Final Report

On

Understanding the Relationship Between Filling Pattern and Part Quality in Die Casting

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Final Report: Understanding the Relationship Between Filling Pattern and Part Quality in Die Casting

1.0 Introduction

The overall objective of this research project was to investigate phenomena involved in the filling of die cavities with molten alloy in the cold chamber die-casting process. It has long been recognized that the filling pattern of molten metal entering a die cavity influences the quality of die-cast parts. Filling pattern may be described as the progression of molten metal filling the die cavity geometry as a function of time. The location, size and geometric configuration of points of metal entry (gates), as well as the geometry of the casting cavity itself, have great influence on filling patterns. Knowledge of the anticipated filling patterns in die-castings is important for designers. Locating gates to avoid undesirable flow patterns that may entrap air in the casting is critical to casting quality – as is locating vents to allow air to escape from the cavity (last places to fill). Casting quality attributes that are commonly flow related are non-fills, poor surface finish, internal porosity due to trapped air, cold shuts, cold laps, flow lines, casting skin de-lamination (flaking), and blistering during thermal treatment.

However, the relationship between fill parameters and part quality is not completely understood. Fill parameters typically include velocity of the molten alloy through the gate(s) at the start of cavity filling, molten alloy temperature, die temperature, time to fill the cavity, intensification pressure, and gate location, size and geometry. Based on previous research, the North American Die Casting Association (NADCA) has published guidelines for practitioners regarding the design of castings, metal entry systems, and die casting machine process parameters to minimize casting defects related to metal flow. It is commonly observed that die casters violate the North American Die Casting Association (NADCA) recommended fill parameters and still make saleable castings. Practitioners also observe that following the NADCA guidelines, at least as a starting point, is the best way to minimize the risks of flow related problems in production. Greater understanding of the apparent contradiction in these statements was the primary objective of the research.

The methods available for assessing filling patterns for high-pressure die-casting are rather limited because the process occurs in an optically opaque steel die. In this research, the water analog technique and computer simulation were employed to study filling patterns. Observation of filling patterns in sand, lost foam and permanent mold casting via radiography has also been reported [1][2][3]. In this project, work was also accomplished toward the goal of real-time radiographic observation of filling patterns in high-pressure die-casting. This goal was considerably more challenging in die-casting because of the short time (milliseconds) and high pressures involved.

This report summarizes project activities for the period of February 2000 through January 2003. Work during the project was focused on water analog testing, computer modeling, real-time radiographic testing, and corresponding casting trials. A summary of project observations, presentations, student participants, acknowledgements and references are also provided at the end of the report.

2.0 Water Analog Studies

2.1 Objectives

The water analog method involves the use of a high-speed camera to record water or low melting alloy flow in transparent dies. The water is typically colored using dyes to make the flow patterns easily visible. Room temperature water has pertinent fluid properties that are very similar to molten aluminum. The only significant difference is that the surface tension of water is much lower than molten aluminum, particularly molten aluminum having an oxide layer on free surfaces in contact with air. The water analog dies are usually machined from slabs of cast transparent polymethylmethacrylate (PMMA). Following machining, the PMMA dies are polished to remove machining marks to improve optical clarity. This method is especially useful in analyzing the direction and the path of the molten metal flow, location of porosity in the die casting cavity, and turbulence in the gating system. One drawback of the water analog approach is that it is isothermal, no heat is lost in the system and therefore no solidification or changes in viscosity occur as they would in a real die-casting operation. Also, because the transparent dies must be mechanically held together by some means during filling, the camera's view of the die is usually only from one direction – normal to the parting line opposite the shot sleeve. Therefore, only a 2-dimensional view of the filling pattern is possible.

The specific objective of this task was to investigate filling patterns of simple flat plate and complex flat plate geometries using the water analog test stand (figure 1) at The Ohio State University (OSU). These "flat" 2-dimensional geometries were chosen to minimize third dimension filling activity invisible to the camera. To investigate the effects of cavity geometry on filling patterns, two different geometries of rectangular cavity are employed for the model. One was simple rectangular flat plate cavity, 12.7cm x 17.8cm (or 5"x 7") with a chisel fan gate. The intermediate complexity cavity is the same sized flat plate, but has four ribs, 1.8cm x 6.4cm (or 0.7"x 2.5"). Two ribs are on the left wall at the bottom and the other two are on the right side of wall at the top inside the rectangular cavity. Figures 2a and 2b show exploded assembly diagrams of the transparent PMMA tooling used for the simple and complex flat plate geometries, respectively. Note that the tooling was constructed in segments such that various gate designs could be easily tested without manufacturing entirely new dies. Water analog experimental results were intended primarily as a baseline for subsequent comparison with computer numerical simulations of filling patterns of the same die geometries.

Prince Machine, Holland, MI, built the OSU test stand, which features a real-time closed-loop servo-valve controlled shot system. The test stand is controlled and monitored with a VisiTrak system. A high-speed camera, Kodak EKTAPRO 4540-HS Motion Analyzer was used to record the filling pattern images. The recording rate was up to 4500 frames per second.

2.2 Accomplishments

A variety of water analog tests were conducted using the two geometries, various gate velocities and pre-fill percentages. Pre-filling is a departure from NADCA recommendations that many die casters use successfully. NADCA recommends that the molten metal exit the gates at a minimum velocity (1187 in/sec for aluminum) to create atomized flow of the molten metal into the cavity.

Pre-filling involves partially filling the casting volume at a very low gate velocity, then quickly ramping up to high gate velocity to complete filling before the alloy solidifies. Figure 3 shows example filling pattern results for the simple and complex geometry dies.

Figure 1. Photograph of the Prince Water Analog System in the OSU lab.

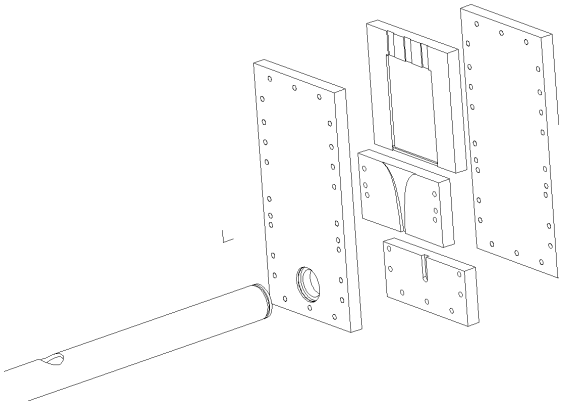


Figure 2a. Simple Complexity Die Assembly.

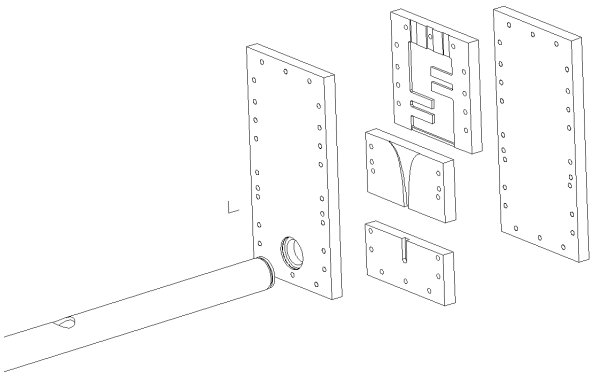


Figure 2b. Intermediate Complexity Die Assembly.

