SIMULATION OF LCM PROCESSES USING CELLULAR AUTOMATS

M. Henne [1] and G.A. Barandun [1]

[1] *University of Applied Science Rapperswil HSR, Institute for Material Science and Plastic Processing, Oberseestrasse 10, CH-8640 Rapperswil, Switzerland,* mhennel@hsr.ch

ABSTRACT: Finite Element Methods (FEM) are at present available for simulating resin injection processes. However, they are extremely time-consuming, and even then they demand excessive computing power if an iterative process is used for optimising the injection parameters; furthermore, the quantitative predictions of the filling time and the evolution of the pressure during the filling of the mould are very inaccurate. For these reasons FEM-based simulation is scarcely ever used in practice.
In the work described here a cellular automat is used to simulate the injection process. The algorithm calculates the pressure in a cell from the pressures in the neighbouring cells and from the properties of the cell. It takes account of all the factors that have an influence, such as permeability, porosity and the geometry of the cavity. It is tuned to give a picture of the mould-filling that is as realistic as possible, using experimental results and values based on experience.

KEYWORDS: Liquid Composite Moulding LCM, Resin Transfer Moulding RTM, Simulation, Cellular Automats

INTRODUCTION

Liquid Composite Moulding (LCM) covers a class of manufacturing processes of high-quality fibre reinforced composites for various applications. LCM processes are closed processes, i.e. during injection the mould cavity is open only to the vacuum vent and the injection point where liquid resin mix is flowing in. For this reason it is difficult to follow the process of mould filling or to control it in any way. At best, sensors can deliver a signal at the instant the filling front reaches them. Suitable process control is decisive in ensuring process repeatability and the quality of the finished component. If either the injection points or the mould evacuation points are incorrectly chosen, then air pockets may occur, impairing product quality. Apart from this, the process should be laid out to achieve the shortest possible cycle time and hence the highest productivity.
Finite Element Methods (FEM) allow the optimisation of liquid moulding of composite parts by virtual process simulation. The central physical equation used in finite element codes is Darcy’s Law, which describes the behaviour of liquids flowing through porous media [1]. Process simulations based on FEM allow the numerical accurate calculation of mould filling processes. In real life liquid moulding may be influenced by many additional effects, which are hard to consider in numerical simulations. Mainly race tracking effects in areas of low porosity are dominating the propagation of the flow front. Because of those reasons it is crucial, that the user of the software has deep knowledge on liquid moulding processes, which help to programme a simulation and to interpret the results. Additional many of the features of commercial software such as

thermal simulation and consideration of cure kinetics may have minor influence on most infusion processes and are therefore not useful. For these reasons process simulation it is seldom used in practice. In particular in small and medium size enterprises the process simulation is not applied, because of the high license costs for the software, missing material data and the lack of knowledge of the engineers in application of simulation tools.
A new approach to the simulation of resin injection processes is taken in this study, based on the idea of cellular automats. Numerical simulations using cellular automata are easy to use and require in many cases fewer calculations and can therefore substantially reduce the computing time required.

CELLULAR AUTOMATS

Cellular Automats were first proposed in 1940 by John von Neumann, Stanislav Ulam und Alan Turing at Los Alamos [2]. They are valid for spatially discrete time-dependent systems, in which the state of an individual cell at a given time step depends primarily upon its own state and those of the cells in a predefined neighbourhood at the end of the previous step.
In order that cellular automats may be used to simulate physical phenomena that are described by sets of differential equations, they must be approximated either by the top-down or by the bottom-up method. In the top-down method the cellular automat is derived from the differential equation that governs the behaviour of the object itself. In the bottom-up approach on the other hand the cellular automat is programmed so as to ensure that its behaviour corresponds purely and simply to that observed in the real system. In the case under consideration a middle way is preferred, whereby in the bottom-up approach the algorithm is based on the influence of the individual parameters according to Darcy’s law.
The cellular automat presented here was developed specifically for hollow shell-shaped components – “2½ dimensional” – which is often the form of fibre-reinforced plastic structures, though the algorithm can in principle also be used for true three-dimensional structures. The algorithm calculates the state of the pressure distribution in a cell during filling from the pressure in the cell itself as well as that in the neighbouring cells, and from the properties of the cells in that region at that time, according to:

