Simulation of die filling for the wax injection process: Part II numerical simulation

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Abstract

This paper is the second of two papers dedicated to the modeling of wax injection for the investment casting (or lost wax) process. This paper presents the experiments and the numerical simulations carried out in order to validate the models developed and presented in a previous paper [1]. Three different experiments have been used. The first was to characterize the flow of the wax during the filling and the capacity of the models developed to describe it accurately, in the liquid state. The second experiment was to test the capacity of the models to predict the apparition of filling defects. The third was to compare the predictions in liquid and paste or semi-solid state. A good agreement between experiments and simulations has been found, showing that the models are able to represent the behavior of the wax used.

Keywords: investment casting; wax injection; numerical simulation

1. Introduction

The prediction of defect formation during the wax injection stage of the investment casting process will enable the process engineer to reduce scrap by improving the die design through better positioning of the in-gates and the ability to tune the injection process parameters (mainly temperature and pressure) so that a defect free wax can be produced. In a previous paper [1] the modeling of the thermo-mechanical behavior of the wax was presented. A selection of models was given for describing the rheological behavior of the wax as a function of temperature and shear rate. The compressibility of the wax was also studied and modeled with two different approaches that can be used in different simulation packages.

In this paper the simulation of the wax injection process using the models shown in the previous paper [1] is presented. Three different experiments have been modeled and the results obtained have been compared with experimental results.

2. Flow visualization experiments

A transparent die was designed which encompassing thick (35 mm) and thin (5 mm) sections similar to a simplified geometry of a turbine blade. Three different gate positions were selected. This allowed the visual recording of the filling front motion during the injection. Figure 1 presents a schematic of the patterns produced with the three different in-gate systems.

The process parameters investigated in the experiments were:

- wax temperature;

- injection pressure;
- in-gate location;

The simulations were carried out using Flow-3D®[1] from Flow Science Inc., Santa Fe, NM, USA. The aim of these numerical simulations was to examine the predictive capability of the model with different in-gates. Simulations were carried out for the three different in-gates using a single temperature, 70 °C, and a single injection pressure of a nominal value of 2.5 MPa (25 bar). Simulations were made with the assumption of a perfect venting, i.e. no build up of air pressure in the die during the filling was taken into account.

Different injection machines have different ways of controlling the flow of wax during filling. Some machines can be controlled by applied pressure and some by flow rate. In both cases, the pressure applied is displayed most of the time on the machine or recorded for quality control or other purposes. One of the main problems is that the pressure measured by the machine is never the pressure at the in-gate of the die but rather, in the best cases, the pressure in the nozzle. To carry out a reasonable simulation, reasonable boundary conditions are needed. As the geometry of the nozzle is not usually modeled, the pressure at the boundary, which will be in this case the in-gate of the die, needs to be known. Therefore, the pressure in the in-gate was recorded during the experiments with a pressure transducer and has been used as a boundary condition. Figure 2 shows the pressure recorded at the in-gate in the case of the lateral in-gate situated in the middle of the face, with a nominal pressure of 2.5 MPa (25 bar). A second possible source of discrepancy between the experiment and the simulations is the temperature of the wax. In the simulation a wax temperature of 70 °C has been assumed. Recent experiments carried out at the University of Birmingham within the main research project have shown that the measurement of the *real* wax temperature is a difficult problem due to the low thermal conductivity of the wax. A thermocouple inserted into liquid wax is immediately coated with a shell of solidified low thermal conductivity solid wax that doesn't allow the measurement of the real temperature. The temperature control used by the injection machines in these experiments is made by controlling the wax temperature in the wax reservoir and in the nozzle thus the value used in the simulation may be wrong. From these recent experiments the real temperature may be within ±2 °C of the temperature displayed by the machine.

The surface tension of the wax can be taken into account in the Flow-3D simulation package. A constant value of 40 mPa.m has been used in all the presented simulation results [3]. One of the simulations has been re-run with the measured value presented in the figure 3 of [1] in order to evaluate the influence of using the measured value of surface tension on the filling front. The measured value was in the 30-40 mPa.m in the range of temperatures used, and thus the results were similar. The temperature dependency of the surface tension has therefore not been considered.

Figure 3 presents the results obtained with the in-gate situated in the middle of the lateral face. It appears that the predicted filling front moves faster than the experimental one, and that the thin part of the die is filled a lot faster. This could be a result of the compression of air in the die cavity that creates a resistance to the flow due to inadequate venting in the experiment, or to too low a viscosity being used in the simulations.

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[1] For more information, http://www.flow3d.com

Figure 4 presents the results obtained with the in-gate situated in the bottom of the lateral face. The predicted filling front and the experimental one are in very good agreement. Even features such as the jump at the entrance of the large cavity at 0.08 s and the formation of outgrowth are predicted as shown on Figure 4 at 0.12 and 0.20 s.

Figure 5 presents the results obtained with the in-gate situated in the bottom face. Here again, the viscosity predicted by our model seems to be too low, with a faster filling and a wax flowing too easily along the wall of the die.