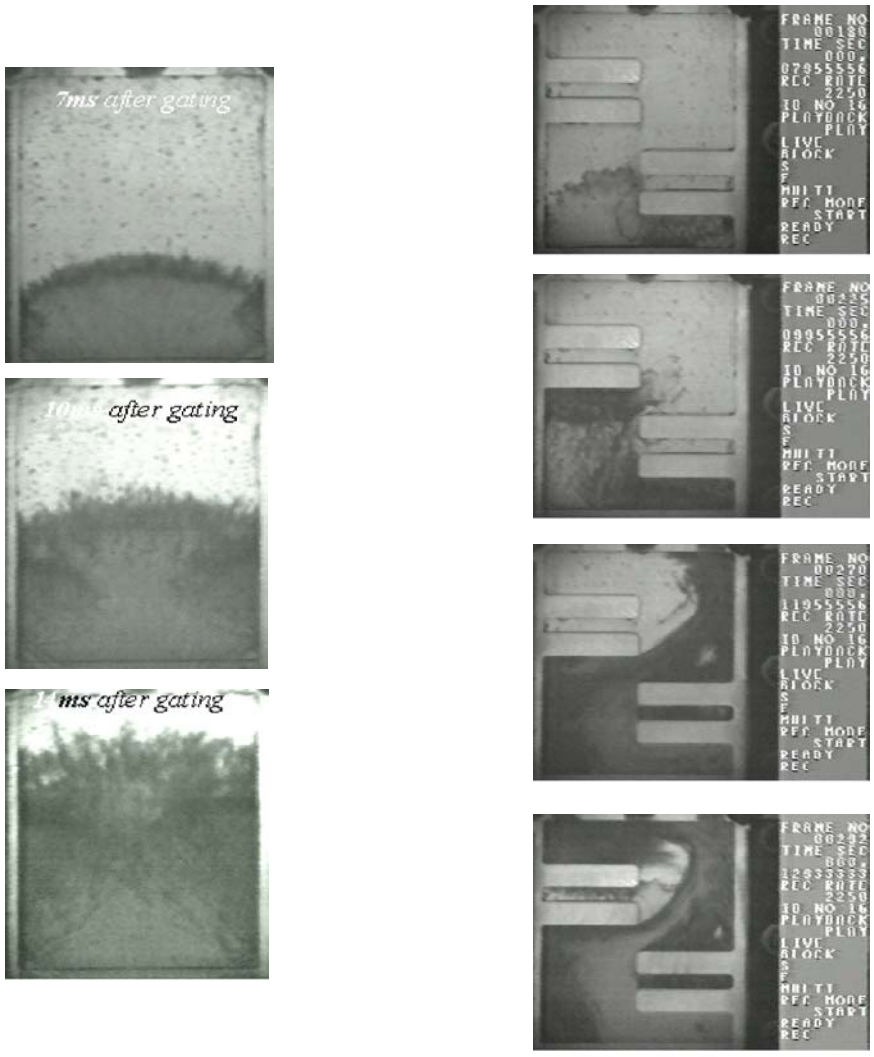


Figure 3. Example water analog filling patterns for simple (left) and intermediate complexity dies (right). Filling sequence progresses from the top images to the bottom.

For the simple complexity die cavity, the gate velocity was 1187 in/sec with no pre-fill. The images shown are from 7, 10 and 14 milliseconds after the water exited the gating. The filling conditions for the intermediate complexity die cavity shown were 20% cavity pre-fill (by volume) with a gate velocity of 292 in/sec, followed by 1132 in/sec fast shot velocity. The images shown are from 80, 100, 120 and 123 milliseconds after the water exited the gating.

Results of the water analog work demonstrated that pre-filling certainly does influence the fill pattern observed. The complex flat plate geometry showed a significant filling pattern improvement using various percentages of die cavity pre-fill. The simple geometry showed virtually no improvement in filling pattern using pre-fill. However, pre-fill is only a feasible option when the casting geometry is massive enough (thick wall sections) to allow longer total cavity filling times. Otherwise the molten alloy would solidify before the cavity could be filled.

In addition to general filling pattern, an important factor influencing the quality of die-cast parts is the character or flow regime of molten metal during cavity filling. NADCA recommends high velocity atomized flow at the gate because previous research has indicated that lower gate velocity causes "jetting" type flow (individual rivulets of aluminum) out of the gate. The surfaces of aluminum jets oxidize very rapidly and subsequently produce flow lines and seams in the casting that do not totally fuse together (cold flows). This degrades casting surface finish, mechanical properties, and also may cause castings that are supposed to be pressure tight, to leak. It should be noted that the gate velocity chosen for pre-filling is very low – closer to the laminar flow range, so jetting does not occur. The images of the simple flat plate in figure 3 were also chosen to illustrate that the atomized flow that NADCA recommends did not prevail for very long after the start of cavity filling. As shown, just 7 milliseconds into cavity filling in the simple flat plate geometry, the flow exiting the gate is no longer atomized (top left photo in figure 3). The free fluid front moving up the cavity is actually quite coherent (contiguous). It can be concluded that impediments from die wall friction, back-pressure from air in the cavity, and interaction with the molten metal which has already entered the cavity influence the flow regime at the gate, and throughout the cavity, as a function of time.

3.0 Computer Modeling

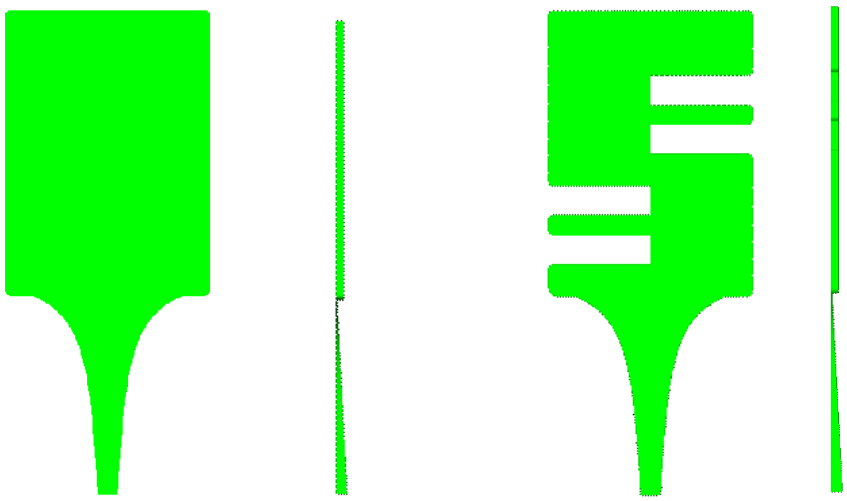
3.1 Objective

The primary objective of this task was to conduct computer simulations of filling patterns for the simple and complex flat plate geometries using commercially available software. The computer simulations were generated to compare with water analog simulation fill patterns and with the fill patterns from radiographic experiments. This exercise could be considered as direct validation of the computer simulation approach. More importantly, it provided some additional information regarding how computer simulation can be more effectively used as an engineering tool.

The software employed for filling pattern simulations in this project and the persons or companies that performed the simulations are shown in table 1. Both the simple complexity and intermediate complexity geometry were evaluated. The dimensions of the simple and complex part geometry, the vents, gate, and runner systems were consistent with the manufactured transparent dies used in the water analog experiments. The parametric solid models for both parts and the gating systems were constructed in Unigraphics™ as shown in Figure 4. The parametric solid models were then exported from Unigraphics™ as STL models and loaded into the simulation software packages.

Table 1. Commercially Available Software Used For Filling Pattern Analyses

Software	Method	Simulations performed by:
CastView	Qualitative Reasoning	Haijing Mao, OSU
MAGMASOFT™	Finite Difference	Haijing Mao, OSU
NovaCast™	Finite Difference	Walkington Engineering
Flow3D™	Finite Difference	Amcan Castings Ltd., and Haijing Mao, OSU
dieCAS™	Finite Element	Technalysis® Inc.



(a) (b)

Figure 4. Parametric solid models: a) simple complexity part front view and side view, and b) intermediate complexity part front view and side view.

3.2 CastView

CastView is a design visualization tool that presents die-casting specific information in 3-dimensional graphical form. CastView provides a very fast analysis of die-casting part designs without the need for extensive input data or significant experience with computer simulation or computer-aided engineering. The primary advantage of CastView is that it requires virtually no setup and provides results very quickly. However, in contrast to quantitative reasoning or numerical calculation of the quantities (temperature, pressure, etc) of the die-casting process, CastView uses geometric reasoning methods and general, broad principles to establish patterns. CastView generated fill patterns strive to have the qualities (general order, sequence) of casting phenomena, but not the precision of the corresponding numerical quantities. Thus, CastView can be used as an effective screening system for future numerical analysis.

The results for the simple complexity part are displayed in figure 5; the initial, middle and final stages of filling are shown. Figure 6 shows the filling sequences for the intermediate complexity flat plate. The CastView filling pattern is a visualization of the qualitative filling pattern, accounting for the obstructions to the flow of the fill path. Flow in high-pressure die-casting is governed predominantly by inertial flow. This means that the material tends to move at high rates in a direction initially determined by the gate. Once obstructions are met, the pattern is altered by reflection off the obstacle. The filling pattern produced by CastView is calculated by geometrically mimicking these conditions. As shown in the figures 5 and 6, flow is initialized in the runner and continues straight in this direction until an obstruction is met. Flow is then deflected and begins to fill the other parts of the die cavity geometry.

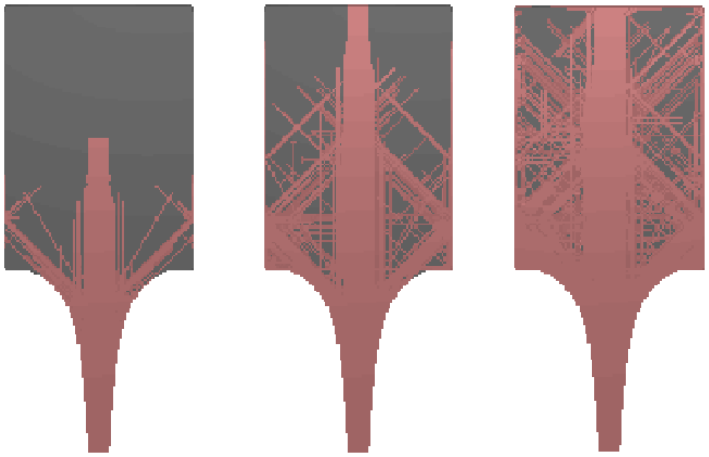


Figure 5. Simple part filling sequence using CastView.

