NUMERICAL INVESTIGATION OF THE EFFECT OF GATE VELOCITY AND GATE SIZE ON THE QUALITY OF DIE CASTING PARTS

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ABSTRACT

A numerical model based on FLOW-3D a three dimensional finite difference software based on the SOLA-VOF free surface modeler has been developed, to simulate the transient, inertia dominated and complex cavity filling in high pressure die castings. In order to determine the accuracy of this approach in modeling the complicated flow conditions in die casting, a comparison with experimental filling patterns obtained from water analogy results in the literature was conducted and selected results are presented. Numerical experiments were then carried out to evaluate the effect of fill times and gate velocities on the filling patterns in dies, at the slower fill times that are increasingly common in the die casting industry. The results of this investigation are then presented.

INTRODUCTION

Die casting processes are high volume production processes which produce geometrically complex parts of nonferrous metals with excellent surface finishes and low scrap rate. Production rates of 200 parts per hour and production batches of 300,000 parts are not uncommon.

In die casting, the flow of the molten metal from the shot sleeve into the periphery of the casting is accomplished by a runner system, while the entry of the molten metal into the casting is controlled by a gating system. An optimum gating system design will create a preferred filling pattern within the die cavity, and consequently produce sound castings. An improper design of the runner gate system or of the die cavity will however result in defects such as lack of fill, cold shuts, gas and shrinkage porosity etc., commonly seen in die castings.

Typically, a number of accepted design rules and practices related to gating and casting design, and selection of process parameters are used to reduce defects in die cast parts and to increase die life. These design rules while providing a framework for design are not quantitative in nature and are difficult to apply for complex parts. Using these design rules, the design process often involves long turnaround times and expensive die tryout to produce defect free castings, which with the cost of dies (some dies cost upto a million dollars) can be a very expensive process. Therefore analysis tools that provide a quantitative estimate of the effect of design and process parameter changes, on the metal flow and solidification, will provide a better understanding of the "design for die casting process" and help reduce the guess work involved in producing an optimum design.

The requirements of a die casting process simulation software to achieve these objectives, and the capabilities and limitations of existing die casting process simulation models is outlined in the following section. Available numerical schemes for mold filling and solidification were then evaluated in order to choose and modify software to improve the process of die design in the die casting [Venkatesan and Shivpuri, (1993a,b, 1994)]. After this initial evaluation a model based on FLOW-3D (1994) a three dimensional finite difference software was chosen for this study. In order to verify the accuracy of this scheme in modeling the die casting process, a comparison was conducted with experimental water analogy results available in the literature and the results are presented.

Technological advances have allowed processes such as slow injection die casting and squeeze casting to become increasingly popular in die casting. Having verified the filling model for high velocity die casting, an analysis of the effects of gate velocities and gate sizes at the slower fill times of these processes (squeeze casting or slow injection die casting) is presented.

DIE CASTING PROCESS SIMULATION MODELS: REQUIREMENTS AND CAPABILITIES OF EXISTING MODELS

The most important requirement of a die casting process simulation model is the fluid flow modeling during mold filling, as critical defects such as lack of fill, cold shuts, and gas porosity (entrapped air) commonly seen in die occur during mold filling. Fluid flow modeling is however difficult as the fluid flow during this stage is highly transient, inertia dominated and often turbulent with Reynolds numbers in excess of 10,000, due to flow of high velocity metal, through rapidly changing geometry in the runner-gate system or in the casting

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cavity. Within the die cavity, jetting, splashing and liquid droplet and atomized spray formation are quite common [Smith and Wallace (1963), Stuhrke and Wallace (1964, 1965)] due to the high metal velocities. Therefore common simplifications used for modeling less taxing flow problems in sand casting and injection molding, such as the assumption of laminar and viscosity dominated flow such as Poisseule flow (used for modeling highly viscous flows in injection molding), are no longer valid. The solution of the Navier Stokes equations to calculate transient velocity and pressure changes, with some degree of turbulence modeling is thus an essential requirement for any fluid flow model used in die casting. The other main requirement is free surface modeling of the fluid flow, that is capable of accurately tracking the complicated flow fronts seen in die casting, as well as the formation of droplets and sprays caused by high velocities and splashing. The simulation of die filling is further complicated by the three dimensional geometry of the die cavity and the simultaneous occurrence of fluid flow and heat transfer.