3. Prediction of surface defects

The prediction of the motion of the filling front were considered as reasonable, the next step was to predict the formation and development of defects.

The experiment consisted of the filling of a die to make the stepped cylinder depicted in Figure 6. Three different injection points can be used and so mould filling and solidification can be studied under a wide range of conditions. The die was made of aluminum, so only the surface defects can be compared between the experiment and the simulation. The part was produced using different process parameters (wax temperature, injection pressure or flow rate). The use of different injection points leads to the development of different defects. These tests permitted the assessment of the model capability to predict these defects using MoldFlow®[2].

MoldFlow® allows the use of three kinds of elements (Figure 7):

- The first mesh is named "midplane". With this kind of model, the geometry is approximated by its mean surface, and all the properties are calculated on the mean surface, defined as the surface which describes the midpoint of all the sections of the geometry. The model obtained is thus effectively 2D. The problem then is to create such a model from a 3D CAD model.

- The second mesh is called "fusion". With this kind of model, the surface envelope approximates more closely the real geometry and is essentially a hollow model. The properties are then calculated on both surfaces, and their variations in the thickness of the geometry are estimated. The model obtained is 2.5D. It looks like a 3D model but in fact it does not really consider the behavior in the thickness.

- The third mesh is true 3D. With this kind of model, a classical 3D approach is used, with 3D elements. Nevertheless, using this approach, some assumptions can be made to decrease the calculation time. These assumptions are linked to the flow of the material (fast algorithm or full Navier-Stokes algorithm), and the importance of the inertial forces. The results presented here have been obtained with the fast algorithm. The fast algorithm makes some simplification of the Navier-Stokes equation by neglecting the inertial forces. The calculation time is lower, but the predicted flow may not be as accurate as with the full Navier-Stokes algorithm.

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[2] for more information, http;//www.moldflow.com

Due to the increasing complexity of the models, it is expected that the calculation times will increase from the midplane mesh to the 3D mesh. For example the simulation presented in figure 8 used the three kind of geometrical description. The calculation time and mesh size for each geometrical description are given in table 1 for MoldFlow® (MPI 3.1) running on a dell WorkStation 530 with 2 Intel® Xeon™ 1.5GHz.

Table 1: calculation time with different type of meshes

Mesh type	Number of nodes	Number of elements	Calculation time (s)
Midplane	1425	2780	231
Fusion	3408	6816	810
3D fast algorithm	16195	83568	2351
3D full Navier-Stokes	16195	83568	16077

Models used. For the flow of the wax, despite the presence of a Carreau model in MoldFlow®, a second order model has been preferred, as it predicts the viscosity more accurately. The second order model describes the viscosity as a second order polynomial function of temperature and logarithm of the shear rate. The difference between Flow3D® and MoldFlow® for the Carreau model is in the way the different parameters of the model (η_0, η_∞, λ, n) can depend on the temperature. In Flow3D®, the dependency has been implemented in user's subroutines, whereas in MoldFlow® they are predefined and cannot be changed, and that give less flexibility in the fitting of the experimental data. The heat capacity and heat conductivity have been assumed to be constant in MoldFlow®, as it is not possible to have any temperature dependency in the version of the code used in this work. The latest version of MoldFlow® can consider temperature dependant heat capacity and conductivity. The evolution of density or volume with temperature and pressure has been entered from the PVT experiment, using the two-domain Tait equation.
The results presented here are for a filling time of 10 s and a wax temperature in the nozzle of 70 ^{o}C.

First injection point. The simulation results are shown in Figure 8. Figure 9 presents a picture of the injected part obtained using a filling time of 10 s at a temperature of 70 ^{o}C. The filling path predicted by the simulation with the three kinds of element shows that in the thinner section half of the part is filled at the beginning of the injection and half at the end. This probably results in a weld line where these two domains join. The freeze or solidified map shows that at the end of the injection, a significant proportion of the wax is behind the *solidification* point in the first filled area, whereas in the last filled area next to it, it is still mostly liquid. In fact, MoldFlow® can predict the weld line position in the case of the midplane and fusion meshes, and in these cases it predicts a weld line at the location where the two domains join. Figure 9a shows that on the injected pattern, there is effectively such a weld line at this location.

Second injection point. The simulation results are shown in Figure 10. For these simulations, the predictions obtained with the three models are different. The midplane and fusion models predict a weld line above the injection point in the thinner section. Only the midplane and 3D results are presented in Figure 10. The 3D mesh predicts a mis-run in the same location as shown on Figure 10c. The experimental results show that there is a weld line but no mis-run, Figure 9b.

Third injection point: The simulation results are shown in Figure 11 for the fusion mesh only. In this case, the simulation using the midplane mesh did not predict any weld lines, whereas the simulation using the fusion mesh predicted some defects on the bottom surface of the cylinder, near the injection point. The 3D simulation did not show any obvious surface defect. The experimental results shown in Figure 9c indicate a weld line due to a surface defect and an undulating surface. Figure 9d shows, for comparison, the same surface when injected using the second injection point.