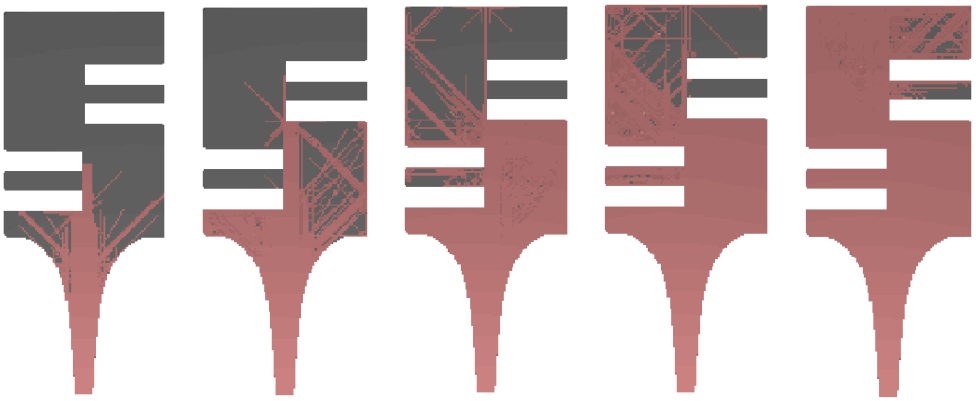
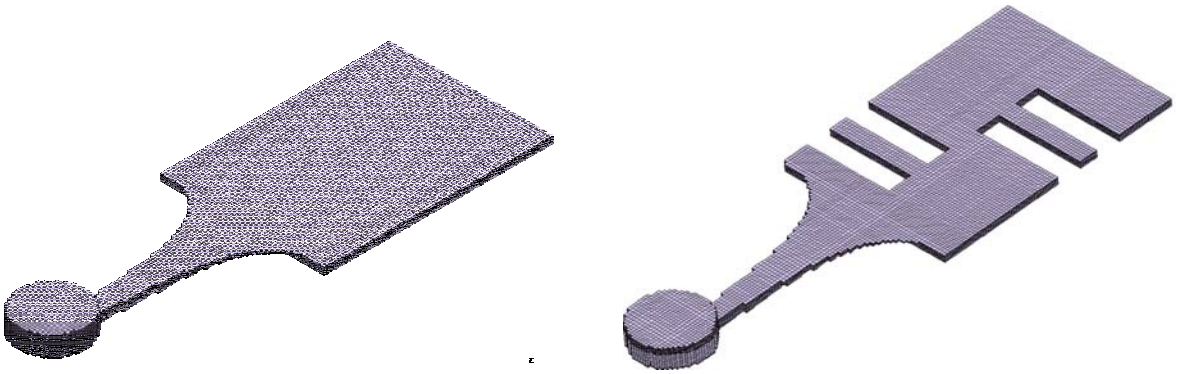


Figure 6. Intermediate part filling sequence using CastView.

3.3 MAGMASOFT™

MAGMASOFT™ is a Finite Difference Method (FDM) numerical simulation program. The filling pattern and heat loss in the casting can be simulated. The filling pattern of the cavity can be considered initially, followed by simulation of cooling and solidification of the melt and the residual stresses in the part.

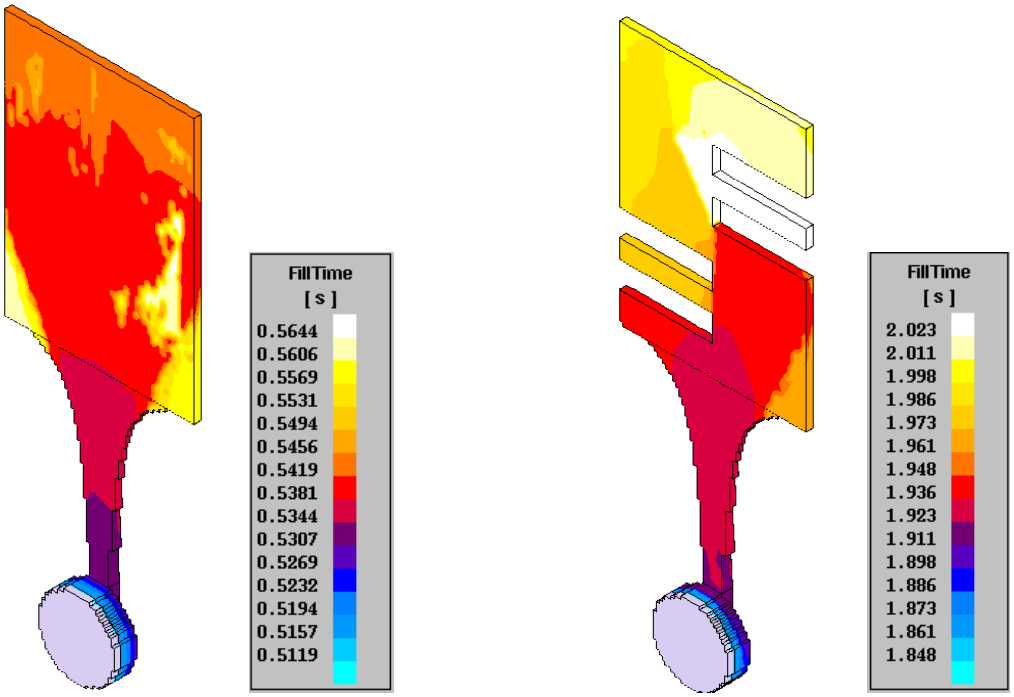
STL models were imported into MAGMASOFT™ and then meshed using the standard mesh generator in the MAGMASOFT™ simulation module. The meshed models (of the part geometry only) are shown in Figure 7. A common zinc alloy, Zamak™ 5 was selected as the molten alloy for these simulations in preparation for comparison with radiographic filling pattern experiments where both lead and zinc alloys would be involved. The die material in this simulation was aluminum with an initial die temperature of 250°C with a molten alloy temperature of 420°C. The total gate area was 0.942cm^2 (0.146in^2) and gate velocities of 10m/s (380in/s), 19m/s (760in/s), and the NADCA recommendation for zinc alloys of 40m/s (1600in/s) were simulated.



(a) (b)

Figure 7. Meshed MAGMASOFT™ model: (a) simple part, (b) intermediate part.

Figure 9 shows filling pattern via fill time maps for the simple and complex geometry flat plates. The filling time shown in the figure here is not the absolute filling time, but rather a relative filling time for the sequence.



(a) (b)

Figure 9. MAGMASOFT™ filling time simulation: (a) simple part, (b) intermediate part.

Several fill parameters, such as gate velocity, absence or presence of vents, die temperature, and gravity effects were studied to learn how the filling pattern was affected. It was found that the filling pattern was more sensitive to gate velocity and venting than any of the other parameters.

3.4 NovaCast™

Using the same solid model constructed at OSU, Walkington Engineering provided NovaCast™ simulation results (figures 10 and 11) for Zamak™ 5 alloy in an aluminum die. The three ribs at the top of both casting geometries were designed as vents, which are simulated as part of the casting here. They were not included in the CastView and MAGMASOFT™ simulations. The color scale represents the alloy velocity ranges. The general methodology for NovaCast™ is FDM. It also captured the filling details and clearly demonstrated the back filling, which is in agreement with MAGMASOFT™ results. Also, the last place being filled is in consistent with MAGMASOFT™ results.

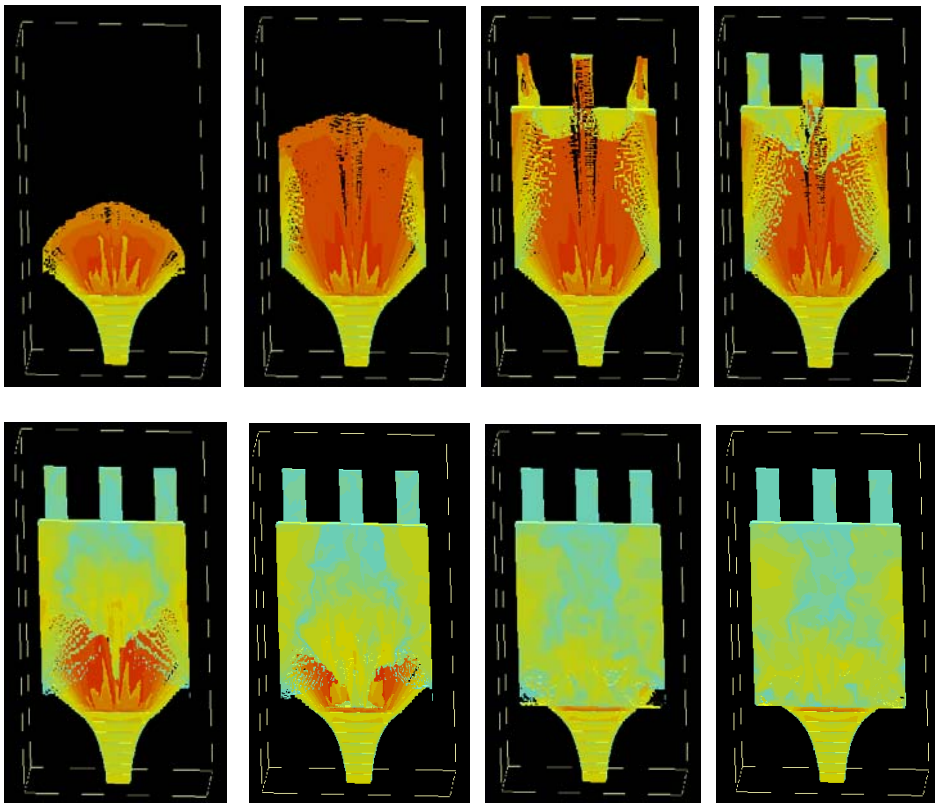


Figure 10. Simple part filling steps simulated by NovaCast™.