Of all the software reviewed [Shivpuri et al. (1991), Venkatesan and Shivpuri (1993a,b, 1994)], FLOW-3D (1994) which is an extension of the SOLA (1975) and SOLA-VOF (1980) family of free surface modelers has the best mold filling modeling capability. It has superior free surface modeling capability which allows the handling of free surface breakup, unlike most other models which assume continuous free surfaces. FLOW-3D is therefore capable of handling the complicated free surface movement caused by jetting, flow separation, splashing, liquid droplet formation, and turbulence, as well as the transient flow [Hirt et al. (1991)] which occurs during the filling of die cavities under high velocities and pressures.

FLOW-3D has traditionally been used to model complex free surface problems in space applications. Since most current filling models are incapable of handling the jetting and complex free surfaces that exist during mold filling in die casting, it was decided to extend FLOW-3D to develop a numerical model for the filling of mold cavities in high pressure die casting. Such a numerical model based on FLOW-3D has been developed, to simulate the transient, inertia dominated and complex cavity filling in high pressure die castings [Venkatesan and Shivpuri (1993a,b, 1994a, 1995)]. While this numerical model is capable of modeling the complicated flow situations and geometries that commonly exist in die casting, the accuracy of the filling patterns obtained has not been determined. In order to determine the accuracy of this approach in modeling the complicated flow conditions in die casting, a comparison with experimental filling patterns obtained from water analogy results in the literature was conducted and is described in the following section. The general approach that is used by FLOW-3D in modeling free surface fluid flow, and its capabilities and limitations are described in Venkatesan and Shivpuri (1993a, 1994).

MODELING OF FLUID FLOW IN DIE CASTING DIES

One of the fundamental problems in designing the runner-gate system in order to obtain a desired fill pattern, is that visualization of the metal flow in actual die casting operations is practically impossible. Before the availability of computational fluid flow techniques to allow numerical simulation of mold filling, water analogy studies (where the flow of water through transparent die cavities is used to model the flow of molten metal in an identical cavity) were utilized to visualize die cavity mold filling and study the effect of runner and gate geometries. Even though the water analogy method cannot be used to evaluate the effect of the molten metal temperature and solidification in die casting, the method is useful for visualizing the flow path of molten metal, estimating locations of porosity in the casting cavity, and turbulence in the gating system.

A number of water analogy studies have been conducted over the years by among others, Wallace and his co-workers [Smith and Wallace (1963), Stuhrke and Wallace (1964, 1965)], Booth and Allsop (1983), Frommer (1933), and Moorman and Sheptak (1962), for different gate, runner and cavity geometries for a range of process conditions. These water analogy studies exhibit the complicated flow conditions such as jetting, splashing and spray formation, which distinguishes the flow in die cavity filling from that of sand casting or injection molding.

While the results of these water analogy studies indicate the difficulties in modeling the fluid flow in die casting processes, they also provide an excellent benchmark to test the capability of a free surface solver in simulating the mold filling in a die cavity. Die cavity filling simulations using the developed model, were therefore compared with water analogy studies available in the literature for a range of die geometries, gate shapes and sizes, and gate velocities, to test the capability of the numerical model in simulating the mold filling of a die cavity. The gating systems considered include chisel gates, side gates, fan gates, straight tapered gates and tangential tapered gates. The results of some of these comparisons with water analogy experiments of chisel gated cavities is presented in the following section.

FILLING OF FLAT PLATE CAVITIES WITH CHISEL GATES

Wallace and his coworkers [Smith and Wallace (1963), Stuhrke and Wallace (1964, 1965] performed a series of water analogy experiments to study the flow patterns obtained in die cavities for a variety of runner and gate geometries, shot sleeve fill percentages and gate velocities. Comparisons of flow patterns with those obtained from the FLOW-3D based model for some of the cases considered is outlined below.

The filling sequence of a 15x10x0.32 cm vertical die cavity, filled from the bottom through a 1.25 x 0.05 cm gate with a typical die casting velocity of 3780 cm/sec as obtained by Smith and Wallace (1963) is shown in Figure 1. The fluid stream as it enters the cavity, flows through the cavity without much change in its shape or direction until it impinges upon an opposite wall. The stream which impinges on the wall opposite the gate then splits into two parts (forerunners). The inertia of the jet further causes the forerunners to follow the cavity perimeter on each side back to the gate, where they meet the incoming jet thereby causing vortex formation and resultant porosity. This typical flow pattern first suggested by Frommer (1932) is now widely accepted as the actual mode of filling in die castings. In a metal casting this would result in a sealing of the vents and consequent entrapment of air in the casting.