4. Paste state injection

This experiment was design to look at the effect of the gate velocity of the wax on the entrapment of air. In our simulation, the air, and therefore the formation of the bubbles have not been modeled; only the filling front motion has been observed. The aim of these simulations was to determine if our model was able to predict the difference of behavior of the wax when the viscosity of the wax is high, in the so-called *paste state*. Figure 16 shows a schematic of the experimental apparatus. Figure 17 shows a comparison of the predictions of the model and the experiments in the liquid state. This shows a good agreement between the experiment and the predicted filling. Figure 18 shows a comparison in the paste state. Here again, the comparison of experiments and simulation results shows a good agreement. The experiments and simulations were carried out with a flow rate of $50\times10^{-6}\,m^3.s^{-1}$ ($50\ cm^3.s^{-1}$), which corresponds to an in-gate velocity of $1\ m.s^{-1}$.

Discussion

Mould filling

The results presented here have shown that the predictions of our model do not consistently align perfectly with the experimental results. The experimental results could be questioned, as in some cases the behavior predicted in the thin/thick die experiment implies a less viscous fluid, in the first and third in-gate, and a more viscous fluid in the second in-gate. As said previously, that can be explained by the possible discrepancy on the temperature and a possible inadequate venting of the die. Nevertheless, it seems that the predictions are representative of the flow during the filling. The computation times to perform such simulations are very large, as most of the properties are temperature dependant and the viscosity is temperature and shear rate dependant. Therefore our model is strongly non-linear and this is a disadvantage for any commercial application. For these reasons, some studies should be carried out for an optimization of the ratio between accuracy of the prediction (i.e. complexity of the model) and computational time, and simplifications such as a density dependant only on the temperature could then be made.

Defect prediction

These results show that MoldFlow® is able to predict the development of these defects. The accuracy of the position of the defects is less clear. Experiments have been carried out with this same cylindrical pattern using the first injection point, with different wax temperature and different injection flow rates. The experiments used the technique of "short shots" which consists in doing interrupted filling to be able to see the position of the filling front at different injection times. These "short shot" experiments allow the determination of the locations of the last parts of the pattern to fill, and measurement of the angle between the last parts to fill in the thinner section and the in-gate. Figure 12 shows an example of such a sample and the numerical simulation results corresponding to the process conditions. The results obtained are summarized in Figure 13.

The prediction of the weld line positions from the mid-plane and fusion meshes have been compared with the location of the last part to fill, for a wax temperature of 70 ^{o}C. The problem is that there is no possible comparison if no weld line is predicted. Figure 14 shows an example of prediction of weld line position with both meshes. Figure 15 presents the comparison between the experimental results and the numerical results.

From Figure 15, if the prediction of the simulation package were perfect, the fitted line should have a slope of 1 and coefficient of correlation R^2 equal to 1. Looking at the figure it is then clear that the predictions of the mid-plane mesh, which give a slop of 1.03 and a coefficient of correlation of 96.9 %, are better than those of the Fusion mesh, which give a slope of 1.31 and a coefficient of correlation of 38.3 %. The comparison is only done for the flow rates from 5×10^{-6} to 20×10^{-6} $m^3.s^{-1}$ (5 to 20 $cm^3.s^{-1}$) as these are the only flow rates giving a flow line prediction.

Paste injection

Looking at Figure 17 and Figure 18, it appears that the predictions of the filling on this very simple geometry are good. It should also be noted that the prediction of the filling in the paste state is surprisingly realistic, with the creation of the 'worm' like shape of the "extruded" wax during the filling, and a development in a very similar way.

Conclusion

This study has shown that it is possible to model accurately the filling of a die during the wax injection process, in both liquid and paste state. It has also shown that it is possible in some case to predict the formation of surface defects and to have a good estimation of their locations.

The different models used have been presented. It has been observed that the compressibility of the wax during the injection may not be significant due to the relatively low pressure involved in the case of mould filling. The Carreau model that has been used in Flow-3D is complex, with a strong dependency of the viscosity on temperature and shear rate. This complex model involved large computation times. Therefore, from an industrial point of view it is interesting to look at possible simplifications to this model. The temperature variations during injection are not large in the bulk of the wax due to the low thermal diffusivity of the wax. This low thermal diffusivity results in a very thin layer of wax in contact with the die that sees a decrease of temperature, whereas the wax not in contact with the wall does not see any significant temperature variation during the injection. Small temperature variations of the bulk of the wax pattern have been highlighted during the study of the de-waxing process where a wax cylinder of 72 mm diameter was not fully re-melted after 4 minutes in an autoclave at 180 ^{o}C. So, as the injection process is a fast process, it may be possible to calculate the temperature dependent terms only at the beginning of the simulation and then only take into account the shear rate dependency.

Acknowledgement

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Bibliography

[1] J.-C. Gebelin, M.R. Jolly, A. M. Cendrowicz, J. Cirre and S. Blackburn: Met. Mat. Trans. B, Vol 35, No 4, August 2004.

