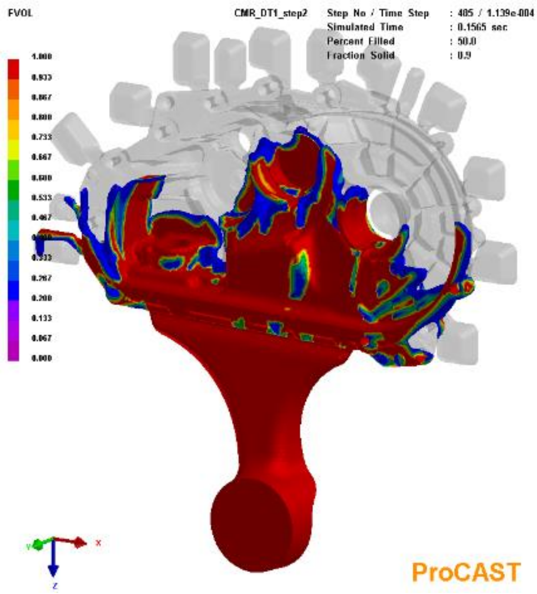


Fig2a: Progressive filling in the cavity

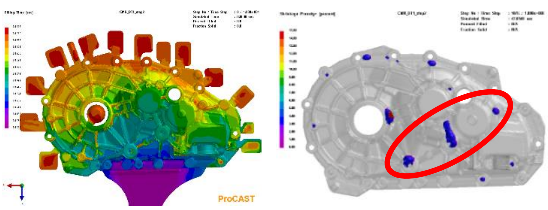


Fig2b: Filling time plot (left), confirming the overflow locations to have filled the last and Shrinkage Porosity (right) highlighting the hot spots in the casting

Step 3: Die Design (without cooling lines)

Pre-shot timings are assumed to simulate this step, including the spray sequence.

Fig 3a shows a temperature profile through the shots taken on the hottest mold/casting interface. The trend line indicates the reduction in the delta of peak temperatures between shots, indicating reaching of the stabilized die temperatures. It means that the current external cooling is designed well to ensure quick thermal stability of the die. Ofcourse temperatures are at a higher end. Cooling lines at appropriate locations will only help this in the next step.

Fig 3b shows the hot spots in the both the mobile & fixed dies, as well as the cooling circuits (indicated in light blue circles and bars) used in the 2011 die are highlighted. Some cooling circuits are positioned well right in front of the hot spots, and some not.

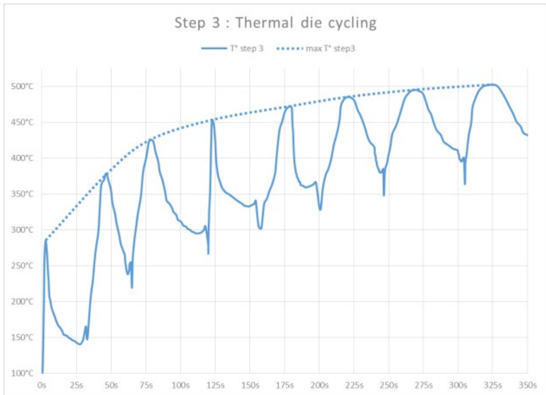
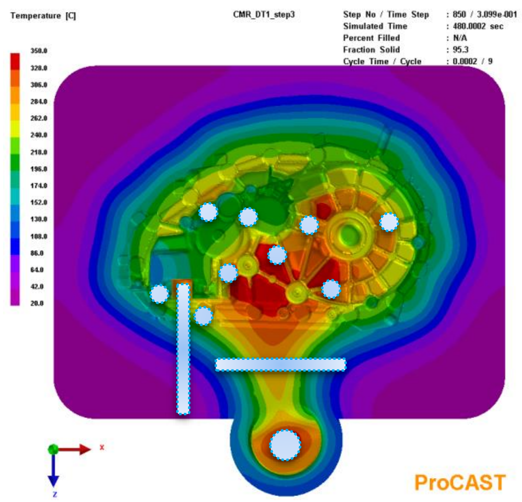


