Numerical Methods in Industrial Forming Processes, Chenot, Wood & Zienkiewicz (eds)
© 1992 Balkema, Rotterdam. ISBN 90 5410 087 7

Numerical simulation applied to the production of automotive foundry components

J. B. Dalin, J. M. Le Guilly, P. Le Roy & E. Maas
Service R&D Fonderie/Mécanique, Direction des Technologies de Production, Renault, Boulogne-Billancourt, France

ABSTRACT: Simulation tools are developed in Renault to reduce both costs and adjusment 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 tranfer 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 adjusment 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 involded 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 theorical 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 (Louvo 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-

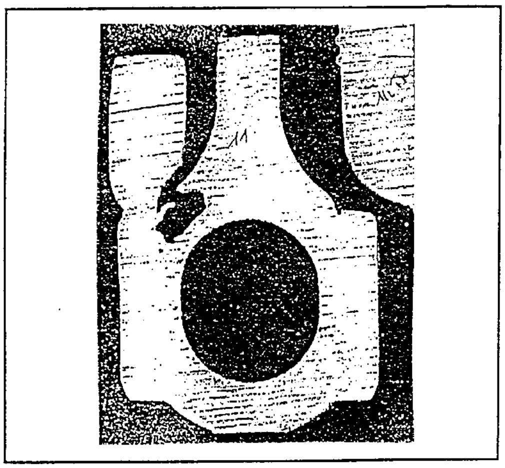


Figure 1. Shrinkage defect in the head of cast connecting rod.

tem can be performed. If the component is free of defects, one can draw the plans and cast the part. Otherwise, feedback is necessary to calculate a modified riser system taking into account the new solidification times and then, a third calculation must be performed.

2.2. Solidification simulation

For the simulation, the software FLOW-3D from Flow Science Inc. (Los Alamos, USA) is used. This Finite Difference (FD) program was adapted by Renault to solve the phase change problem using the enthalpy method with an explicit time step scheme. The volumic CAD description of the geometry is sent to FLOW-3D using our own interface program which treats precisely the component surfaces. One can define the material properties for both cast metal and sand mold, and the thermal boundary conditions. In the case of cast iron, a nearly perfect thermal contact is obtained between mold and metal.

2.3. Application to real casting

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.

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.

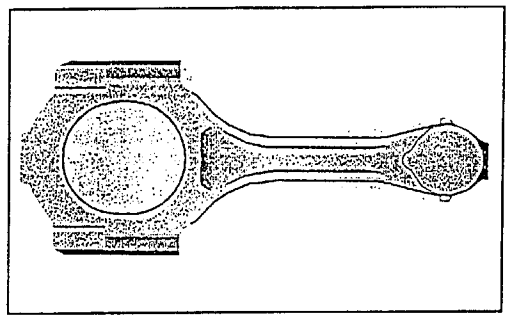


Figure 2. 3D CAD solid modeling of the component without riser system.

2.4. Solidification without riser system

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

$$M = V/S \quad (1)$$

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

$$t_s = 3.5\ 10^6\ M^2 \quad (2)$$

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.

	M_{shape} (10^{-3}m)	t_s (sec) estim.	ts (sec) simul.	M_{shape} simul.
Foot	4.45	69	85	4.92
Body	2.06	15	25	2.67
Head	3.90	53	82	4.84

2.5. Solidification with ris

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

$M_{neck} > f\ M_{shape}$

where f depends on the m
melt. In other terms, the
time must represent more
the component shape one.
This simple empirical
body of the connecting rod
the feeding from the foot
the solidification contracti
be put at the top of the foo
each side of the connecting
on figure 3.
The feeder dimension (
both cast material contracti

$V_{feeder} = V_{shape}\ S/X$

where S equals 6% to 8% f
equals to 5.25% for the cast

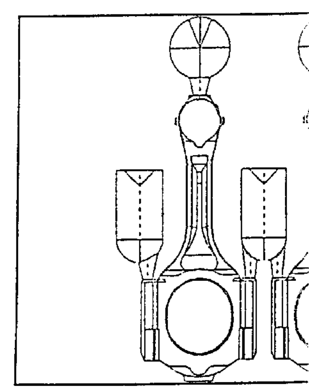


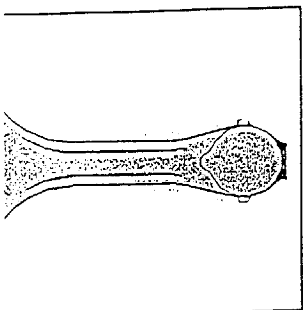
Figure 3. Riser system of th

Using the calculated val
obtain the feeder dimensions

Table 2. Calculated feeder d

	Feeder type	Dia (10
Foot	Spherical	
1/2 head	Cylindrical	

hite (SG) iron is cast in a 'he initial uniform tempera- is 1390 °C. Mold is at room e industrial configuration, s are cast vertically side by ıld.