$$p_{t+1} = p_t + \underbrace{\left(\frac{K}{\overline{K}}\right)^q}_{A} \cdot \frac{1}{m} \cdot \sum_{i=1}^{m} \underbrace{\left(\frac{d_i \cdot \phi_i}{d \cdot \phi}\right)^r}_{B} \cdot \underbrace{\left(\frac{\bar{l}}{l_i}\right)^s}_{C} \cdot \left(p_{i,t} - p_t\right) \qquad (1)$$

p	Pressure of the cell	[N/m^2]
$\overline{K}$	Average permeability	[m^2]
d	Height of the cavity	[m]
ϕ	Porosity ($\phi = 1 - v_F$)	[-]
l	Distance to the neighbouring cell	[m]
$\bar{l}$	Average distance between cells	[m]
q, r, s	Weighting factors (chosen 1, 1, 2)	[-]
m	Number of neighbouring cells taken into account	[-]

All the influential parameters, such as permeability (Term A), flow volume of the cell (represented by cavity height and porosity, Term B) as well as cell spacing (Term C) and are normalised. Term A considers the local permeability of the cell. Term B adjusts the weight of the cell in relation to that of its neighbours, depending on their properties. Term C makes the cellular automat independent of the cell density, i.e. it ensures that irrespective of the cell density the filling behaviour is always the same for the same cell properties. The parameter m prescribes the number of neighbouring cells to be taken into account in calculating the pressure, i.e. the same number of neighbours is always used, irrespective of the cell density.
The weighting factors *p*, *r* and *s* must be adjusted in order to obtain the best approximation to the real flow behaviour. In this form the algorithm is formulated for isotropic permeability *K*. The effect of anisotropy – which anyway has a subordinate effect in real components – can if need be allowed for by an extension of the cellular automat.
Initially all cells have set to zero pressure and are dry. The injection point is determined, for which a constant injection pressure is allotted. The calculation starts, and this pressure extends throughout the surrounding cells. The pressure field is evaluated at each step of the calculation, and a decision made as to whether a given cell is to be considered as still dry or as filled with resin mix. The threshold criterion for complete filling of the cell is the partial vacuum pressure.

$$\text{if } p_{t+1} \geq p_{vac} \rightarrow \text{cell wetted} \qquad (2)$$

whereas p_{vac} is the vacuum pressure. That is to say, the cell is considered to be wetted with resin mix as soon as its pressure exceeds the partial vacuum pressure of evacuation of the mould cavity. It follows that for the simulation a cell can in this respect be in only one of two states: either completely dry, or else completely wetted with resin mix. Intermediate states obviously exist in reality, but in practice have minor influence on the outcome.

EVALUATION AND INTERPRETATION

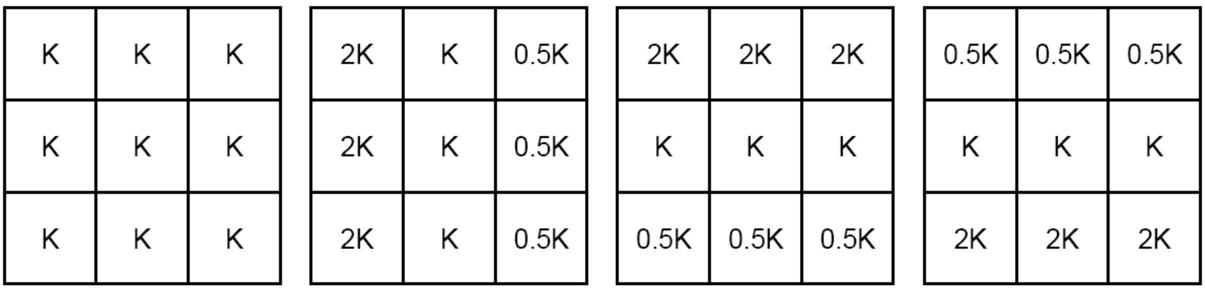
In a test programme, individual parameters of the cellular automat are adjusted and the resulting filling pattern is displayed graphically. The test component is a square plate 500 mm x 500 mm, and is divided into nine equal square elements, whose properties can be individually varied. Increases in permeability in the edge zones (which occur in reality) are not taken into account in the model. The individual factors are systematically varied in the way described in Table 1.