Fig 3a: Die temperature profile taken at hottest mold/casting interface



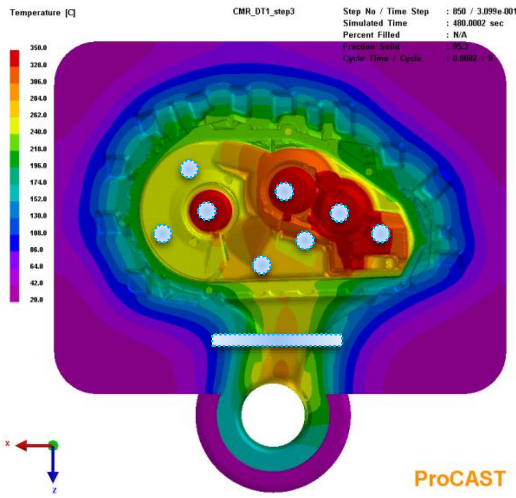


Fig 3b: Die temperature profile of Mobile Die (Top) and Fixed Die (Bottom) at the end of 8 cycles (shots). Light blue circles and bars indicate the cooling circuits of the 2011 die

Such simulation results during the die design stage, enable the designer to determine the locations of the cooling channels in a more smarter way, thereby arriving at an optimized die design. The dimensions of the cooling channels, are determined based on the amount of heat still required to extract from those hot spots in the available time during the shots.

Step 4: Full Die Design & Process Validation

Thermal Cycling simulation results shows that die thermal steady state is achieved almost the same way compared to previous simulation without cooling systems (Fig 4b left). Even if temperature profile is equivalent, internal die cooling has a clearly visible effect on temperature decrease of about 70°C at die skin on the hottest mold/casting interface point.

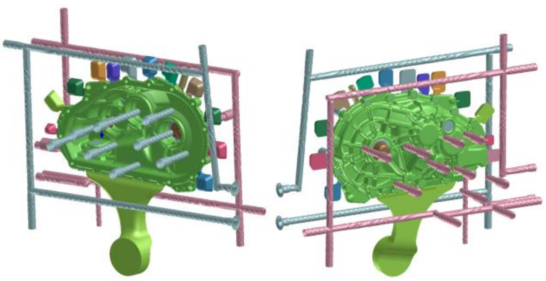


Fig 4a: Die cooling circuits

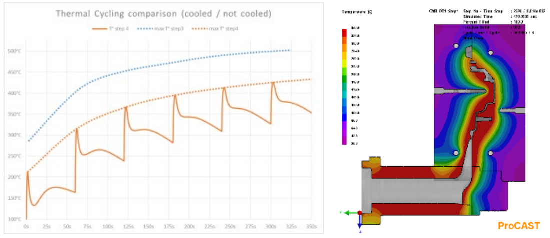


Fig 4b (left): Die temperature profile taken at hottest mold/casting interface, (right): cross section of the die showing the influence water coolants just before the mold is opened.

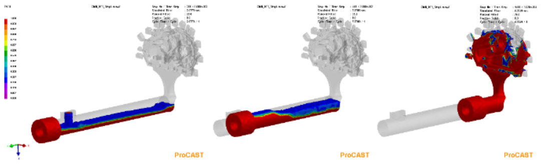


Fig 4c: Progressive filling starting from the sleeve filling and plunger movement in the sleeve to cavity filling.

Sleeve filling seems to be quiet enough to avoid any major turbulences inside the sleeve (Fig 4c). The slow shot V1, shows a wave that encloses slight air in the sleeve, which can lead unfortunately to oxides and air entrainment inside the part that are very difficult to anticipate without simulation. Fig 4d shows possible air entrainment locations at the end of the filling. These are qualitative results and shall be validated further as experience grows. The current locations indicated are close to core pins, and overflows, which can help pulling out this air and lead to fortunately no gas problem for this DT1 loop. Part fill time plot (Fig 4e left) shows very similar behavior to previous steps, confirming this to be an interesting parameter to follow during all the simulation.