solid modeling of the com- :r system.

without riser system

ɜ extract both volume V and te its modulus M by:

(1)

linked to solidification time al Chvorinov's law that we xperimentally for SG iron:

(2)

hand, simulation gives the of each shape cooling from lidus temperature. From the e obtain the simulated modu- ɜ summarized in table 1. The ted values could be explained ng and 3D effects.

ıl modulus and solidification simulated values.

t_s (sec) estim.	ts (sec) simul.	M_{shape} simul.
69	85	4.92
15	25	2.67
53	82	4.84

2.5. Solidification with riser system

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

$$M_{neck} > f\ M_{shape} \quad (3)$$

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:

$$V_{feeder} = V_{shape}\ S/X \quad (4)$$

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

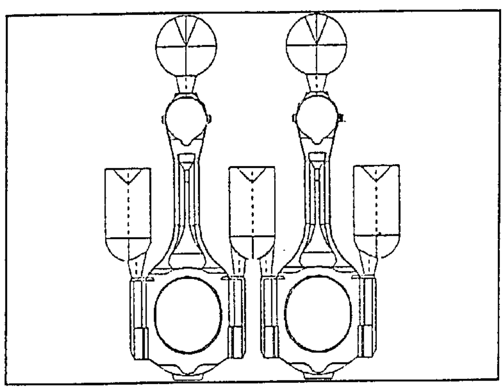


Figure 3. Riser system of the casting.

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

Table 2. Calculated feeder dimensions.

	Feeder type	Diameter (10^{-3} m)	M_{neck} (10^{-3} m)
Foot	Spherical	40	1.5
1/2 head	Cylindrical	30	1.5

The result of the solidification simulation are shown on figure 4 in the mid-section of the casting. Due to the symetry, 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.

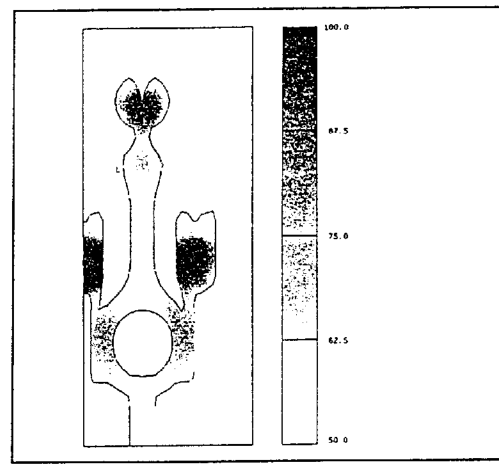


Figure 4. Simulated solidification times (sec.) in the connecting rod andits feeders.

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.

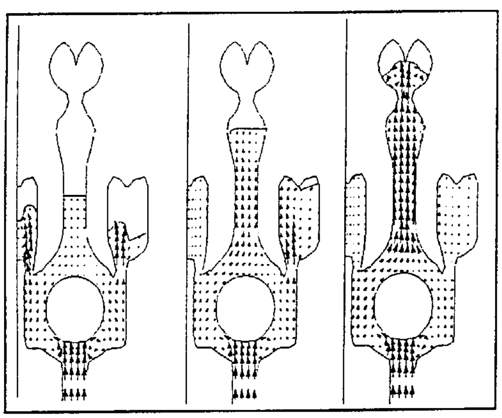


Figure 5. Simulated velocity field during filling for three steps.

At the end of the filling simulation at t= 3.1 sec., inhomogeneus 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.

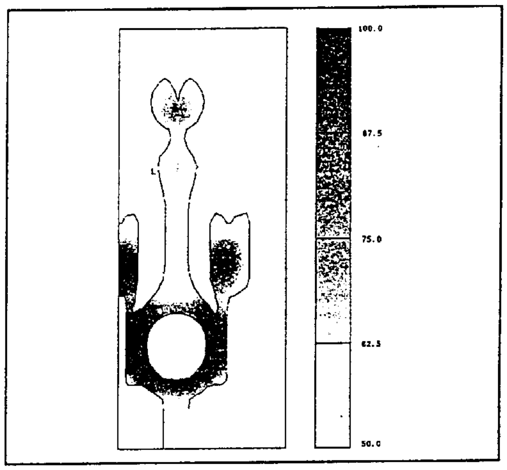


Figure 6. Simulated solidification times (sec.) after previous filling simulation.

