Numerical simulation applied to the production of automotive foundry components

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ABSTRACT: Simulation tools are developed in Renault to reduce both costs and adjustment times for the production of automotive foundry components. According to each kind of problems, different approaches are provided to simulate mold filling, both thermal control and mechanical response of permanent metallic molds, solidification and defects formation of complex aluminium or iron casting. To validate these approaches, numerical results are compared to precise physical measurements. Some practical examples will be shown in this paper with the referenced methods used. Design methodologies are proposed, using the simulation results for the conception of feeder system for S.G. Iron components and for the cooling control of permanent molds for the production of sound aluminium components.

1. INTRODUCTION

The recent use of numerical simulation in foundry is due to the complexity of the process. To simulate the physical phenomena, it is necessary to know various fields as fluid mechanics, both heat transfer and solidification, metallurgy and at the end, the computer development of these models.

The foundryman problems could be summarized by this simple request: reduce both costs and adjustment time for the production of foundry components. For example, to make an iron cast component free of shrinkage defects, one can spend about one year during which several feeding configurations are tried. Almost every time, the foundryman goes on with this challenge which means high cost of both energy and money!

Renault is involved in foundry process simulation in collaboration with various research centers and software companies to develop industrial tools intended for its plants. In this paper, two examples of casting processes are presented: sand mold cast iron and low pressure aluminium die casting. Methodologies and applications are developed with references to experimental studies.

2. IRON CASTING

2.1. Methodology for riser design

Contraction during solidification leads to shrinkage defects in iron castings (figure 1). Then, feeders are added to displace the defects out of the component into the feeders.

The traditional modulus method offers a reasonable and practical method for the riser design. It is an analytical approach based on the combination of empirical observations and theoretical facts in order to estimate the solidification times of the different component shapes. However, solidification simulation can be used to obtain more accurate results. A new methodology combines the modulus calculations and the solidification results (Lavo 1990). Starting from the solidification simulation of the component without riser system, one can pick up solidification times for the different component shapes. Then the results are converted to modulus values using the Chvorinov’s empirical rule (Ruddle 1975). The feeder neck modulus and the feeder modulus are evaluated from the previous component shapes modulus so that the riser design is obtained. A second simulation of the component with its riser sys-
Spheroidal Graphite (SG) iron is cast in a green sand mold. The initial uniform temperature of liquid metal is 1390 °C. Mold is at room temperature. In the industrial configuration, two connecting rods are cast vertically side by side in the same mold.

2.5. Solidification with riser system

A riser system can be proposed for the previous results. The riser system must verify:

\[ M_{\text{neck}} > f M_{\text{shape}} \]

where \( f \) depends on the metal melt. In other terms, the riser system must represent more than 5% of the component shape one.

This simple empirical rule states that the body of the connecting rod is the first to be fed, so the riser melt must be put at the top of the feeding system. Then, the solidification contraction must be put at the top of the feeding system. Each side of the connecting rod is monotonic on figure 3.

The feeder dimension (vol) is given by both cast material contraction:

\[ V_{\text{feeder}} = V_{\text{shape}} S / X \]

where \( S \) equals 6% to 8% for cast iron and equals to 5.25% for the casting shell.

To illustrate the previous riser design methodology, we choose to simulate the solidification of a connecting rod (figure 2). We divide the casting in three shapes: the head (left hand on figure 2), the foot (right hand) and the body which is the thin shape joining head and foot.

2.4. Solidification with riser system

For each shape, we extract both volume \( V \) and surface \( S \) to estimate its modulus \( M \) by:

\[ M = \frac{V}{S} \]  

(1)

The modulus is linked to solidification time \( t_s \) by the empirical Chvorinov’s law that we have determined experimentally for SG iron:

\[ t_s = 3.5 \times 10^6 M^2 \]  

(2)

On the other hand, simulation gives the solidification time of each shape cooling from 1390°C to the solidus temperature. From the relationship (2), we obtain the simulated modulus. The results are summarized in table 1. The increase of simulated values could be explained by both sand heating and 3D effects.

Table 1. Empirical modulus and solidification times compared to simulated values.