[2] S. Chakravorty: 24th BICTA Conference on Investment Casting, paper 1, 6-8 June 1999, Oxford, UK

[3] D. R. Lide: Handbook of Chemistry and Physics, 74th edition, CRC press Inc., Boca Raton, Florida, 1993, pp **6.**144-**6.**147

[4] S. Jones, M.R. Jolly, S. Blackburn, J.-C. Gebelin, A. Cendrowicz and K. Lewis, "Measurement of Autoclave Thermal Profiles During High Pressure Steam Dewaxing of Investment Shells Part 2: Wax Body Profiles", Journal of Material Science and Technology, in Press

Figures

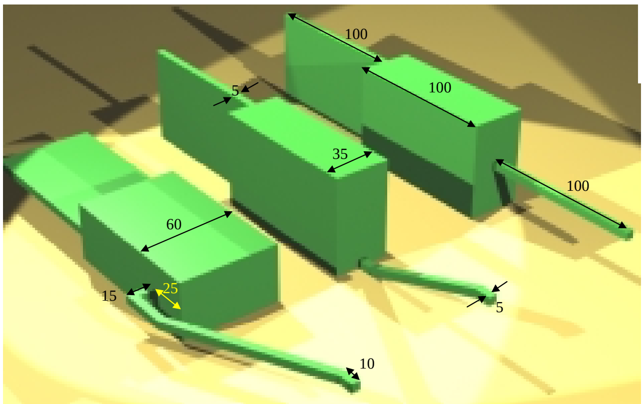


Figure 1: Thin-thick die

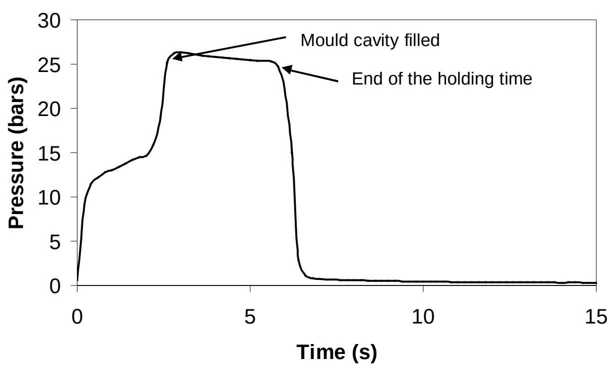


Figure 2: Pressure at the ingate recorded during the injection of the thin-thick pattern with a machine pressure of 25 bars (2.5 MPa)

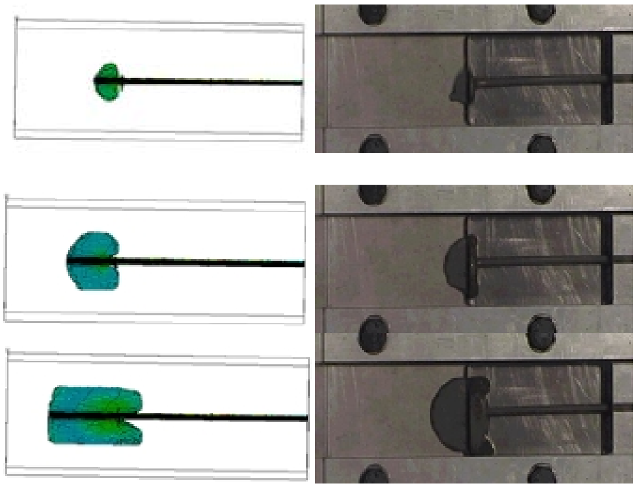


Figure 3: **Comparison of the filling front predicted with Flow-3D and recorded during the experiment at t=0.08s, t=0.12s and t=0.24s**

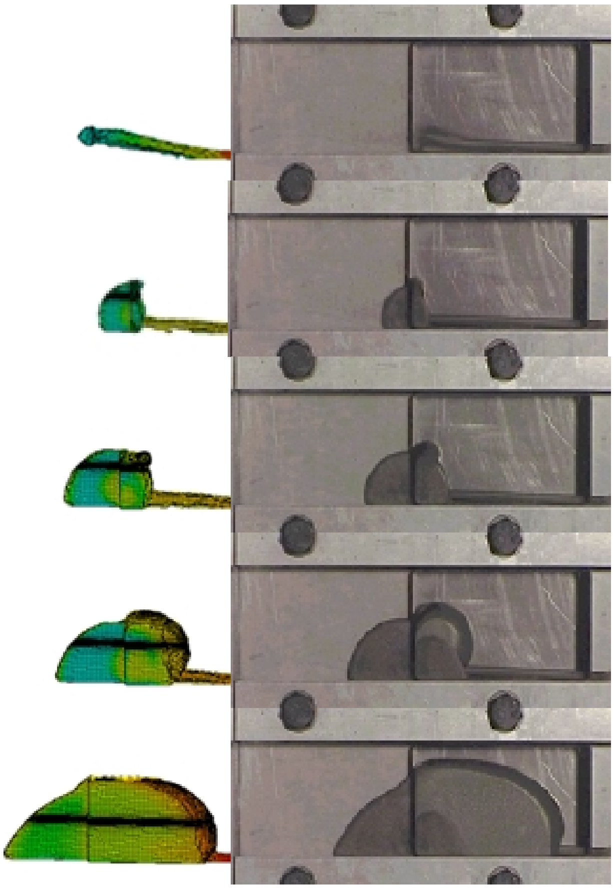


Figure 4: Comparison of the filling front predicted with Flow-3D and that recorded experimentally at t=0.08s, t=0.12s, t=0.20s, t=0.40s and t=1.04s