Table 1: Test programme

Variation	**Description**
Distribution of the cells	Comparison of the results for a uniform distribution of the cells with those for an arbitrary distribution, the total number of cells being the same in both cases
Note: In the remaining cases only arbitrary cell distribution is used in the model.	
Position of Injection	Qualitative behaviour for injection point placed in the middle of

point	a side, at a corner and in the middle of the field
Injection pressure	Effect of doubling or halving the injection pressure (pressure held constant during filling)
Cell density	Variation of the cell density in the direction of injection and at right angles to it. Cell density declining stepwise from left to right (A), from top to bottom (B) or from bottom to top (C)
Permeability	Variation of the permeability in the direction of injection and at right angles to it. Permeability declining stepwise from left to right (A), from top to bottom (B) or from bottom to top (C)
Porosity	Variation of the porosity in the direction of injection and at right angles to it. Porosity declining stepwise from left to right (A), from top to bottom (B) or from bottom to top (C).
Cavity height	Variation of the cavity height in the direction of injection and at right angles to it. Cavity height declining stepwise from left to right (A), from top to bottom (B) or from bottom to top (C).

Example: Figure 6 shows the pattern of variation for permeability.



Starting Position Case A Case B Case C

Fig. 1: Variation of permeability.

The results are illustrated and described in the following figures 2 to 8 and the associated text. The numbers show the number of calculation steps after the start of injection. The solid line is the flow front and the broken line the pressure front.

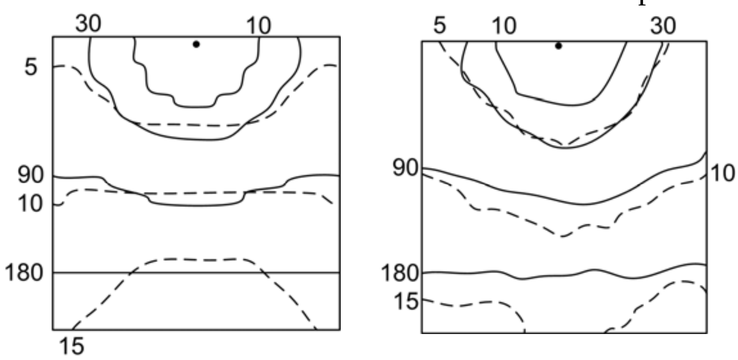


Fig. 2: Results for regular (L) and irregular (R) cell distribution

The results for regular and irregular cell distribution are shown in figure 2; they do not differ greatly, from which it follows that for a more complex geometry the cells may be arbitrarily positioned, but still as evenly as possible.

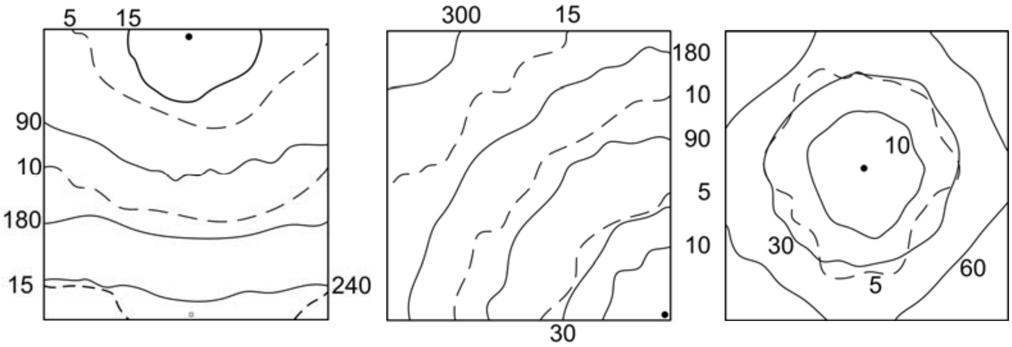
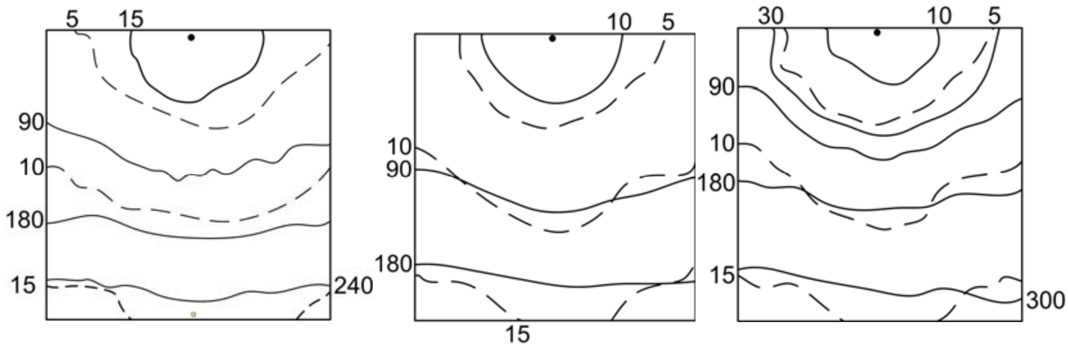