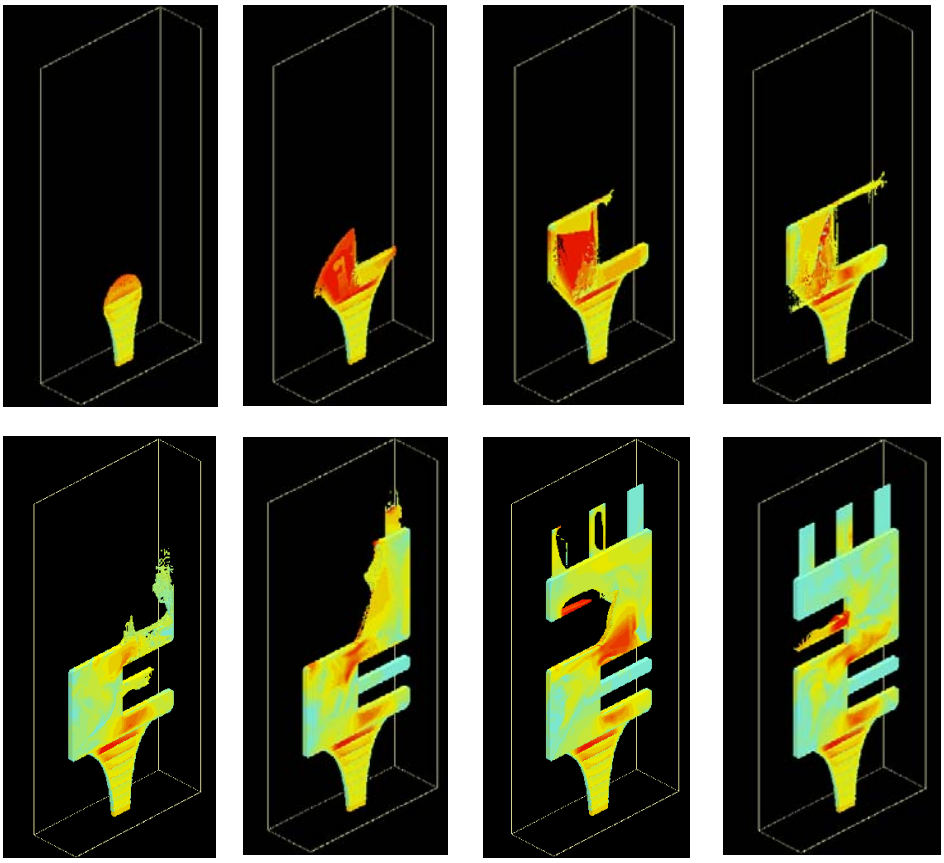


Figure 11. Intermediate part filling steps simulated by NovaCast™.

3.5 Flow3D™

The general methodology employed by Flow3D™ is FDM. The first simulations conducted with Flow3D™ were done to compare directly with the water analog simulation results. An example comparison of filling pattern results for the simple geometry flat plate geometry from water analog simulation and Flow3D™ computer simulation for aluminum alloy in a steel die is shown in figure 12.

A second set of Flow3D™ simulations were conducted using the same solid models to simulate the die-casting of Zamak™ 5 alloy in an aluminum die for the radiographic filling pattern experiments. The die material was modeled as AlSi9Cu3 alloy and the heat transfer coefficient used was supplied by the Flow3D™ database. The flow was modeled as a k-e turbulent model with adiabatic bubbles to simulate the back-pressure effect from die cavity air. No solidification during filling was considered in the flow model simulation. In other words, no change in viscosity of the alloy was recognized even if the temperature dropped below liquidus for the alloy. Figures 13 and 14 illustrate the filling pattern sequence for the simple flat plate and complex flat plate geometry, respectively.

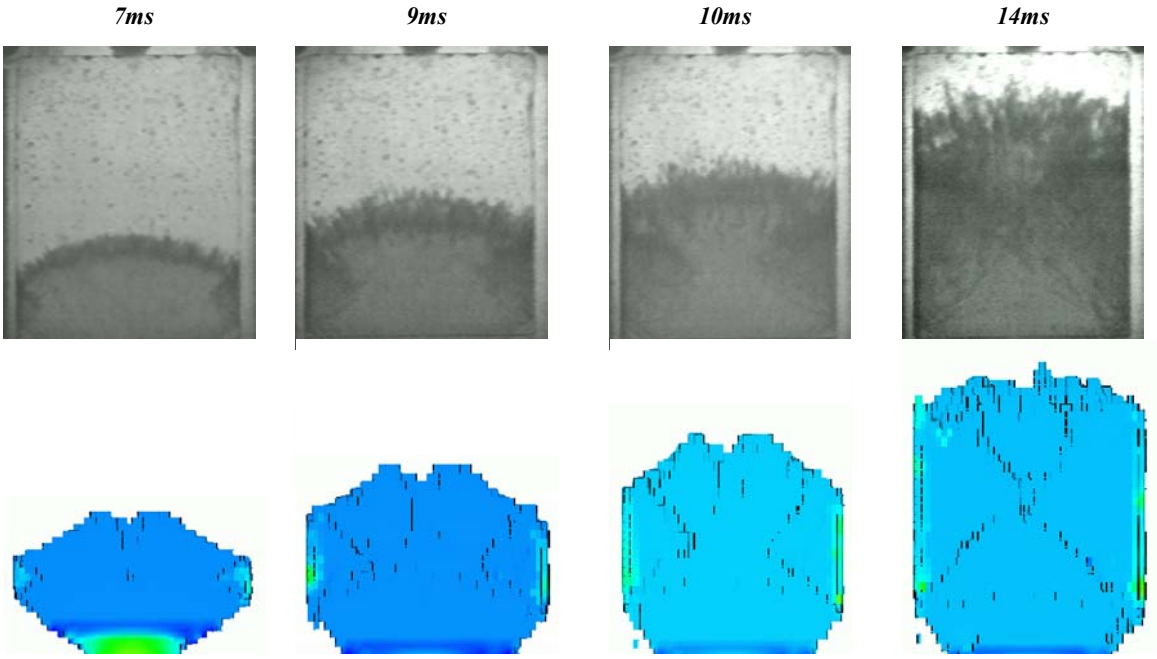


Figure 12. Comparison of water analog and Flow3D simulations for aluminum die casting, no pre-fill, gate velocity of 1187 in/sec, at 7, 9, 10, and 14 milliseconds.

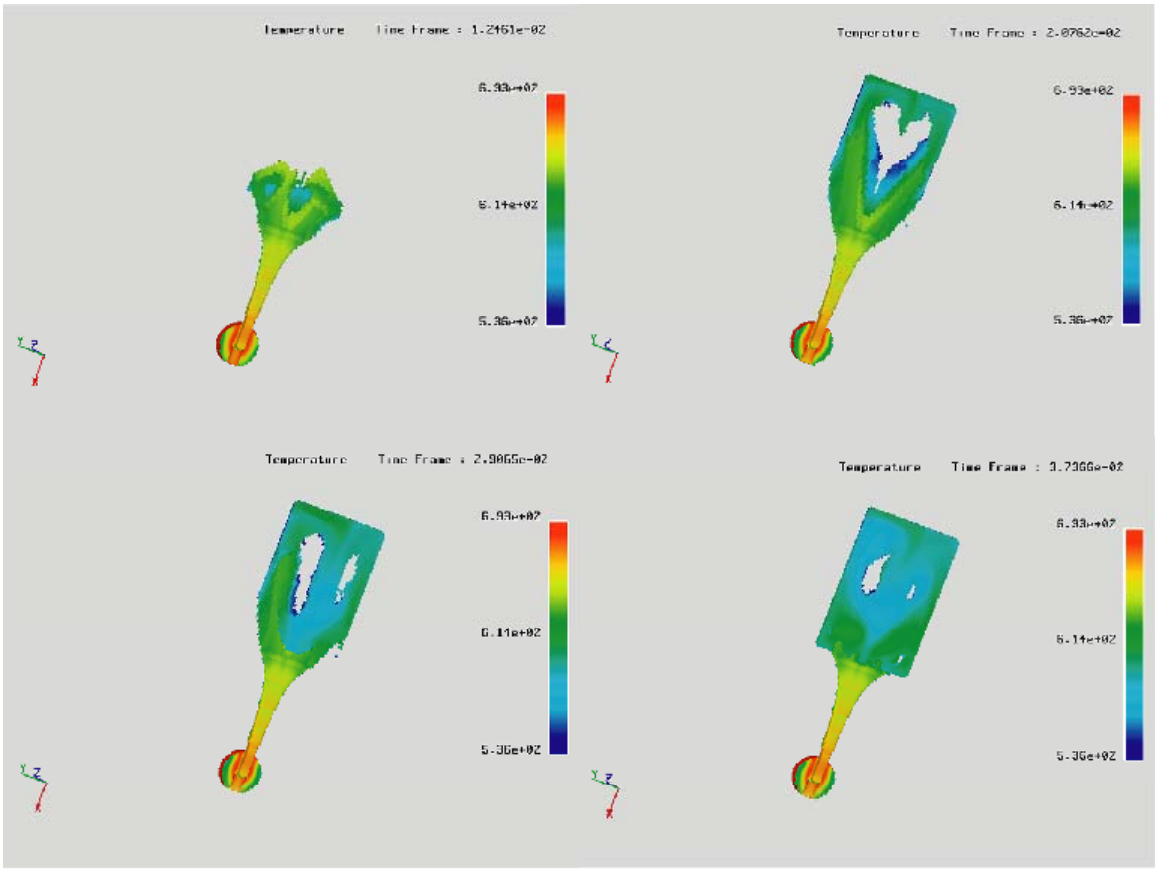


Figure 13. Simple part filling Steps simulated by Flow3D™.