A typical flow pattern obtained from the FLOW-3D based model for similar instants of time (Figure 2) shows a good correlation with the experimental fill patterns shown in Figure 1. The importance of modeling inertia is clearly seen in this numerical simulation. Viscosity dominated flow assumptions commonly used in the simulation of sand casting or injection molding would have resulted in a prediction of a continuous flow front from the gate to the opposite wall. This would have led to predictions of porosity on the wall opposite the gate unlike what is actually seen in the experiments and in the numerical simulations.

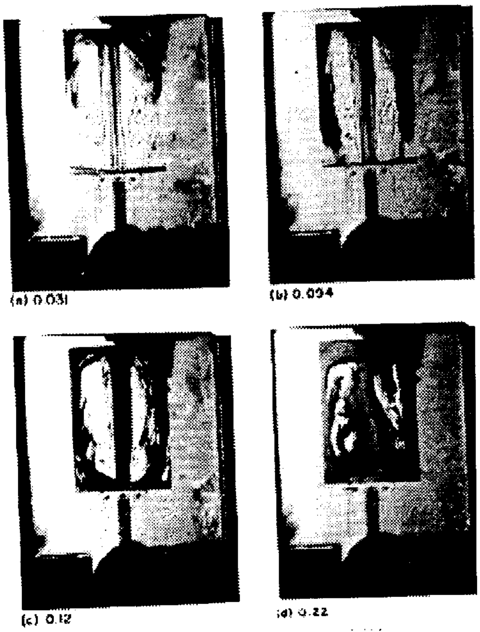
(a) 0.031 (b) 0.094 (c) 0.12 (d) 0.22

Figure 1. Cavity fill sequence with a gate velocity of 3780 cm/sec and a 1.25 x 0.05 cm gate for a 15x10x0.32 cm plate die. [From Smith and Wallace (1963)]

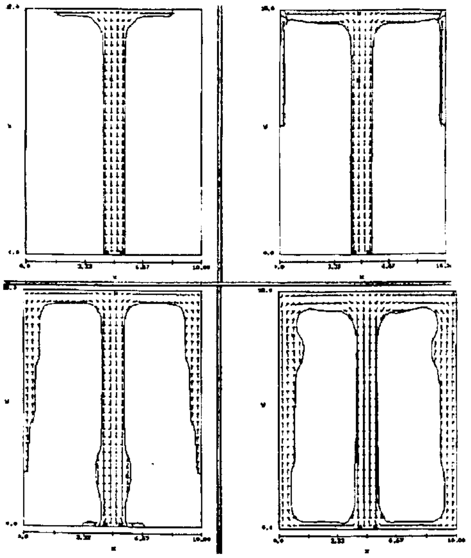

Figure 2. Fill sequence obtained from the numerical simulations for the same gate geometry and gate velocity shown in Figure 1, at approximately similar instants of time.

Horizontal or Side Injection

Another common mode of filling of a die cavity is by horizontal injection with chisel gates from the side of a cavity. A sequence of horizontal or side injection into the vertical plate die cavity (15x10x0.32 cm) for a gate velocity of 1050 cm/sec as obtained by Smith and Wallace (1963), is shown in Figure 3. The corresponding time sequence of filling from a FLOW-3D simulation is shown in Figure 4. As can be seen in both figures, the stream strikes the opposite wall, flows upward against the force of gravity, strikes the upper corner, flows along the top edge, and finally flows down to meet the incoming stream at the gate. A large vortex formation is thus seen in the numerical and experimental simulations at nearly the same locations, resulting in air entrapment.

Smith and Wallace also considered impinging streams as a possible means of reducing inertia leading to a continuous flow front. Figure 5 shows the results of water analogy studies for the same plate dies of Figures 1-4, at a gate velocity of 1560 cm/sec. The corresponding flow pattern obtained from the numerical simulations is shown in Figures 6 and appears to show a good match. The importance of flow solvers capable of handling inertia dominated flow is also clearly seen in these side injection experiments.

The comparison of the mold filling patterns from water analogy studies, with the results of numerical simulations using a FLOW-3D based model, indicates that the numerical model appears to simulate the inertia dominated mold filling of die castings very well. It has been suggested that jetting flow in die casting is undesirable as it may result in air entrapment and die erosion. While the recommended gating practice is for fanned or tangential gates with lower metal inertia, jetting flow is quite common due to other limitations caused by the complexity of the die cast part and other considerations. Thus software which is capable of modeling this complex jetting phenomena is required for modeling the mold filling process during the design stage.