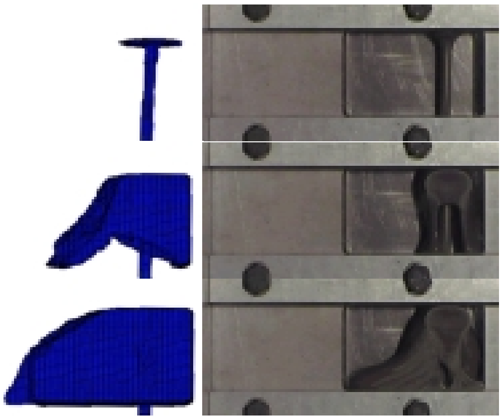


Figure 5: **Comparison of the filling front with Flow-3D and the recorded experimentally at t=0.8s, t=0.52s and t=1s**

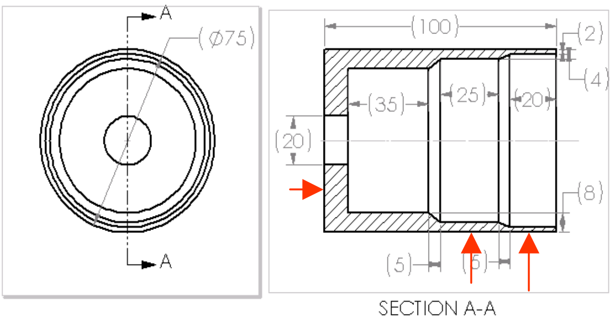
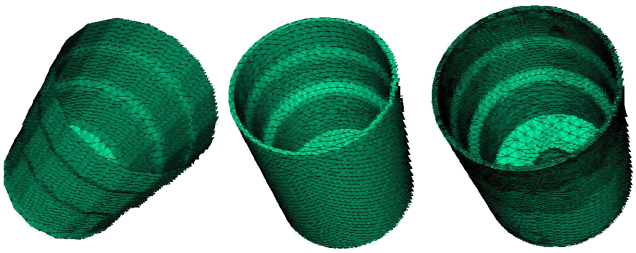


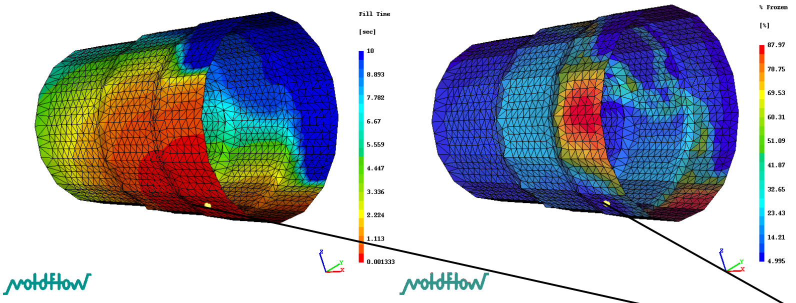
Figure 6: **CAD drawing of the stepped cylinder pattern**



(a) (b) (c)

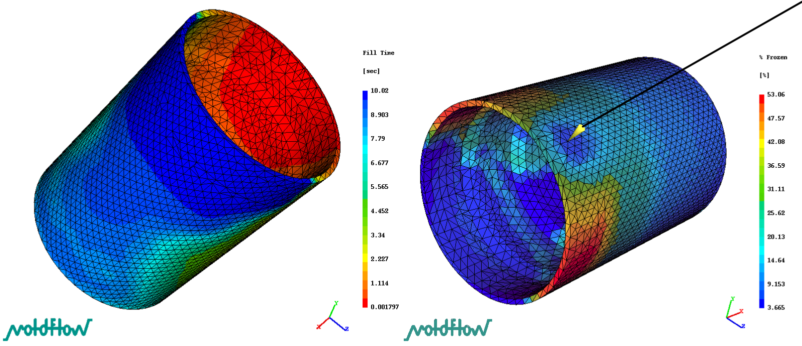
Figure 7: **Three kind of meshes. (a) midplane; (b) fusion; (c) 3D**