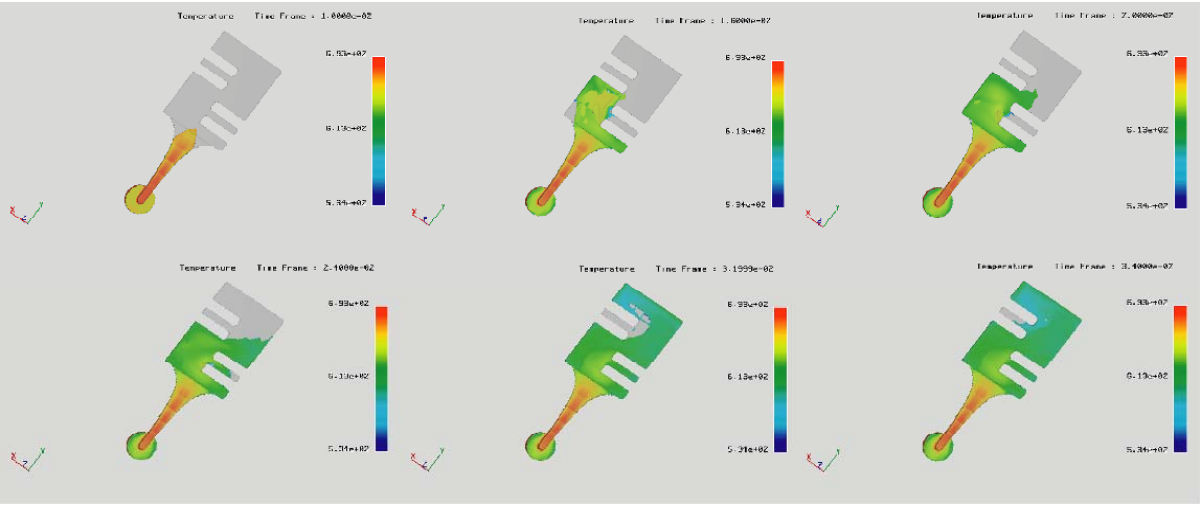


Figure 14. Intermediate complexity cavity filling steps simulated by Flow3D™.

3.6 dieCAS™

The dieCAS™ software is based on the Finite Element Method and the simulations were conducted by Technalysis®. Three cases were simulated for the simple flat plate as shown in table 2. The term "Two Shot" indicates that a pre-fill approach to filling was used. Table 3 shows the process parameters used for the Case 1 simulation. Figure 15 shows the results.

Table 2. Summary of Simulations Conducted on the Simple Flat Plate

	Shot Profile	Back Pressure
Case 1	Two Shot	Atmospheric
Case 2	Two Shot	Atmospheric
Case 3	Two Shot	Atmospheric

Table 3. Summary of Process Parameters for Simple Geometry Case 1

Tip Diameter : 2 in
Dwell Time : 5 sec
Cycle Time : 53 sec
Metal Temperature in Sleeve : 724 ^{o}F

Shot Profile

Stage	Position (in)	Speed (ips)	Transition Time (sec)
1 (Slow Shot)	0	27.559	0
2 (Fast Shot)	14.917	74.803	0

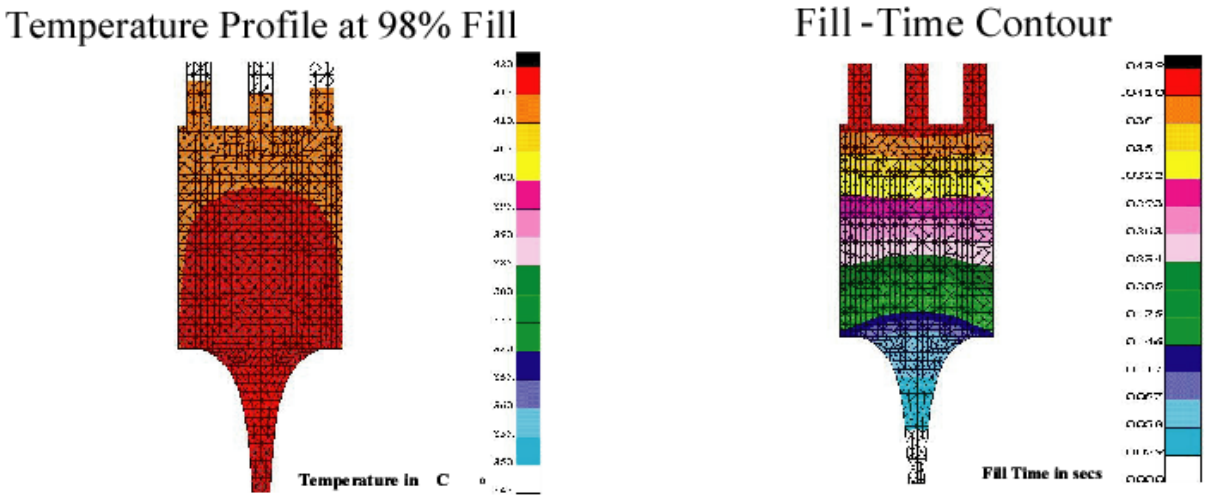


Figure 15. Temperature profile map at the end of filling (left) and fill-time contour map (right) for the simple flat plate geometry.

Table 4 shows a summary of simulations accomplished using dieCAS™ software for the intermediate complexity flat plate geometry. Table 5 shows the process parameters used for the Case 1 simulation shown in table 4. Figure 16 shows the results of the Case 1 intermediate complexity geometry simulation.

Table 4. Summary of Simulations Conducted on the Intermediate Complexity Flat Plate

	Shot Profile	Back Pressure
Case 1	Two Shot	Atmospheric
Case 2	Two Shot	Atmospheric
Case 3	Two Shot	Atmospheric
Case 4	One Shot	Atmospheric
Case 5	One Shot	Atmospheric
Case 6	One Shot	Atmospheric
Case 7	Two Shot	Vacuum
Case 8	Two Shot	Vacuum
Case 9	Two Shot	Vacuum

Table 5. Summary of Process Parameters for Complex Geometry Case 1

Tip Diameter : 2 in
Dwell Time : 5 sec
Cycle Time : 53 sec
Metal Temperature in Sleeve : 724 ^{o}F

Shot Profile

Stage	Position (in)	Speed (ips)	Transition Time (sec)
1 (Slow Shot)	0	27.559	0
2 (Fast Shot)	15.31	74.803	0

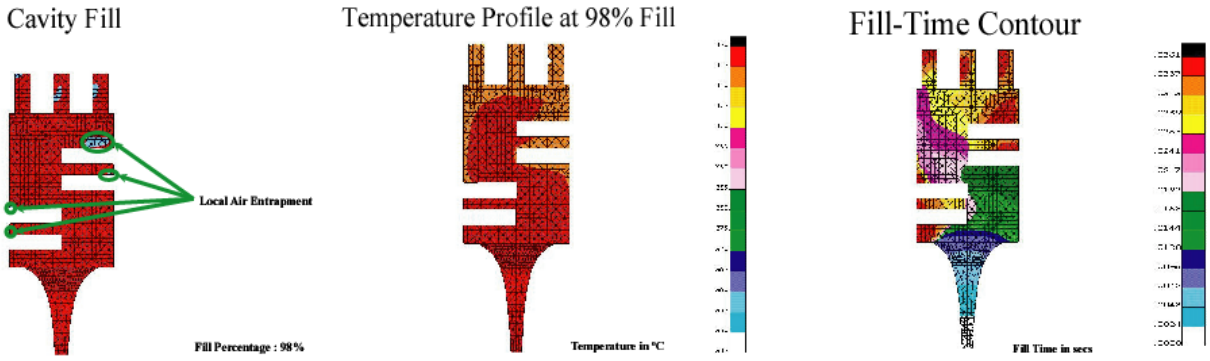


Figure 16. Local air entrapment shown at end of cavity filling (left), temperature profile map at the end of filling (center), and fill-time contour map (right) for the intermediate complexity flat plate geometry.

