

Infiltration technique modelling

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Casting techniques, which consist in infiltrating a porous network by a metal, enable to make cheap metal foams with very regular cell shape. To make a right foamed part, the pouring device has to be sized with a number of gates sufficient to fill completely the porous network before metal solidification. Nevertheless, the number of gates must be as low as possible for economical reasons. As a consequence, it is necessary to estimate the length of network that can be infiltrated from one gate to optimize the pouring device.

In this article, a model to predict the length of porous network that can be infiltrated by the metal before solidifying is presented. It considers fluid mechanics and thermal aspects separately. Its predictions are compared with experimental measures in the case of the infiltration of a chloride sodium preform by an AlSi10Mg alloy.

1 Introduction

Infiltration techniques, or replication processes, belong to the most interesting ways to manufacture metal foams. They consist in casting metal into a mould, in which a porous network, called “preform”, is inserted. Once metal is solidified, the preform is removed to produce metal foam^[1,2,3]. **Fig. 1** sums up the steps of such techniques.

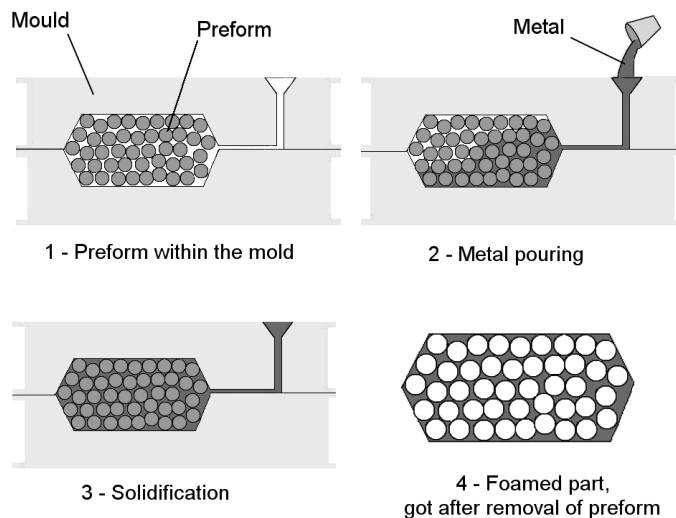


Fig. 1. Main steps of replication processes

One way for making the preform is to stack spheres or granules, called precursors, into the mould. In that case, materials such as salt^[4] - which can be easily removed by

dissolution after casting -, agglomerated ceramic particles or sand ^[5], or soft ceramic balls ^[6] can be employed. Another way is to use an open-cell polymeric foam as a temporary pattern, to invest it by ceramic slurry and then burnt it ^[7,8]. Anyway, the porosity level of the preform ranges from 10 to 50%, with cell sizes from few micrometers to few millimetres ^[1,2,3]. Thus, ducts through which metal flows during infiltration are very narrow and important head losses and metal cooling occur - heat losses could be avoided by heating mould before casting but it is often not interesting for economic reasons. As a consequence, metal can solidify while running and the length of porous network that can be fed by metal is limited. So, casting conditions and running system must be adapted to fill a thick part.

This article presents the model developed to evaluate the distance covered by metal into a porous network when flowing from one gate, according to casting conditions. The final goal is to adapt casting conditions and to size running systems for manufacturing complex cast parts with foam. First, the model will be presented. Then, a case study, considering an AlSi10Mg alloy poured into packed 9.5 mm spheres of salt (NaCl), will illustrate the capacity of the model to predict length that can be infiltrated by the alloy.

2 Theoretical considerations

Infiltration of metal into porous networks has been largely modelled, particularly to control metal matrix composites processing ^[9-12]. As a consequence, almost all studies on the subject deal with preforms in which cell size is lower than 1 mm. Thus, Reynolds numbers of metal flows are quite low and Darcy's law is sufficient to describe head losses into the porous network.

But when manufacturing metal foams, cell size is not necessary sub-millimetric and turbulent head losses can't be neglected anymore ^[13]. Consequently, present model was developed to take into account turbulent head losses, as well as inertial effects, and to consider all infiltration cases.