Fig. 3: The effect of altering the injection point (the black spot)

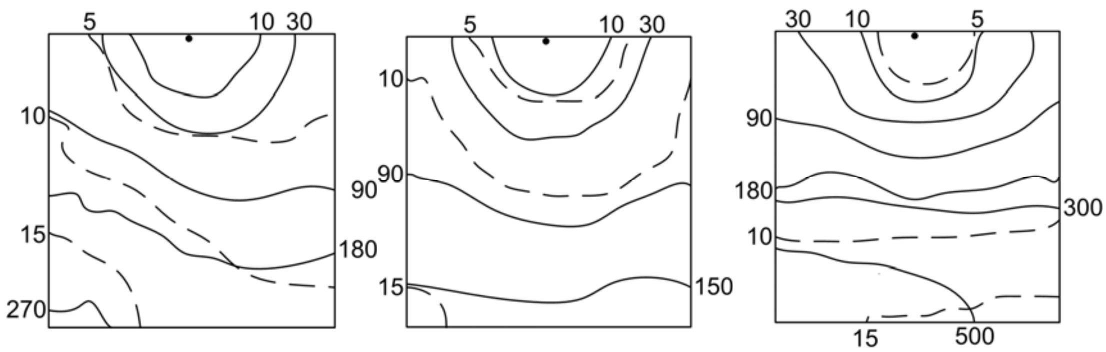
The effect on the filling time is clearly to be seen in figure 3. Essentially, it is possible to place the injection point anywhere, but as with actual injection, the mould fills considerably faster with a central injection point than with one in the corner. The model also allows for injection from multiple injection points at different locations, opened at different times.



(a) (b) (c)

Fig. 4: Effect of varying the injection pressure. (a) normal, (b) halved (c) doubled

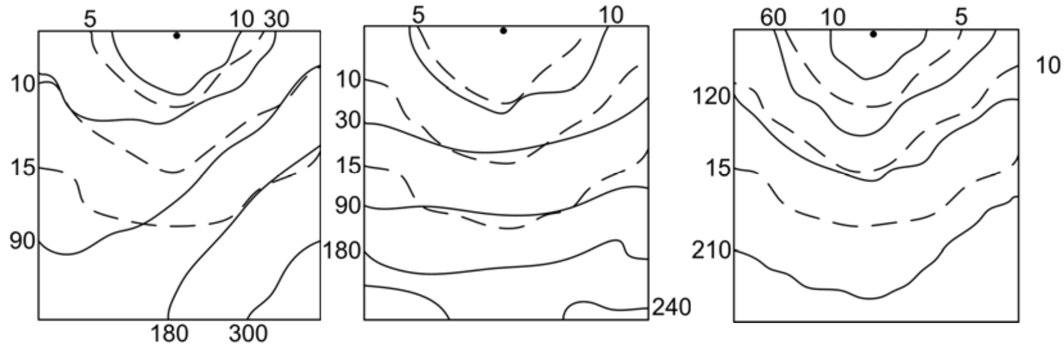
As figure 5 shows, after the same number of calculation steps the flow front is further advanced at double than at normal pressure but develops in much that same way.



(A) (B) (C)

Fig. 5: Effect of varying the cell density (A) falling left to right, (B) falling top to bottom (C) rising top to bottom.