<table>
<thead>
<tr>
<th>Shape</th>
<th>( M_{\text{shape}} ) (10^{-3} m)</th>
<th>( t_s ) (sec) estim.</th>
<th>( t_s ) (sec) simul.</th>
<th>( M_{\text{shape}} ) simul.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>4.45</td>
<td>69</td>
<td>85</td>
<td>4.92</td>
</tr>
<tr>
<td>Body</td>
<td>2.06</td>
<td>15</td>
<td>25</td>
<td>2.67</td>
</tr>
<tr>
<td>Head</td>
<td>3.90</td>
<td>53</td>
<td>82</td>
<td>4.84</td>
</tr>
</tbody>
</table>

Table 2. Calculated feeder dimensions.

<table>
<thead>
<tr>
<th>Feeder type</th>
<th>Diameter (10^{-3} m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>Spherical</td>
</tr>
<tr>
<td>1/2 head</td>
<td>Cylindrical</td>
</tr>
</tbody>
</table>
2.5. Solidification with riser system

A riser system can be proposed starting from the previous results. The feeder neck modulus must verify:

\[ \text{M}_{\text{neck}} > f \text{M}_{\text{shape}} \quad (3) \]

where \( f \) depends on the metallurgy of the iron melt. In other terms, the neck solidification time must represent more than 52% to 63% of the component shape one.

This simple empirical rule shows that the body of the connecting rod is too thin to ensure the feeding from the foot to the body during the solidification contraction. One feeder must be put at the top of the foot and two feeders on each side of the connecting rod head as shown on figure 3.

The feeder dimension (volume) depends on both cast material contraction and sand type:

\[ V_{\text{feeder}} = V_{\text{shape}} S/X \quad (4) \]

where \( S \) equals 6% to 8% for green sand and \( X \) equals to 5.25% for the cast iron in our case.

![Figure 3. Riser system of the casting.](image)

Using the calculated values of table 1, we obtain the feeder dimensions (table 2).

**Table 2. Calculated feeder dimensions.**

<table>
<thead>
<tr>
<th>Feeder type</th>
<th>Diameter (10^{-3} m)</th>
<th>M_{\text{neck}} (10^{-3} m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>Spherical</td>
<td>40</td>
</tr>
<tr>
<td>1/2 head</td>
<td>Cylindrical</td>
<td>30</td>
</tr>
</tbody>
</table>

The result of the solidification simulation are shown on figure 4 in the mid-section of the casting. Due to the symmetry, only one half of the mold is represented. One can observed that a vicinity effect between the two connecting rods delays the solidification in the head left side. The solidification time of this shape is about 85 sec, while the central feeder neck solidifies in 60 sec, which is higher than the acceptable limit before shrinkage appears. For the rest of the riser system, the solidification times seem to be also correct.

![Figure 4. Simulated solidification times (sec.) in the connecting rod and its feeders.](image)

2.6 Filling simulation

The software FLOW-3D solves general fluid mechanic problems with free surfaces using the Volume of Fluid method (Hirt 1981). In foundry applications, incompressible metallic fluid is assumed without turbulence nor viscous effect. Gas pressure in the cavity is kept constant. The thermal cooling of metal is taken into account during filling.

A previous work (Ben Cheikh 1990) presents the comparison between experimental and numerical results for the filling of a test mold. Gallium is used both because it is a low melt point metal (30°C) and because of its fluid properties closed to the iron or aluminium ones. The free surface evolution was recorded using a video system while temperatures was measured in both metal and sand mold. There was a
good agreement between experiments and FLOW-3D results (Le Roy 1990).

2.7. Influence of filling on solidification

The connecting rod geometry with its feeder system is kept to simulate the filling. The fluid metal goes through a thin source ingate at a prescribed velocity. In the ingate, the fluid temperature is kept constant equal to 1390°C.

In spite of the rather simple 3D geometry, some singularities of the fluid flow occur during the filling. For example, at the end of the filling of the right hand feeder, there is a violent redistribution of the fluid velocity in the component body (Figure 5). Those phenomena are hardly support by the FLOW-3D because of the incompressibility assumption.

Figure 5. Simulated velocity field during filling for three steps.