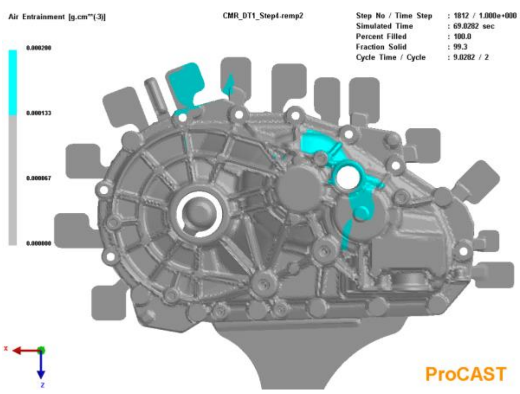


Fig 4d: Air Entrainment

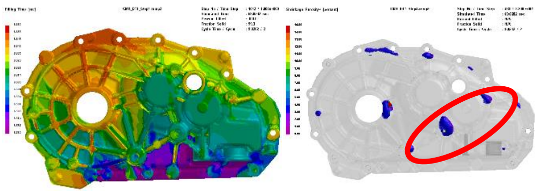


Fig 4e: Filling time plot (left), and Shrinkage Porosity (right)

Finally concerning shrinkage porosity risk (Fig 4e right), the critical regions continue to have porosity. Cooling lines positively influence reduction in porosity in boss B (Fig 5b), while doesn't influence or slightly counter-productive in the boss C & boss D regions (Fig 5b). It must be noted here that the cooling lines used on this die were the way it was developed for the initial 2011 die, and not based on the outcome of Step 3 (already explained in the Step 3, Simulation results and analysis section). Moreover, in Step 1, Manufacturability check, it was identified that the bosses and ribs around this region are quite thick, making it difficult to get them cooled quicker, and drastically reduce the porosity. A product design change was the best solution analyzed at the beginning, but not considered for this paper, as it was not adopted in the 2011 die at the beginning but considered later after exhausting different options from physical trials.

5. Observation: Comparison of Simulation vs Reality

Fig 5a shows the 3 main zones (boss) which are mandatory for this part to be considered porosity free. ProCAST's APM porosity results capture these locations well, highlighting the highest risks of porosity as seen in the earlier porosity images. Fig 5b summarizes the shrinkage porosity comparison vs reality for all thee bosses at different steps of simulation loop and confirms good alignment with reality.

6. Summary & Conclusion

A sum-up table is made available in Table 1, to classify the requirements and expected results to be analyzed in each of these simulation steps used to develop and validate a product design for manufacturing and die design to manufacture high quality castings. It also highlights use of specific Macros designed for Renault processes and the HPDC Workflows from the powerful GUI of ProCAST called the Visual Environment, reducing the set-up time of different simulation steps to a few minutes.

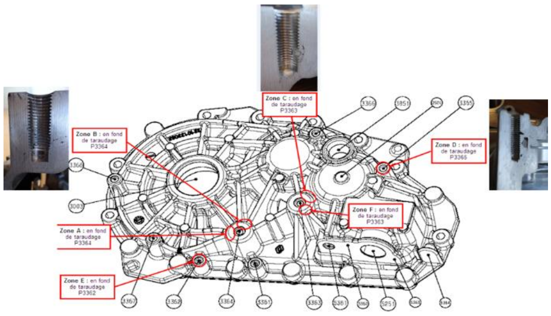


Fig 5a: Shows the 3 main zones (boss) which are mandatory for this part to be considered porosity free