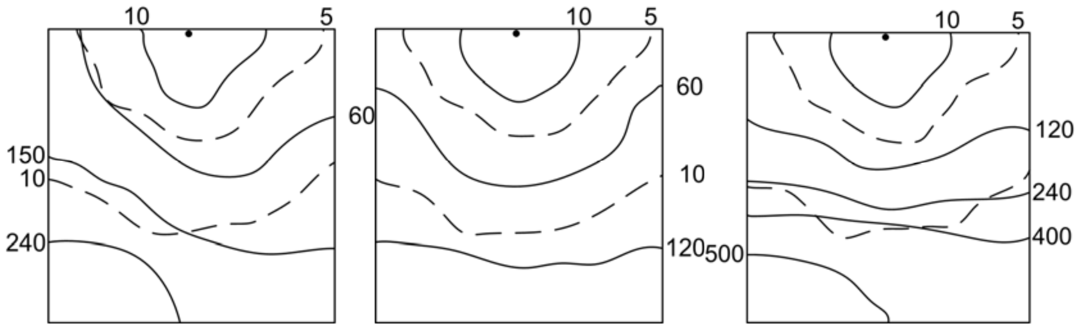
When the cell density is altered, the filling pattern changes substantially (Figure 10). The filling front also develops differently, advancing significantly more slowly where the cell density is higher.



(A) (B) (C)

Fig. 6: Effect of varying the permeability (A) falling left to right, (B) falling top to bottom (c) rising top to bottom.

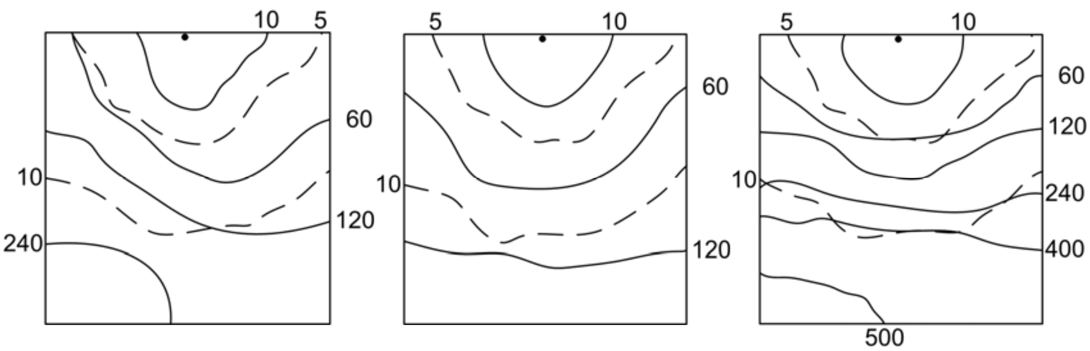
The more rapid advance of the filling front in regions of higher permeability is clearly to be seen in figure 6.



(A) (B) (C)

Fig. 7: Effect of varying the porosity (A) falling left to right, (B) falling top to bottom (B) rising top to bottom.

The slower advance of the filling front in regions of higher porosity is clearly to be seen in figure 7.



(A) (B) (C)

Fig. 8: Effect of varying the height of the cavity (A) falling left to right, (B) falling top to bottom (C) rising top to bottom.

Altering the cavity height also significantly affects the flow pattern, as figure 8 shows. This effect is also observed in practice.

In principle the cellular automat using the proposed algorithm correctly represents the filling process. The predicted effects on the filling behaviour of varying the position of the injection point and pressure, permeability, porosity and cavity height all agree qualitatively with those observed in practice.

The dependency of the filling behaviour on the cell spacing needs to be improved, as the results shown in Figure 10 demonstrate. It will certainly be possible to correct it by adjusting the weighting factors in the algorithm or by modifying the algorithm itself.

CONCLUSIONS

The simulation of LCM processes using cellular automats is in principle possible.

The algorithm developed in this work correctly describes the behaviour during mould filling in a qualitative way, but requires further refinement. The chief difficulties are in dealing with different cell densities, and in the high pressure drop at the injection point. The first few runs of the calculation are decisive for a correct description of the filling process. For this reason it is desirable to improve and refine the modelling of the injection point and the early stages of injection. It is also of interest to extend the model to allow for more than one injection point.

In order to be able to make quantitative predictions of the evolution of the filling process the time step needs to be further investigated, and the resulting predictions compared with corresponding measured values from testing.

In parallel with the latter, the expected improved results should be compared with those from FEM simulation and the advantages of the method set out.

AKNOWLEDGEMENTS

The work described here was financed by the Werner Steiger Foundation.
This support made it possible to carry into practice the idea of simulating the RTM process by means of cellular automats, and the authors hereby acknowledge it with grateful thanks.

REFERENCES

1. H. Darcy, “Les fontains publiques de la ville de Dijon”, *Dalmont*, Paris, 1856
2 J. von Neumann, “Theory of self reproducing automata”, *Burks*, 1966