3.7 MAGMASOFT™ Industry Partner Casting Simulations

In addition to the MAGMASOFT™ simulations of filling patterns for the experimental flat plates, another group of simulations was conducted for a test specimen die used for casting a uniaxial tensile test specimen and 2 tensile fatigue test specimens in aluminum for an industry partner. Figure 17 shows the test bar casting geometry which was created using commercially available CAD software Unigraphics™. The simulations shown in figure 18 clearly predicted local air entrapment and flow path problems in several locations on the test specimens. Die-castings were produced using the test bar die in the 250 ton Buhler die casting machine at OSU during the summer of 2001. Radiographic inspections and microstructural analyses were conducted on the die-cast test specimens. Gas porosity and cold flow defects were discovered in a high percentage of the castings in the same locations predicted by computer simulation (figure 19).

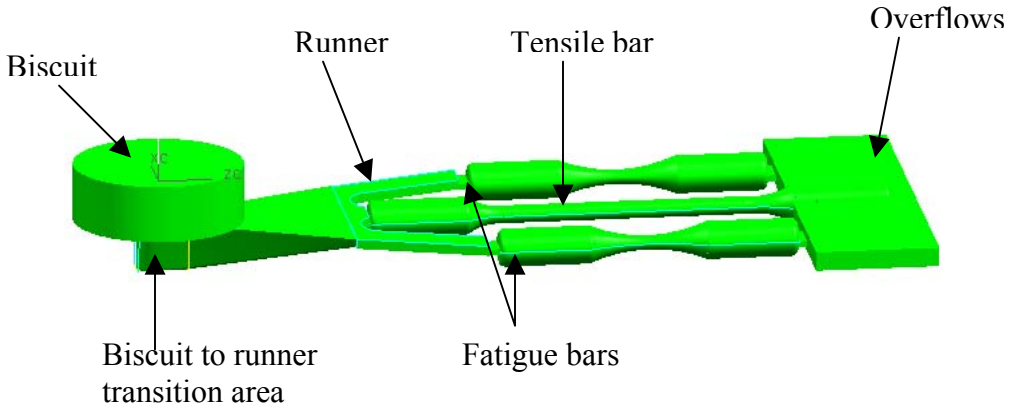


Figure 17. Configuration of the tensile and fatigue test specimen casting geometry.

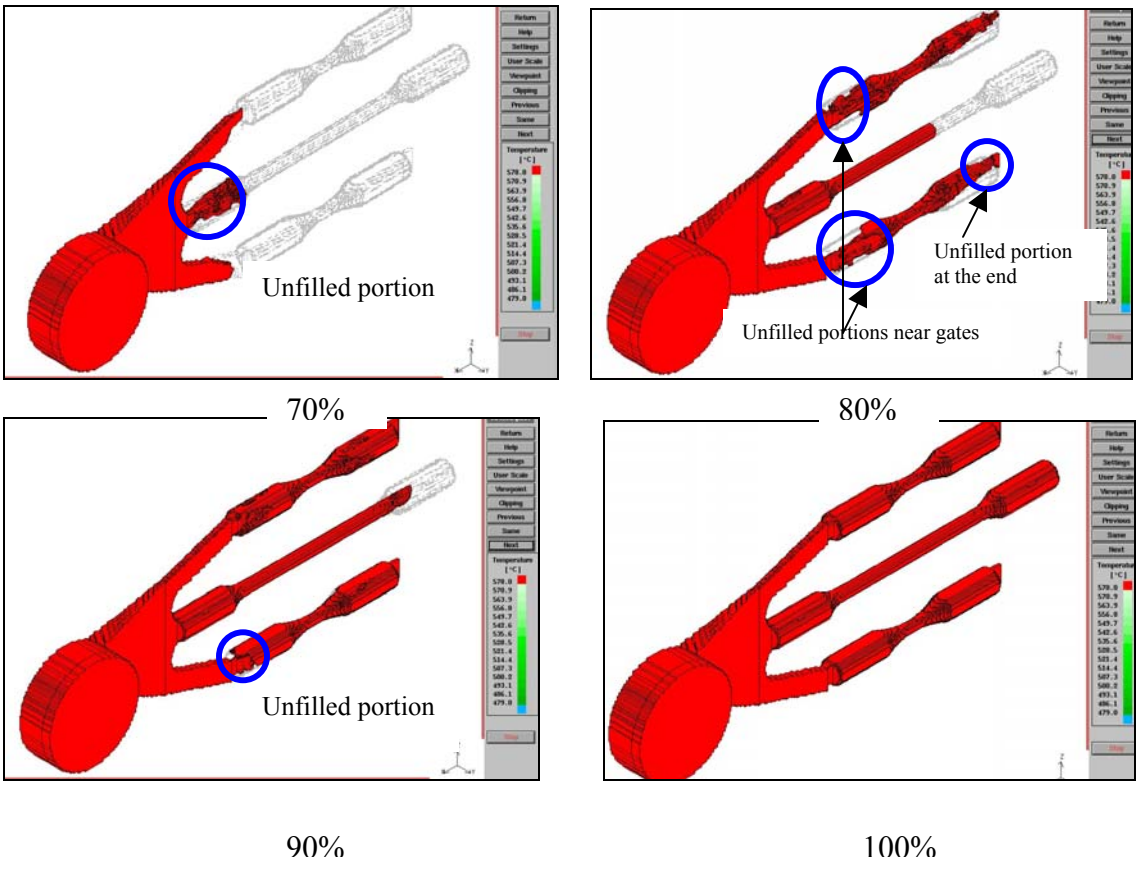


Figure 18. Filling pattern of original geometric configuration at various fill percentages showing areas where flow related problems would be expected in the actual castings.

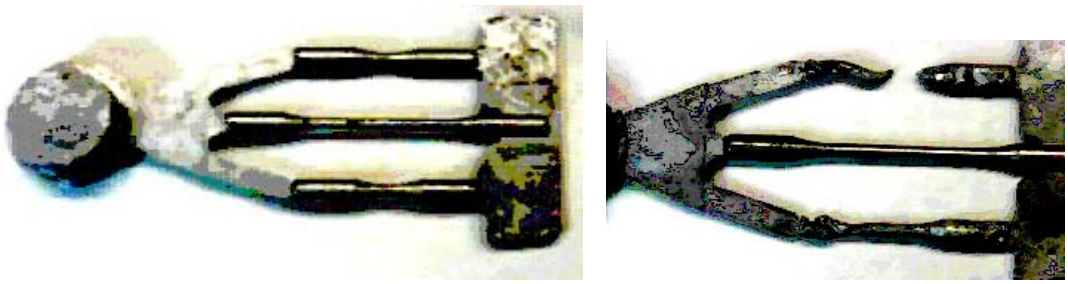


Figure 19. On the left is a photograph of a completely filled aluminum test bar casting which when inspected via radiography showed gross trapped gas porosity in the grip ends of both fatigue test bars. On the right is a casting showing severe flow related problems, accentuating the poor filling conditions existing in the fatigue test bars.

Modifications to the ingate geometry on the fatigue bars were made and new simulations were conducted. The depth of the gates was increased along with the addition of side gates on the fatigue specimens. Figure 20 shows the simulation of die cavity filling pattern for the modified geometry. Results indicate a much improved filling pattern and the tooling ingate geometry is currently being changed.

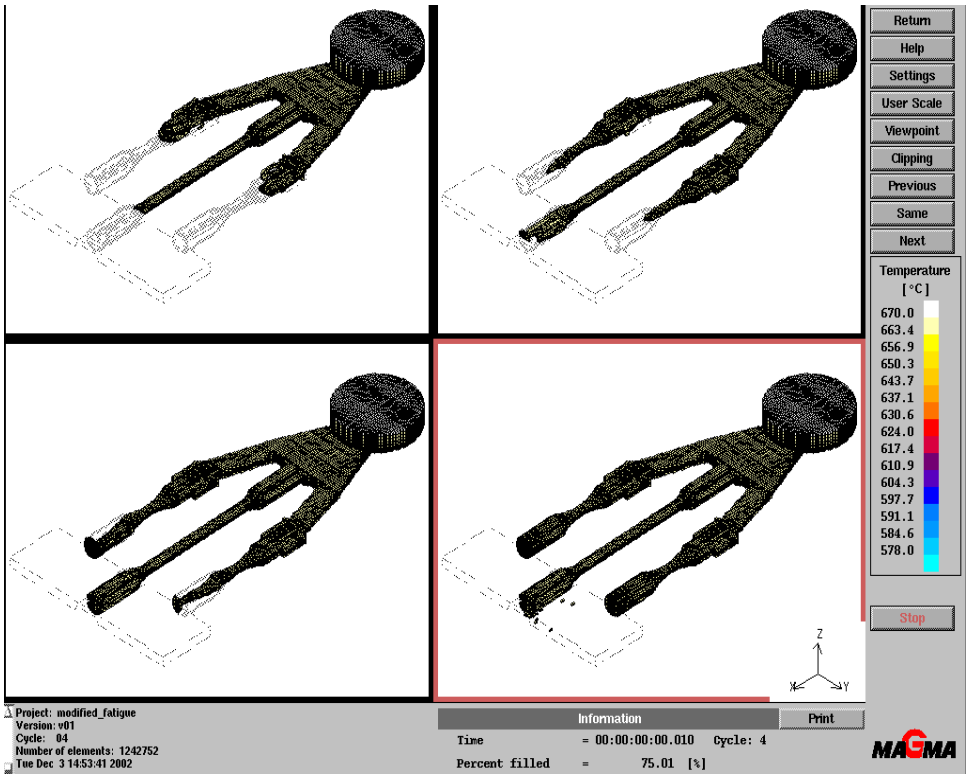


Figure 20: Filling pattern for modified fatigue specimen ingates.