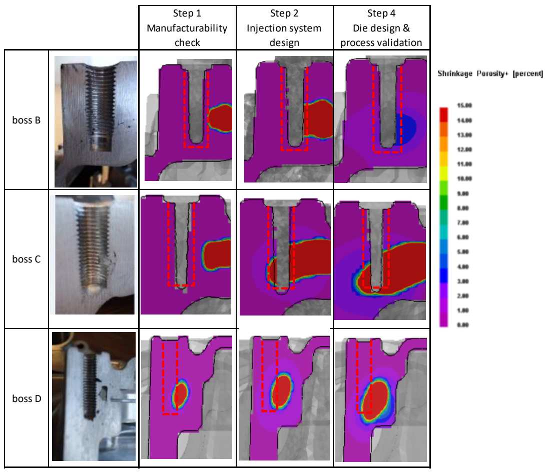


Fig 5b: Shows the shrinkage porosity comparison of simulation vs real cut sections for all the 3 main zones

Executing Step 1 at early stages of product design, helps to identify the challenges of manufacturability, and provides time to iterate with the product designers for any requested design modification. Step 3 indicates the importance of simulation to position the cooling perfectly aligned with the hot spots, else, some counterproductive results shall follow as shown in Step 4.

Simulation is no more a digital expert domain but is now open to wider personas of casting technicians and engineers due to this possibility of automatization of simulation set-ups, for very early simulations or for more complex steps.

Use of simulation is necessary to pre-validate the part quality achievement, to prevent costly die reworking, shorten development loop lead time and then start production with already pre-validated manufacturing parameters. For instance, engineering to manufacturing handover can include piston position/velocity curve, die cooling water T° and flows, shot cycle sequence and casting T°.

Each of these 4 development steps that were applied on this housing are very important to build a robust virtual casting part and die before manufacturing. Some results fields seem to be relevant from the early and simple simulation steps such as part fill time and shrinkage porosity using APM module.

Finally, no more excuse not to use simulation during the whole part and die design, as they are convenient helping on achieving top quality, low cost compared to physical trials loops and leads to development loop time reduction.

7. Future Work

It is known that castings need to be produced with multiple process variations occurring on the shop floor. A very basic instance of this, is the alloy temperature variation in the furnace. These are not the only parameters that can change during production. Hence the design needs to be robust for these process variations. The key to this is management of combination of manufacturing parameters and study its effect on the part quality. To define correctly these manufacturing parameters and associated combinations, ESI Group has embedded its optimizer PAM-OPT into ProCAST, which could be used to define and pilot manufacturing parameters and finally continue to turn Casting Process into Industry 4.0.

8. References

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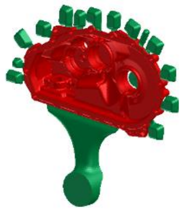
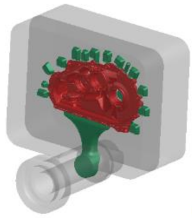
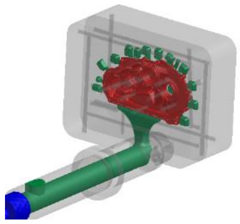
[11] ESI ProCAST 2018.0 User Manual

Table 1: Summary of all the development steps

	Step 1 Manufacturability check	Step 2 Injection system design	Step 3 Die design	Step 4 Die design & process validation
picture				
user needs	ingate position validation overflows positioning hot spots identification / reduction	injection system validation overflow position validation casting parameters definition	die thermal hot spots identification cycling conditions definition	die validation part quality validation process conditions definition
setup conditions	flow + solidification + 3rd stage pressure (APM)	flow + solidification + 3rd stage pressure (APM)	die cycling	die cycling + chamber filling + shot piston + solidification + 3rd stage pressure (APM)
setup tool	macros (mesh + setup + post-treatment)	macros (mesh + setup + post-treatment)	HPDC Workflow	HPDC Workflow
setup time	5'	5'	10'	15'
awaited results	filling + last filled areas + hotspots	filling + last filled areas + shrinkage porosity	thermal cycling + die hot spots	thermal cycling (stabilized trend) + filling + last filled areas + shrinkage porosity