-midplane



-fusion

Injection point



Injection point

-3D

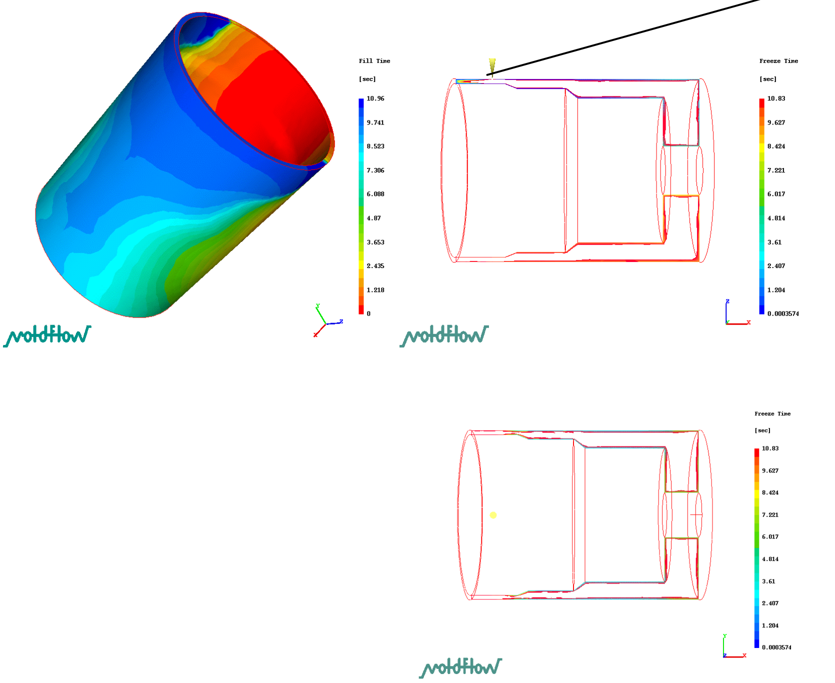


Figure 8: Filling time and solidified material for the first injection point with the 3 type of mesh. First column: Filling time/profile. Second column: %frozen/ freezing time

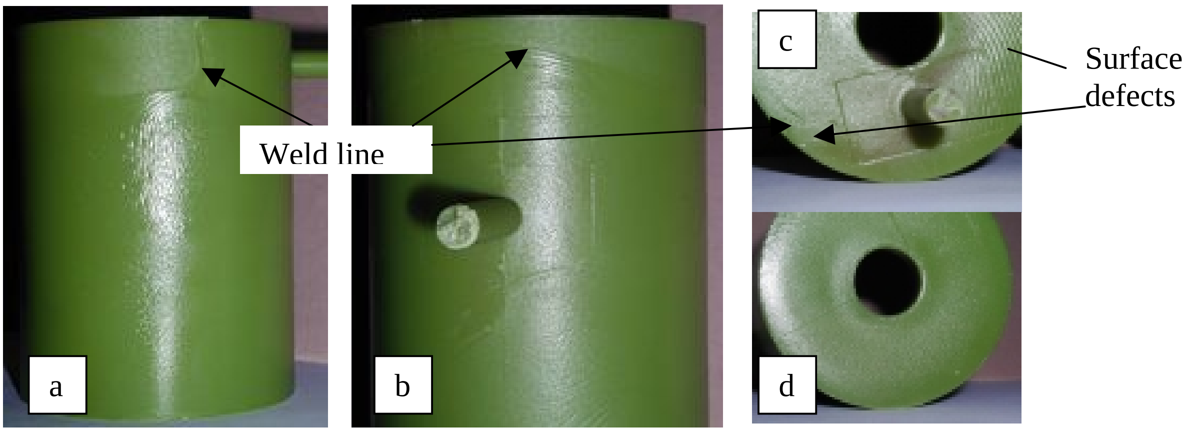


Figure 9: **Injected parts using the first injection point (a), the second injection point (b and d) and the third injection point (c)**