At the end of the filling simulation at t= 3.1 sec., inhomogeneous temperature field is obtained with a maximum decrease of 170°C below the initial fluid temperature in the top feeder. Going on with solidification, we obtain the new solidification times (figure 6). First, the last point to solidify is in the connecting rod head so that macroshrinkage could occur in it. Then foundry facts are observed: cold foot feeder because it is filled with the colder metal, hottest metal in the head because a great part of the flow pass along it, etc... It means that the filling simulation is of a great importance to estimate correctly the solidification times and to find the correct feeder dimensions.

Figure 6. Simulated solidification times (sec.) after previous filling simulation.

3. LOW PRESSURE ALUMINIUM CASTING

3.1. Die casting process

To produce aluminium cylinder heads, cyclical injection of liquid metal is done under low pressure (0.2-0.4 bars) inside of metallic dies. The dies temperatures are permanently regulated using a water cooling system controlled by thermocouples. Die life, sound cast components and productivity are the main industrial objectives. The complexity of this process leads to long adjustment times because the dies conception is generally based on both past knowledge and empirical laws.

To give more accurate informations about die thermal behaviour, one may simulate the entire process. It means first experimental tests to extract the principal variables and to validate the numerical model.

3.2. Experimental schedule

Two kinds of experiments are done: temperature measurements in both dies and cooling system, and temperature measurements in the aluminium component. A special shape design has been used for the component in order to simplify the geometrical analysis but the principal characteristics of a cylinder head have been respected (Figure 7).

Figure 7. Experimental arrangement.

3.3. Numerical simulation

The CAD geometries (external dies, internal cooling channels, ingates and component) and the DEAS solid modeling tool mesh is generated using the software between CAD and FLOW-3D.

Figure 8. CAD description of external and internal casting (cut view)

Three kinds of thermal conditions are used:
- for the interfaces between metallic dies, thermal conduction

$$\Phi = h (T_{metal} - T_{die})$$

where the convection coefficient is the coating used,
- for the interface between core, quasi perfect contact
3. Aluminium Casting

When casting aluminium cylinders, cyclical cooling is done under lower rates inside of metallic dies. These are permanently regulated and cooling is controlled by life conditions. Solid cast components are the main industrial objectives of this process leading to accuracy because the dies conceived on both past knowledge and accurate information about the setup of the experiments. One may simulate the results of the first experimental tests among variables and to validate the schedule.

Experiments are done: temperatures in both dies and cooling stage measurements in the next. A special shape design of the component in order to get critical analysis but the principles of a cylinder head have figure 7).

3.3. Numerical simulation of solidification

The CAD geometries of all the elements (external dies, internal core, cooling system, ingates and component) are made with the IDEAS solid modeling tool (Figure 8). The FEM mesh is generated using the automatic interface between CAD and FLOW-3D.

- for the cooling system into the dies, prescribed temperatures.
- The initial melt temperature is equal to 670°C while for the dies, the temperatures are about 350°C.
- Only one solidification cycle (200 sec.) was simulated at this stage. In the future, several cycles should be carried on to reach the die thermal steady state as it occurs in the real die casting process.

Figure 9 shows the enclosed liquid metal in the component after 100 sec. A directional solidification towards the ingates is obtained.

Figure 9. Enclosed liquid metal in the component after 100 sec. (bottom view of one half of the casting)

3.4. Comparison between experimental and numerical results

Comparing the temperatures measured in the component and calculated temperatures, there is a good agreement after adjusting the convection coefficient h as shown on figure 10.

3.5. Defect formation

Microshrinkage tendency in aluminium alloys can be evaluated using the Niyama criterium (Niyama 1982), (Patin 1987), (Magnin 1990):

\[ V^{1/2} / G > \text{Critical value} \] (6)

where V represents the cooling rate and G is the thermal gradient, during solidification.
Figure 10. Measured and calculated temperatures in the aluminium component.

Risky zones are represented by the high values of the Niyama criterium (figure 11). The results are consistent with the real shrinkage observed (figure 12).

Figure 11. Calculated microshrinkage zone (in black).

4. CONCLUSION

Different computer developments have been applied to real automotive casting processes at Renault. A great importance has been given to the methodologies coupling the solidification simulation of SG cast iron to the empirical rules. The filling phase is of a great importance on the final solidification results. Furthermore, for such complex processes as low die casting, industrial experiments must be done together with simulations to validate the models.

REFERENCES