4.0 Radiographic Testing

4.1 Objective

The objective of this task was to design and build an experimental apparatus suitable for real-time radiography experiments to observe die cavity filling patterns and molten metal flow regime from the point of exiting the gate. Information about flow regime at the gate as a function of gate velocity and time during cavity filling could be very useful for die-casters. Comparison with computer and water analog simulation results was also an objective. Another objective was the identification of important parameters and limitations for real-time radiographic evaluation of cavity fill patterns in die-casting.

The X-ray tube is the heart of any radiographic testing system. A low voltage power supply is use to heat a filament. This process frees electrons from the filament causing them to gather in a "cloud" in the vicinity near the filament. Next a large voltage potential (known as the tube voltage) is applied between the filament and a target. This potential causes the free electrons near the filament to accelerate toward the target. Upon impact the electrons interact with the target material (tungsten) causing X-rays to be emitted. Due to the angled nature of the target the energy involved in the whole process is redirected at a right angle and out of the tube through the tube window. This X-ray beam can then be used for experimental purposes. This process utilizes the basic X-ray tube described above combined with a real-time display unit and a high-speed video camera. The display unit is an image intensifier consisting of a phosphor screen, electron lenses, and an output window. In this process the X-rays strike the phosphor screen liberating electrons that travel to the output window while being focused by the electron lenses. At this point an image is displayed on the output window of the intensifier tube. The high-speed video camera is then utilized to film the results as they are displayed in real time on the display window. After a tape has been made it can be reviewed at slow speeds and the filling process can then be qualitatively analyzed. A basic block diagram of the system is presented in figure 17.

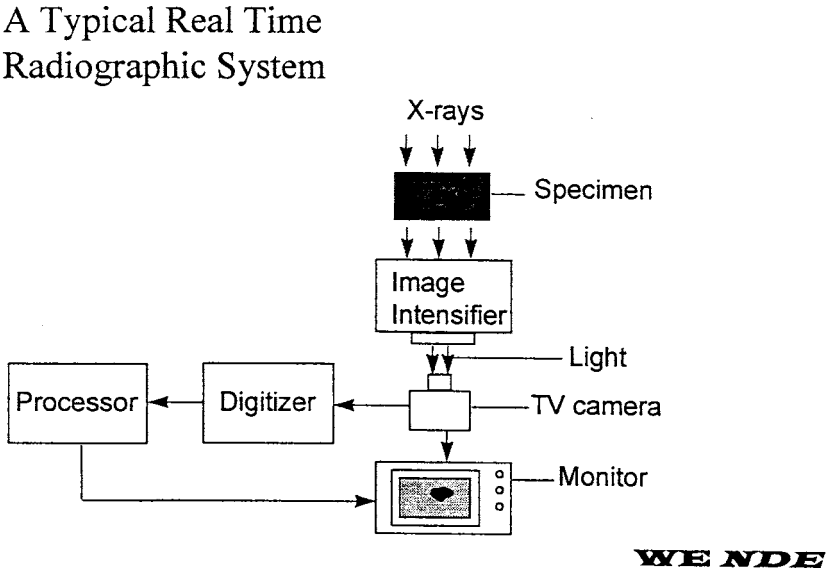


Figure 17. Real-time radiography system diagram.

The feasibility of the system with respect to the speed involved was evaluated. In general the die casting process occurs at speeds in the order of 30 milliseconds. At these speeds issues of resolution and response time of the system become very important. Static radiographic testing results were very promising. Several samples of both lead and zinc target material demonstrated excellent visibility through various thickness of simulated aluminum die material (figure 18). The target materials even showed good results when tested using steel die materials.

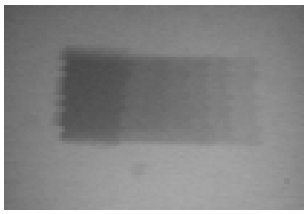


Figure 18a. 0.002”- 0.020” Pb target seen through 4” of Al

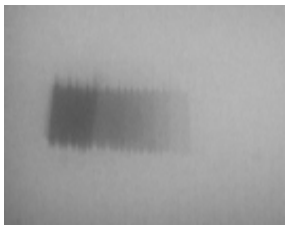


Figure 18b. 0.002”-0.020” Pb target seen through 1” of steel

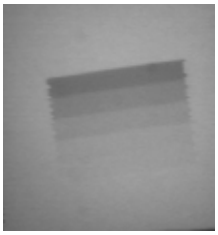


Figure 18c. 0.012”- 0.202” Zn target seen through 4” of Al

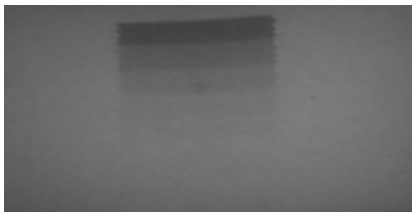


Figure 18d. 0.012”- 0.202” Zn target seen through 1” of steel

Dynamic experiments indicated that droplets (at least as small as 0.02 inches diameter) of Pb or Zn moving at typical die-casting gate velocities could be resolved through aluminum dies with the OSU real-time radiography system. Figure 19 shows a photograph of the dynamic testing apparatus used in the OSU laboratory. An electric motor was used to spin step blocks of Pb and Zn through the x-ray beam at various velocities in the die-casting range. Figure 20 shows the results of the dynamic real-time radiographic experiments. The Pb sample step block can clearly be observed through 2 inches of aluminum with a resolution of 0.4 milliseconds. Likewise, the zinc can be seen easily at 1.3 milliseconds and with some difficulty at 0.4 milliseconds. Based on the static and dynamic radiographic test results, an aluminum die was chosen for use with both Pb and Zn casting alloys. Schematics of the injection system and related equipment for the real time experiments are shown in figures 21 and 22.

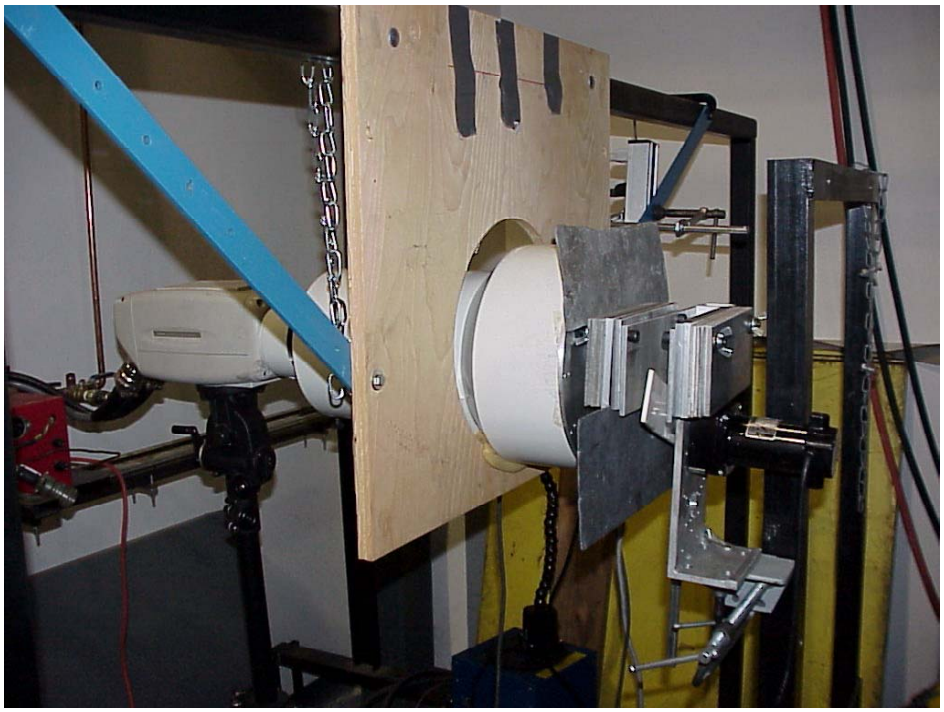


Figure 19. Photograph showing the experimental set-up for dynamic real-time radiographic analysis in the OSU laboratory.

Pb @ 750f/s = 1.3ms

Zn @ 750f/s = 1.3ms

Pb @ 2250f/s = 0.4ms

Zn @ 2250f/s = 0.4ms

Figure 20. Experimental results for the dynamic real-time radiography tests.