-midplane

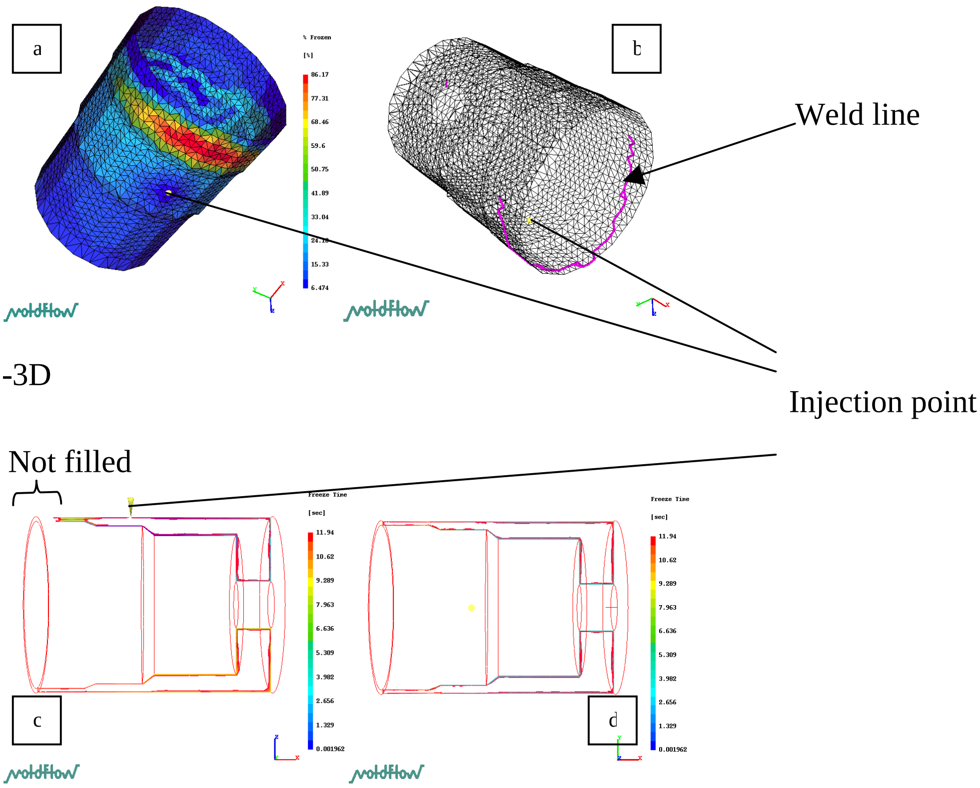


Figure 10: **Results for the second injection point with midplane and 3D meshes**

-fusion

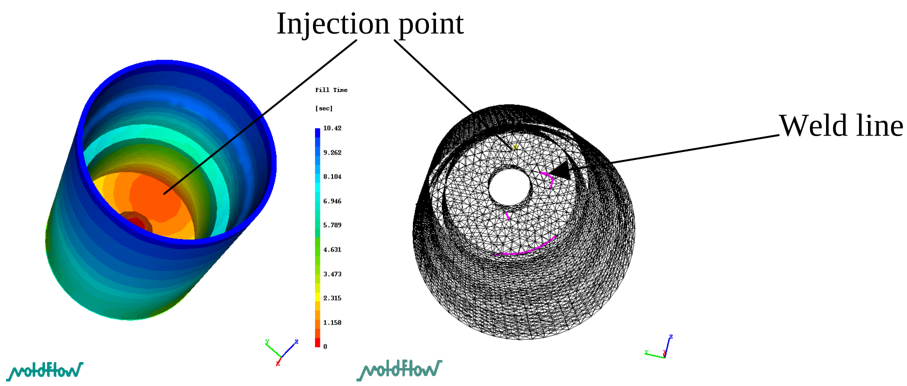


Figure 11: Results for the third injection point with fusion mesh

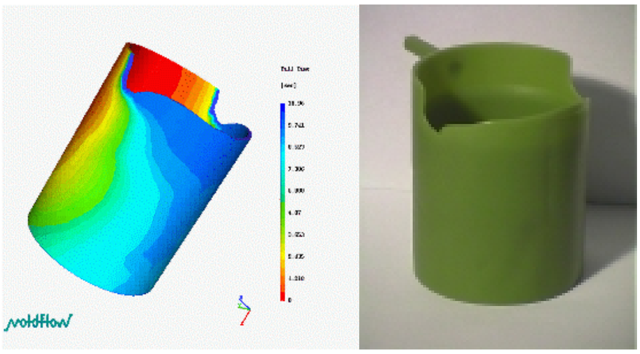


Figure 12: Interrupted filling experiment to determine the last section to be filled and comparison with MoldFlow results

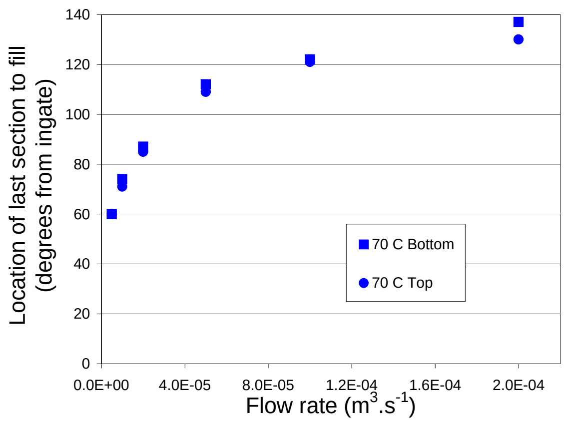


Figure 13: Experimental position of *weld lines*

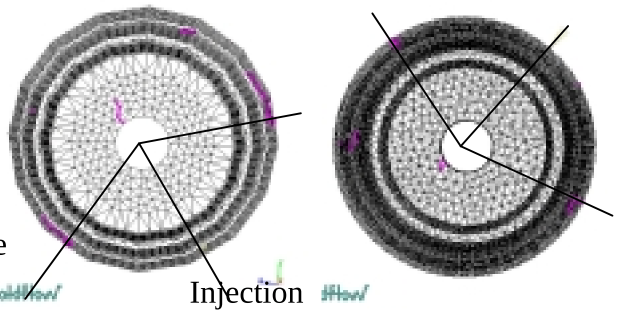


Figure 14: **Weld line location with midplane and fusion meshes for a flow rate of 10^{-5} $m^3.s^{-1}$ and a wax injection temperature of 70°C**