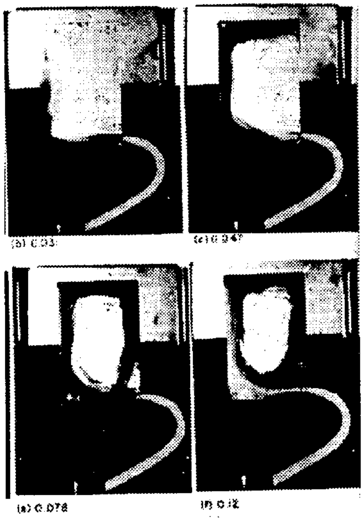
(b) 0.031 (c) 0.047 (e) 0.078 (f) 0.12

Figure 3 Cavity fill sequence for horizontal injection with a gate velocity of 1050 cm/sec and a 0.625x0.32 cm chisel gate for the plate die of Figure 1. [From Smith and Wallace (1963)]

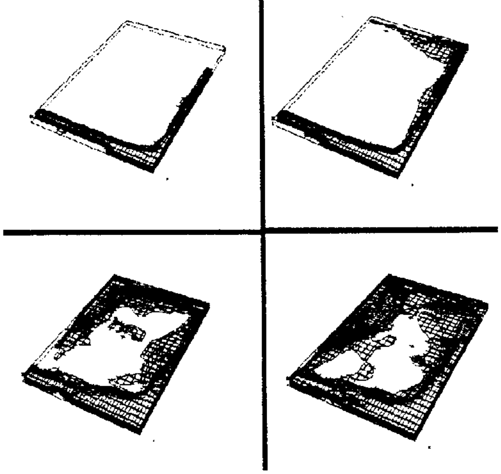

Figure 4 Fill sequence obtained from numerical simulations, for the same gate geometry and gate velocity shown in Figure 3, at approximately similar instants of time.

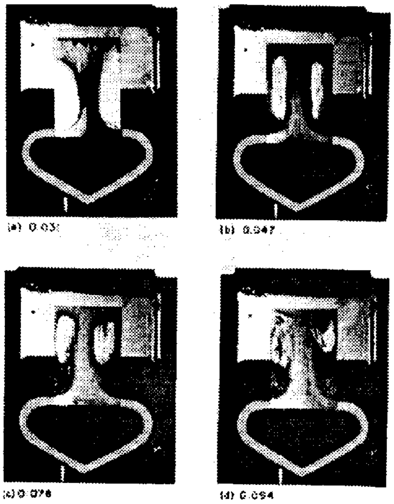

Figure 5 Flow pattern for impinging jets for a gate velocity of 1560 cm/sec for the plate die of Figure 1. [From Smith and Wallace (1963)]

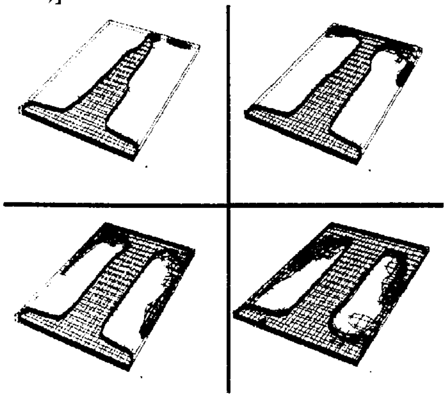

Figure 6 Impinging jet fill sequence obtained using numerical simulations for the same gate geometry and gate velocity shown in Figure 5, at approximately similar instants of time.

EFFECT OF GATE VELOCITY ON THE FILLING PATTERN OF DIE CAVITIES WITH CHISEL GATES

Having verified numerically obtained filling patterns, with experimentally obtained filling patterns, the study was further extended to evaluate the effect of gate velocity and fill time on the filling patterns in die casting dies. Numerical experiments are more easily carried out and important insight or understanding of the filling process can be more easily obtained.

As seen previously, chisel gates typically result in jetting flow and entrapped air within the die cavity (Figures 1-6). It is accepted industrial practice to reduce filling time where possible to reduce these inertia effects and promote a continuous fill pattern. With the advent of squeeze casting and slow injection die casting technology, slow filling is a realistic possibility in modern die casting. Squeeze casting with its perceived advantages of slow filling and consequently lowered entrapped air, is increasingly gaining popularity for use in a variety of parts. While it is widely believed that a larger fill time will reduce metal inertia, and produce a more continuous fill pattern with a consequent reduction in porosity in all cases, the hypothesis remains to be proven. Numerical experiments were therefore carried out to evaluate filling patterns for different gate sizes and fill times. Filling patterns were compared at identical fill times and at identical gate velocities, for different gate sizes. The results of these comparisons are presented below.