To simplify, the model treats fluid mechanics and thermal aspects separately. On the one hand, isothermal infiltration of metal into a porous network is considered. This permits to predict metal front displacement in time. On the other hand, cooling of a flowing metal is considered. Given the thermal properties of the preform and metal, this allows determining a rough time during which metal is liquid and infiltration can occur. By confronting both aspects, the length of preform infiltrated from one gate can be evaluated.

2.1 Fluid mechanics

We consider the case of a unidirectional infiltration, represented in **Fig. 2**. By integrating the general equation of motion along a streamline, considering mass conservation of an incompressible fluid and taking into account inertial effects into the porous network and its entrance, the following equation of metal flow into the preform ^[14] can be found:

$$\left(\alpha \cdot L(t) \cdot \frac{d^2 L(t)}{dt^2} + \alpha \cdot \left(\frac{dL(t)}{dt} \right)^2 \right) + \left(\frac{\alpha}{2} \cdot K \cdot L(t) \cdot \left(\frac{dL(t)}{dt} \right)^2 \right) + \left(\frac{k \cdot \mu_{metal}}{\rho_{metal}} \cdot L(t) \cdot \frac{dL(t)}{dt} \right) = \frac{\Delta P(t)}{\rho_{metal} \cdot \alpha} \quad (1)$$

where variables and symbols are explained in **Table 2**.

Equation (1) gets 3 terms - in brackets - that counterbalance a pressure term - on the right -, i.e. the motion spring. The first term corresponds to inertial effects - fluid mass to be moved increases while metal front progresses -, conversion of pressure into kinetic energy, and shrinkage losses at the entrance of the network, that are slightly under-evaluated for calculations considerations. The second term represents turbulent losses while the third term corresponds to viscous losses (Darcy's law). We will call these terms respectively A, B and C.

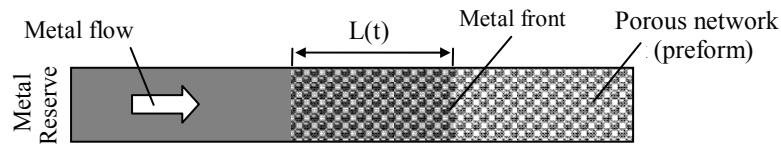


Fig. 2. Scheme of the unidirectional infiltration of a porous network.

A resolution method has been found to solve equation (1) graphically when ΔP is constant^[14]. The method consists in:

- determining predominance domains of head losses - one for each of the 3 terms A, B and C - and plotting them on a nondimensionalized diagram. Borders between these domains depend on casting conditions: pressure, preform permeabilities and tortuosity, metal viscosity and density;
- plotting asymptotic solutions, corresponding to the different predominance cases, on the same diagram;
- refining the solution near domains borders by using implicit exact solutions of equation (1) when one of the 3 terms A, B or C is neglected.

This resolution method is illustrated in **Fig. 3** in case $\left(\frac{K}{k \cdot \mu}\right)^2 \cdot \rho \cdot \Delta P \geq \frac{81}{16}$, i.e. when

the 3 head losses modes can appear during infiltration - otherwise, domain B does not exist and turbulent losses do not occur, as in sub-millimetric cell size infiltration. On that figure, each predominance domain is named as the predominant term on this domain.

For most of infiltration cases, preform permeabilities are such that domain A is very restricted. Only domains B and C can be predominant, depending on casting conditions. Thus, when C is predominant – that is the case when cell size is small –, results found for isothermal infiltration of MMC's^[9,10] are verified. Moreover, when A is negligible – most of cases –, equation (1) has an implicit exact solution, even if pressure term is not constant. A program has been developed to plot this solution.