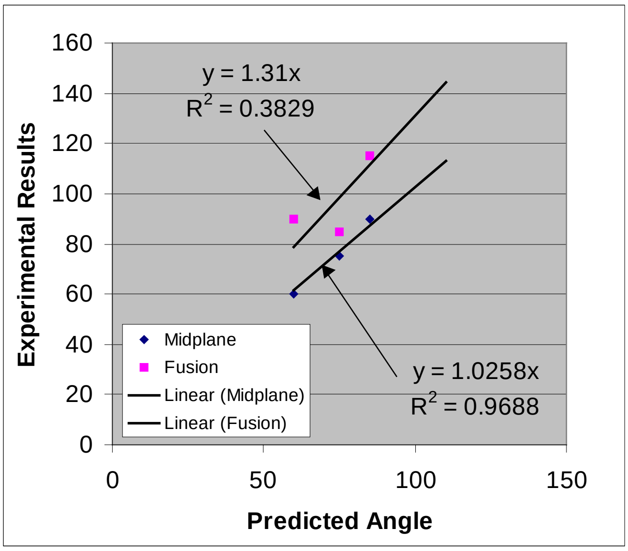


Figure 15: **Correlation between predicted and simulated weld line positions**

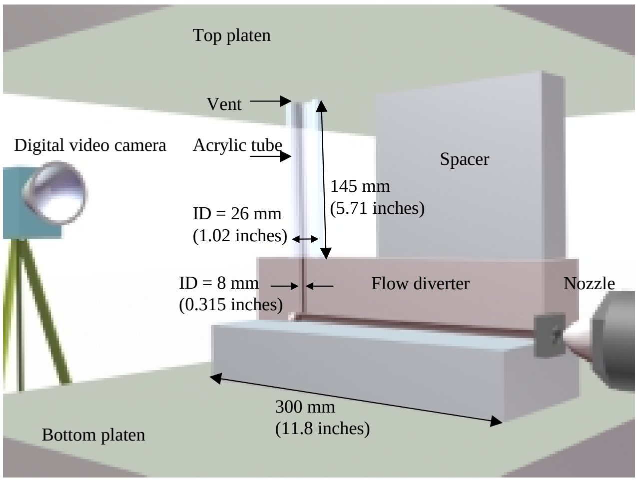


Figure 16: Schematic of the apparatus for the study of bubble formation

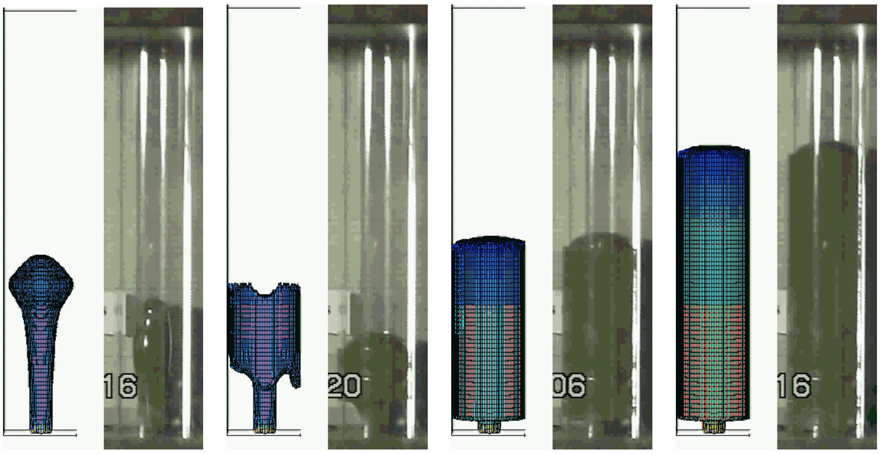


Figure 17: Comparison of experiments and simulation in the liquid state

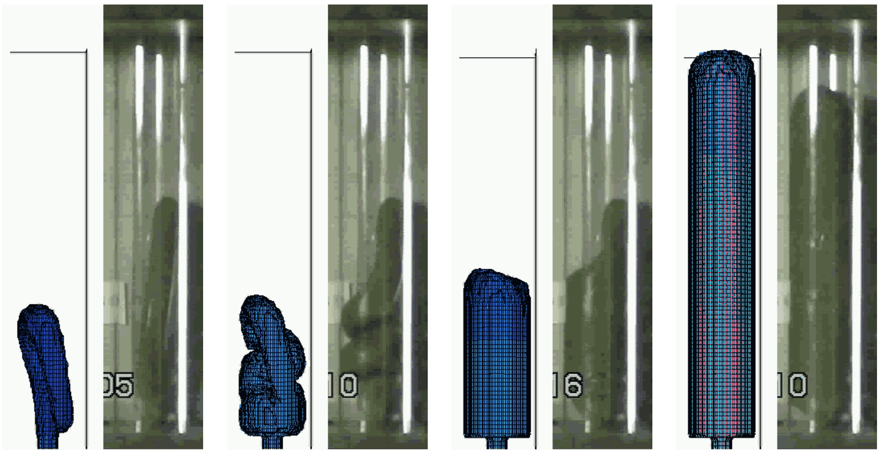


Figure 18: Comparison of experiments and simulation in the paste state