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 adjusment 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).

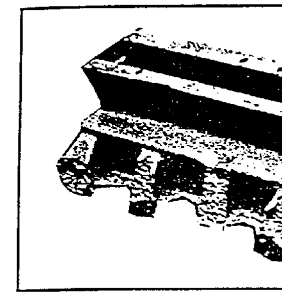


Figure 7. Experimental al
nent.

3.3. Numerical simulatior

The CAD geometries
(external dies, internal c
ingates and component) a
DEAS solid modeling to
mesh is generated using t
between CAD and FLOW

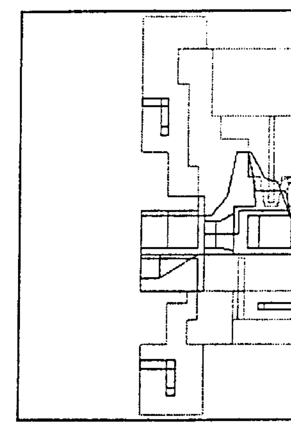


Figure 8. CAD descriptior
casting (cut view)

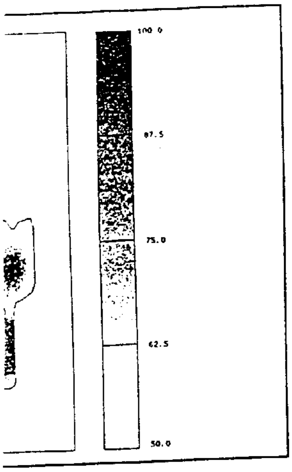
Three kinds of thermal
are used:

- for the interfaces bet
metallic dies, thermal conv

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

where the convection coef
the coating used,

- for the interface betw
core, quasi perfect contact



l solidification times (sec.)
; simulation.

Ξ ALUMINIUM CASTING

:ess

.um cylinder heads, cyclical metal is done under low ars) inside of metallic dies. res are permanently regula- ooling system controlled by life, sound cast components e the main industrial objec- :ity of this process leads to .es because the dies concep- .sed on both past knowledge

ıccurate informations about iour, one may simulate the ıeans first experimental tests ipal variables and to validate el.

schedule

eriments are done: tempera- s in both dies and cooling erature measurements in the nent. A special shape design the component in order to etrical analysis but the prin- cs of a cylinder head have gure 7).

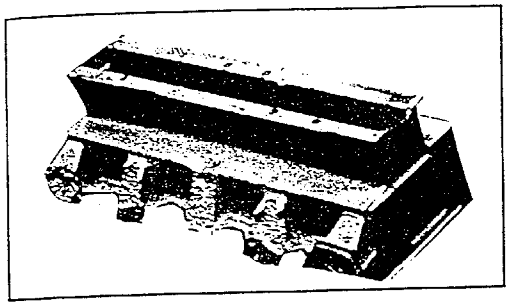


Figure 7. Experimental aluminium cast component.

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 I-DEAS solid modeling tool (Figure 8). The FD mesh is generated using the automatic interface between CAD and FLOW-3D.

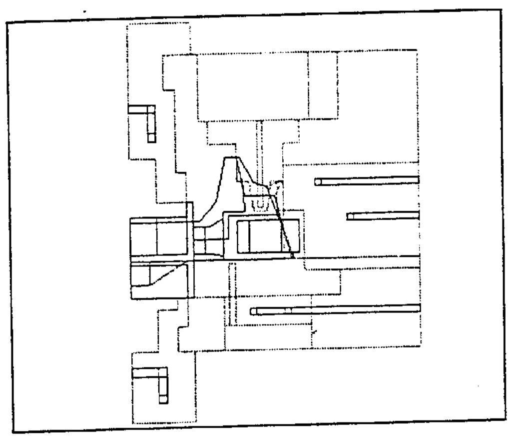


Figure 8. CAD descriptions of low pressure die casting (cut view)

Three kinds of thermal boundary conditions are used:

- for the interfaces between component and metallic dies, thermal convection flow:

$$\Phi = h\,(T_{metal} - T_{die}) \quad (5)$$

where the convection coefficient h depends on the coating used,

- for the interface between component and core, quasi perfect contact
- 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.