2.2 Flowing time

To evaluate time during which metal is still liquid while flowing into the preform, heat transfer equations of a moving liquid into a duct^[15] has been considered. Numerical analysis of these equations shows that heat transfer is essentially controlled by the interface between metal and mould, owing to the narrowness of preform ducts and

infiltration speed. Thus, an expression similar to Flemings' [16] can be used to estimate metal flowing time t_f :

$$t_f = \frac{\varpi \cdot A_{SP} \cdot \rho_{metal} \cdot (f_C \cdot H + C_P \cdot (T_p - T_L))}{h \cdot \left(\frac{1}{2} \cdot (T_p + T_L) - T_0 \right)} \quad (2)$$

where variables and symbols are explained in **Table 2**.

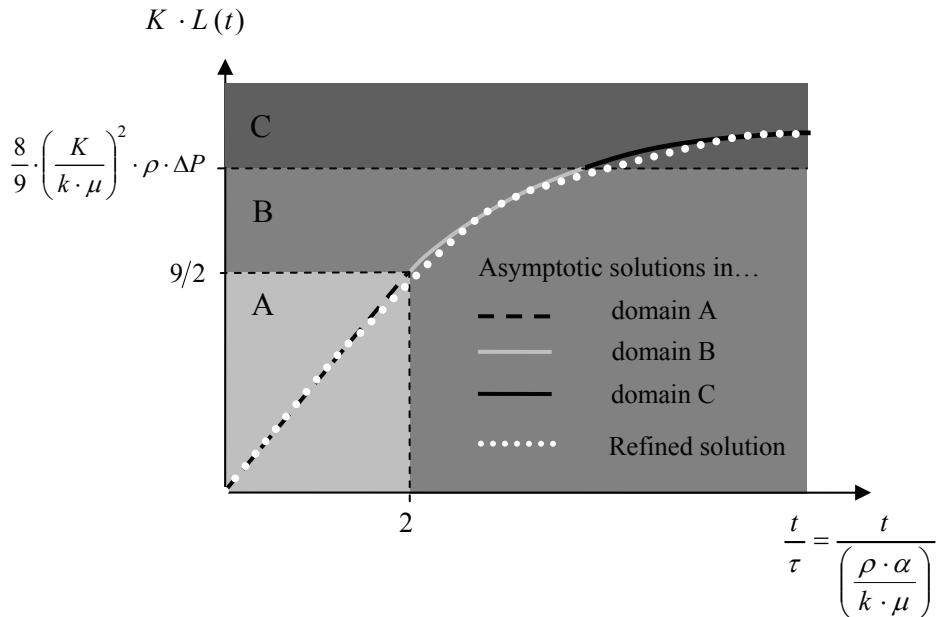


Fig. 3. Nondimensionalized diagram used to solve equation (1) graphically. Predominance domains - that correspond to A, B and C terms - are represented by different colours. Asymptotic solutions are plotted on their corresponding domains, as well as refined solution.

3 Experimentation on a sodium chloride preform infiltrated by AlSi10Mg alloy

Previous model has been used to predict infiltration length of an AlSi10Mg alloy into a preform composed of packed 9.5 mm sodium chloride spheres. Hereinafter, experimental setup and theoretical aspects of this experiment are detailed.

3.1 Experimental setup and conditions

Spheres have been stacked in 50 mm square section moulds and heated at 200°C before casting. To infiltrate them, a metal head of 325 mm - channel and pouring basin included – has been used in each experience. Pouring basin, initially blocked up by a plunger, was open when metal temperature was respectively 720°C, 800°C and 850°C.

To track the infiltration front during each experiment, the Cronofond® system, developed by CTIF, has been employed. It can detect metal presence at a given position by detecting the closure of an electrical circuit in which metal is the interrupter. Thus, metal presence is confirmed - or not - and dated at the porous network entrance and at 50, 110 and 160 mm from the entrance. Scheme of that experimental setup is proposed in **Fig. 4** while results obtained with Cronofond® are plotted in **Fig. 5**. Metal infiltrated about 112 mm of preform in the first experiment and 147 mm in the second. It completely filled the preform in the third experiment. These results are reported in **Table 1**.