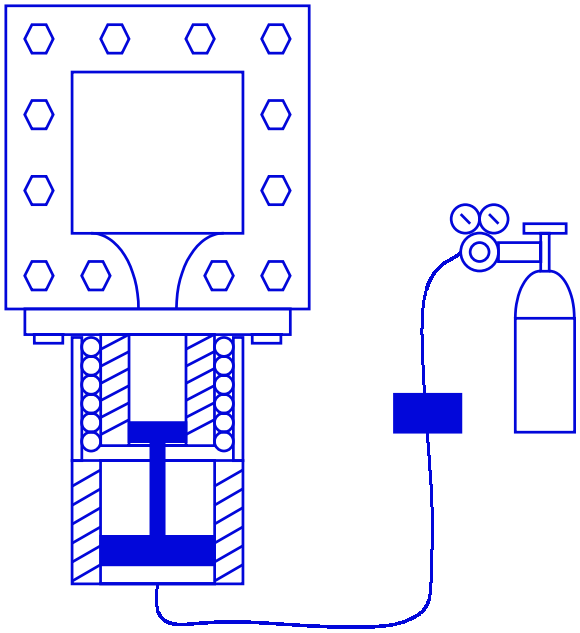


Figure 21. Injection system design schematic.

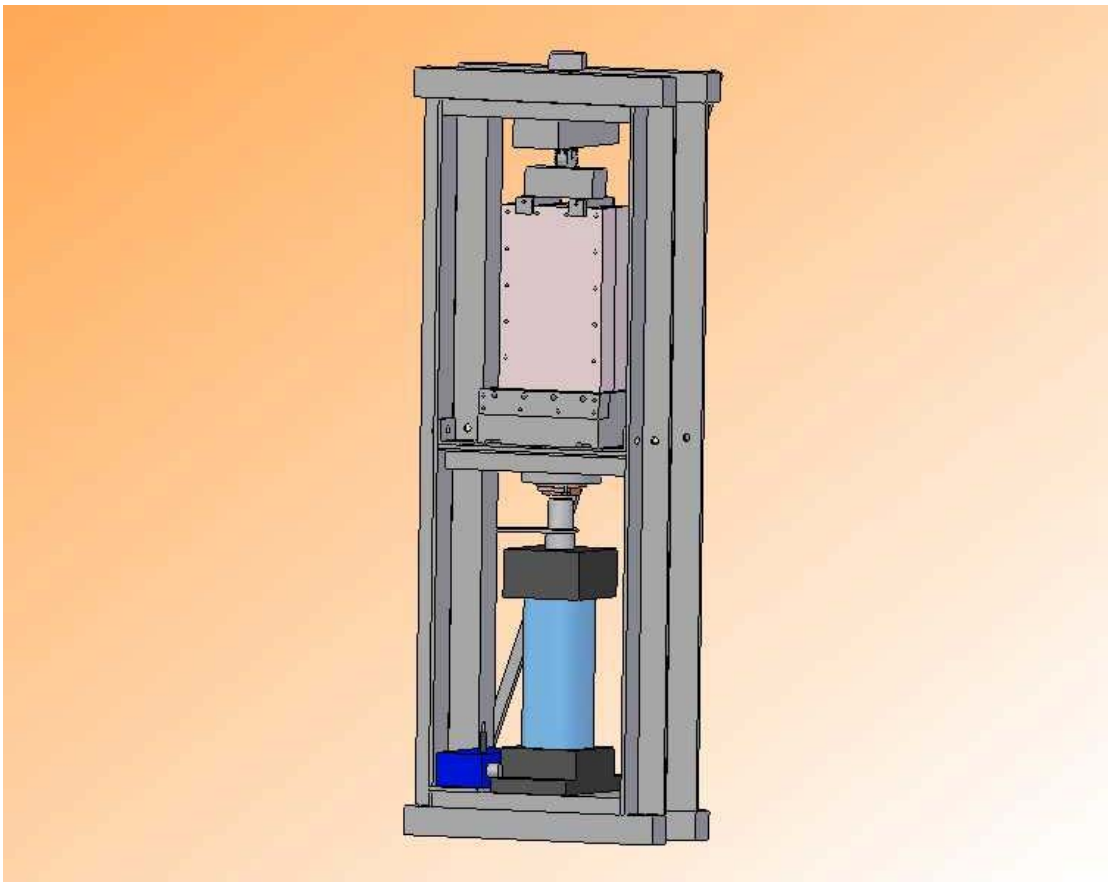


Figure 22. Radiographic die-casting equipment design view.

5.0 Summary

The water analog simulations, computer simulations and comparison of computer simulation predictions to actual casting defects were successfully completed tasks in this project. Toward the objective of better understanding fill patterns in die-casting, several observations can be made. Generally the water analog and computer filling pattern simulations, using the same geometries and filling parameters, yielded results that were strikingly similar. Certainly there are minor local differences that can be seen from one simulation to the next, so the level of precision is still an issue for discussion. From one point of view the similarity is surprising because according to current wisdom, the flow at the gate exit into the cavity is supposed to be atomized. Yet none of the computer simulation tools was capable of modeling atomized flow.

Water analog simulations provided the insight that atomized flow is very short-lived at the gate, and quickly changes to a contiguous flow. Apparently impediments from die wall friction, back-pressure from air in the cavity, and interaction with the molten metal which has already entered the cavity influence the flow regime at the gate, and throughout the cavity, as a function of time. This may be a somewhat special situation in the simple flat plate die because the flow progresses unimpeded by obstacles. Nonetheless, local obstacles may cause turbulence in the flow pattern, and perhaps trapped air, but not atomized flow. These challenges may best be overcome via the pre-fill approach. For the purpose of minimizing trapped air by designing vents at the last portion of the cavity to fill, capturing the complexities of atomized flow does not appear to be a major impediment to predicting filling patterns in die-casting. As demonstrated in this project via comparison with actual castings, on a macroscopic scale, computer simulations of filling patterns have the ability to predict flow related defects in castings.

For predicting local phenomena such as skin de-lamination, then a modeling approach with greater local precision in predicting flow, heat loss and solidification may be required. If the flow regime (atomized, jet, turbulent, laminar) of molten metal entering the cavity and the influence of solid fraction on molten metal viscosity could be predicted as a function of time during filling, then quality aspects related to casting surface finish, skin de-lamination, mis-runs, cold shuts and visible flow lines might also be predicted. Existing computer and water analog simulation methods have extremely limited abilities in this regard.

Fundamental static and dynamic experiments were conducted for real-time radiography of filling patterns in die casting. The dynamic experiments have shown that the technique is feasible. An experimental apparatus for conducting the radiographic experiments has been designed and is nearing completion.

6.0 Acknowledgements

Prince Machine and VisiTrak corporations are acknowledged for their excellent equipment support of this work. In addition, the software and computer modeling support of MAGMASOFT™ , NovaCast™, Flow3D™, dieCAS™, Walkington Engineering, Amcan Castings Ltd., and Technalysis® Inc. was invaluable. The NADCA Computer Modeling Task group was also a tremendous resource for the conduct of this research.

7.0 Project Reporting and Student Participants

Reports of project activities were orally presented and reviewed or submitted for presentation at the following NADCA Research and Development Committee and Computer Modeling Task Group meetings:

NADCA Committee/Group	Meeting Date	Meeting Place
R&D	9/13/2000	NADCA, Chicago, IL
Computer Modeling	12/7/2000	OSU, Columbus, OH
R&D	2/7/2001	NADCA, Chicago, IL
Computer Modeling	4/25/2001	OSU, Columbus, OH
R&D	6/20/2001	OSU, Columbus, OH
R&D	9/25/2001	OSU, Columbus, OH
Computer Modeling	4/24/2002	OSU, Columbus, OH
R&D	6/12/2002	Case Western Reserve University, Cleveland, OH
Computer Modeling	9/11/2002	Prince Machine, Holland, MI
Computer Modeling	12/11/2002	OSU, Columbus, OH
R&D	1/23/2003	NADCA, Chicago, IL
Computer Modeling	4/23/2003	OSU, Columbus, OH
R&D	6/26/2003	Colorado School of Mines Golden, CO
R&D	2/26/2004	NADCA, Chicago, IL

A total of 3 students worked on this project. Ms. Haijing Mao worked on conducting and coordinating the computer simulation aspects of the research. She is presently working on the completion of her PhD degree in Industrial and Systems Engineering on a topic related to computer modeling of filling patterns and flow regimes in die-casting. Ms. Sarika Joshi completed her MS degree in Industrial and Systems Engineering in December 2003. She coordinated the casting trials and quality assessments aspects of this project. Sarika took employment with Ryobi Die Casting in Shelbyville, IN. Mr. John Harm is presently working toward the completion of his MS degree in Industrial and Systems Engineering while working full-time as an engineering manager for N. Wasserstrom and Sons, Columbus, OH. John is responsible for the radiographic evaluation of fill pattern and flow regime aspects of this work.

8.0 References

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