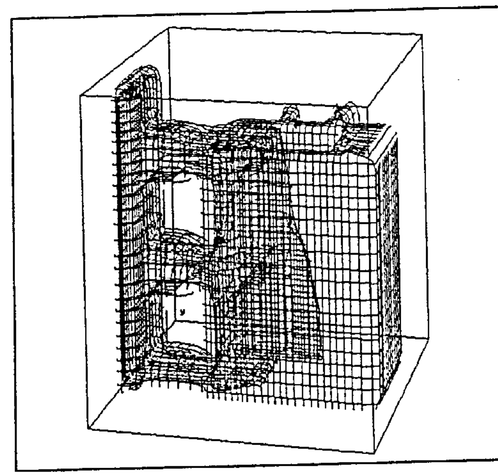


Figure 9. Enclosed liquid metal in the component after 100 sec. (bottom view of one half of the casting)

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):

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

where V represents the cooling rate and G is the thermal gradient, during solidification.

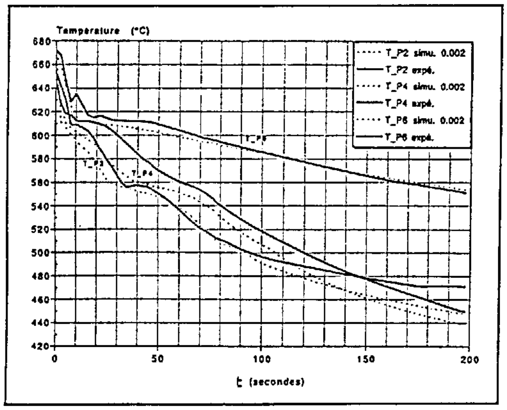


Figure 10. Measured and calculated temperatures in the aluminium component.

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).

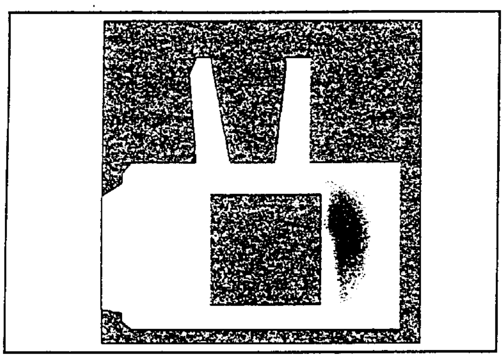


Figure 11. Calculated microshrinkage zone (in black).

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.

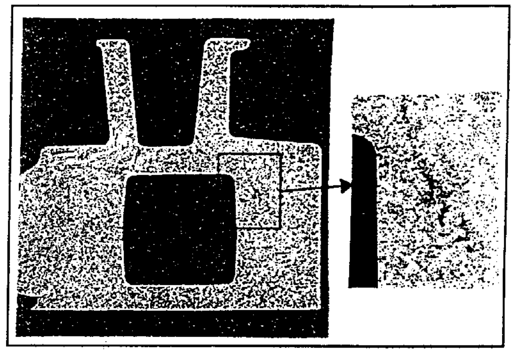


Figure 12. Zoom on the real shrinkage observed in the cast test component.

REFERENCES

Ben Cheikh A., Dalin J.B., Le Guilly J.M., Le Roy P., Maas E.& Vittori J.F. 1990. Proc. Metodos Numericos in Ingenieria: 449-455. Barcelone: SEMNI.

Hirt C.W. & Nichols B.D. 1981. Volume of Fluid (VOF) method for dynamics of free boundaries. J. of Computational Physics 39: 201-225.

Le Roy P.& Angibault P. 1990. Int. Report n°90/299 Renault 0968.

Louvo A., Kalavainen P. & Stefanescu D. M. Methods for ensuring sound SG iron castings. AFS Transactions 90-01: 273-279.

Magnin B. 1990. Etude de la microporosité dans des pièces coulées en alliage d'aluminium. Int. Report Renault 0968.

Niyama E., Uchida T., Morikawä M. & Saito S. 1982. A method of shrinkage prediction and its application to steel casting practice. AFS Int. Cast Metals J.:52.

Patin G. 1987. Mise en évidence d'une relation entre les conditions de refroidissement et la qualité métallurgique des pièces en AS5U3. CNAM thesis. Paris.

Ruddle R.W. 1975. Risering aids in steel foundry practice. American Foundrymen Society Transactions: 577-584.