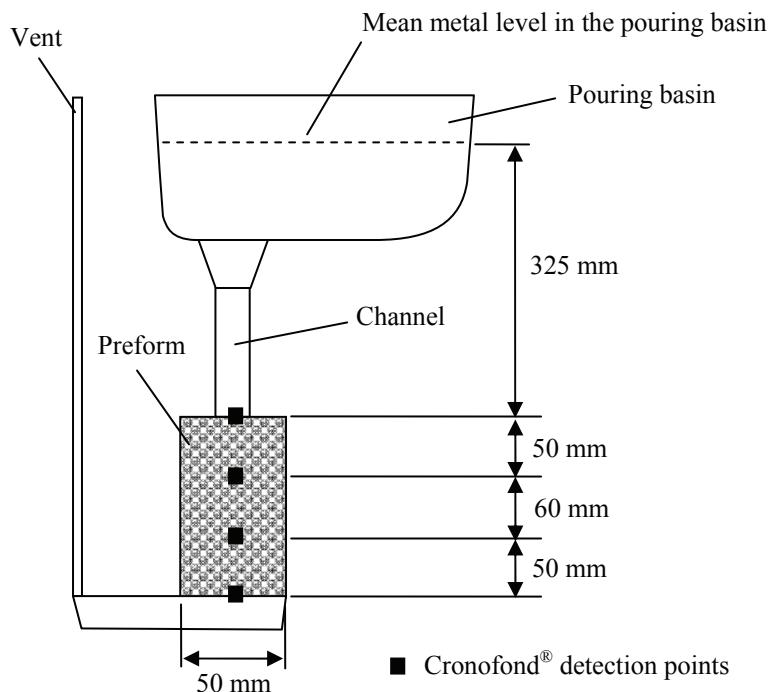


Fig. 4. Scheme of the experimental setup employed to track metal infiltration into a preform.

3.2 Experiment modelling

Retained values to model experiment are summarized in **Table 2**. AlSi10Mg alloy properties - viscosity, density, liquidus temperature, specific heat capacity, latent heat of fusion, critical solid fraction - come from QuickCast® database. Preform characteristics were found in literature - tortuosity [17], shape factor [18] -, or calculated, as preform permeabilities, which has been estimated by using Ergun's law [13]. For that, effective porosity levels of preforms have been determined by weighing produced foam samples after casting. All porosity levels of preforms were found to be near 35% - i.e. porosity levels of foams were about 65%.

Surface specific area was approximated by considering properties of body-centered cubic system - of which porosity level is next to the experimental one -, and interfacial heat transfer coefficient has been estimated from CTIF's experiments - found value seems to be in the good order of magnitude [16].

Method presented in part 2.1 has been applied to this infiltration case by considering an initial pressure of 6750 Pa - that corresponds to a metal head of 325 mm less a capillary pressure of about 1000 Pa, evaluated by formula in literature [9,10]. As domain A is very restricted for such casting conditions, pressure growth, which comes from the extension of metal head into the preform, could also be taken into account. Implicit exact solution of equation (1) is plotted on **Fig. 5**. Obviously, the fluid mechanics model predicts quite well the presence of metal at a given time.

On the other hand, flowing time can be easily calculated from equation (2). It is about 0.31 s when metal temperature is 720°C, 0.41 s when metal temperature is 800°C and 0.47 s when metal temperature is 850°C. Using curve of **Fig. 5**, it can be deduced that metal should infiltrate respectively 120 mm, 150 mm and 170 mm into the preform. These results are reported in **Table 1** to be compared with experimental results: there is a good agreement.

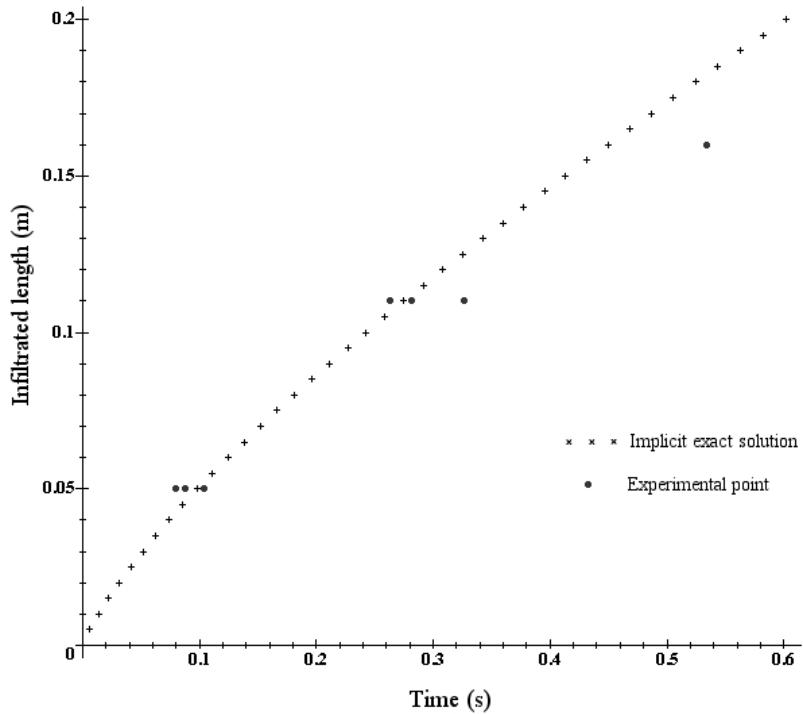


Fig. 5. Infiltration length of metal into the preform, as a function of time: experimental points and predicted curve - implicit exact solution of equation (1).

Pouring temperature	Predicted infiltration length	Experimental infiltration length
720 °C	120 mm	112 mm
800 °C	150 mm	147 mm
850 °C	170 mm	> 160 mm

Table 1. Infiltration length: prediction of the model and experimental measures.

4 Conclusion

A model has been developed to predict the length that can be infiltrated by metal into a preform. Considering fluid mechanics and thermal aspects separately, it gives an easy-to-find result, which is in good agreement with experimental measures. Thus, it can be employed to quickly design a running system of a cast part with foam, which can be then numerically modelled to study filling more precisely.

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Symbol or variable	Signification	Value in example
$L(t)$	Infiltrated length (m).	
$\Delta P(t)$	Pressure difference between the metal reserve and the tip of metal front into the porous network (Pa). This comprises metal head, applied vacuum or pressure, and capillary forces.	
k	Laminar permeability of preform (m^{-2}).	$3,90 \cdot 10^6 m^{-2}$
K	Turbulent permeability of preform (m^{-1}).	$315 m^{-1}$
α	Tortuosity of preform. Ratio between mean distance covered by metal into the preform and length of this preform.	1,47
μ_{metal}	Dynamic viscosity of metal (Pa.s).	$9,1 \cdot 10^{-4} Pa.s$
ρ_{metal}	Density of metal ($kg.m^{-3}$).	$2400 kg.m^{-3}$
t_f	Flowing time (s).	
T_p	Pouring temperature of metal (K).	
T_L	Liquidus temperature of metal (K).	865 K
T_0	Mould temperature (K).	473 K
H	Metal latent heat of fusion ($J.kg^{-1}$).	$510 kJ.kg^{-1}$
f_c	Critical solid fraction. Metal solid fraction at which metal stop flowing.	0,1
C_p	Metal specific heat capacity ($J.kg^{-1}.K^{-1}$).	$1100 J.kg^{-1}.K^{-1}$
h	Heat transfer coefficient at metal/preform interface ($W.m^{-2}.K^{-1}$).	$1800 W.m^{-2}.K^{-1}$
A_{sp}	Specific surface area (m). Ratio between porosity volume of the preform and contact surface between metal and preform.	0,735 mm
ω	Mean shape factor of the preform ducts.	0,75

Table 2. Variables and symbols used in equations, and values considered to model experiment - salt preform infiltrated by an AlSi10Mg alloy.