The geometry chosen was the same as shown in Figures 1-6. Four different gate widths of 0.625, 1.25, 1.875 and 2.5 cm were chosen. The gate thickness was chosen the same as the cavity thickness (0.32 cm), to reduce the computational time. Filling patterns were evaluated for each of these gate widths, for a range of fill times. The fill times (which indicate the volume or mass flow rate) chosen ranged from 30 milliseconds (typical die casting filling times) to 2.2 seconds (squeeze casting filling regime).

The results of a comparison at an identical instant during filling, for a fill time of 60 milliseconds is shown in Figure 7. As can be seen, jetting flow occurs in all cases, and air is likely to be entrapped for all gate sizes, for this geometry. However for a filling time of 1.1 seconds (slow velocity or squeeze casting regime) it is seen (Figure 8) that the 2.5 cm and 1.875 cm gated cavities exhibit nearly continuous fill without jetting and air entrapment, while the other gated cavities still exhibit jetting and air entrapment. Finally for a very slow fill time of 2.2 seconds (which is in the permanent mold casting flow regime), the 1.25 cm, 1.875 cm and 2.5 cm gated cavities exhibit nearly continuous filling patterns, and only the 0.625 cm gated cavity exhibits jetting flow, as shown in Figure 9.

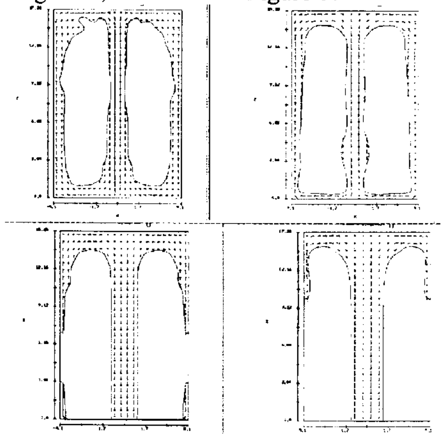

Figure 7 Filling pattern at an identical instant of time (approximately 1/3 fill) for gate sizes 0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm, for a cavity fill time of 60 milliseconds and the cavity geometry shown in Figures 1-6.

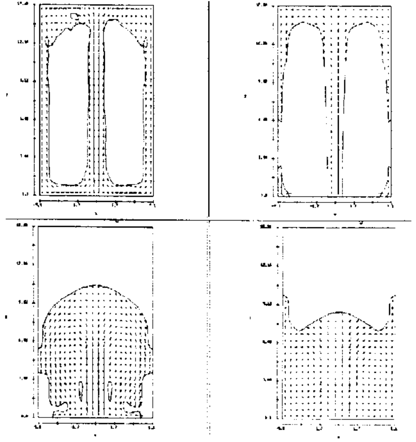

Figure 8 Filling pattern at an identical instant of time (approximately 1/3 fill) for gate sizes 0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm, for a cavity fill time of 1.1 seconds.

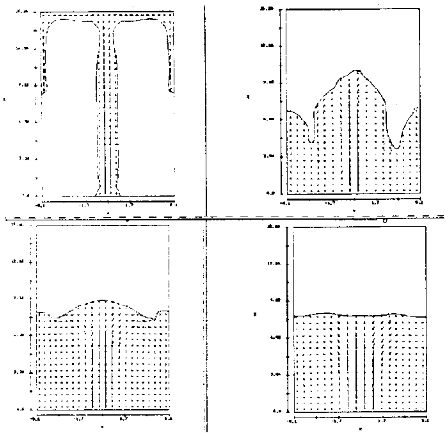

Figure 9 Filling pattern at an identical instant of time (approximately 1/3 fill) for gate 0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm, for a cavity fill time of 2.2 seconds.

Thus even at very large fill times relative to conventional die casting (where filling times are typically in milliseconds), jetting and consequent air entrapment is commonly seen. These results show, that even at identical fill times (mass flow rates), the tendency toward jetting and consequent air entrapment is different for different gate sizes. Thus inertial effects such as jetting are only indirectly dependent on the fill time or mass flow rate. An increase in gate area results in a reduction in inertial effects, at identical fill times and mass flow rates.

It thus appears, that gate velocity is critical in determining the tendency towards inertial effects and jetting. In order to evaluate the effect of gate velocity, the filling patterns for the same gate sizes used previously were observed as a function of gate velocity instead of filling time. The filling patterns for the different gate sizes at a gate velocity of 1860 cm/sec (die casting regime) is shown in Figure 10. As can be seen, jetting flow is seen in all cases. The filling pattern for a slower gate velocity of 220 cm/sec (closer to slow injection die casting regime) is shown in Figure 11 and jetting flow is seen in all cases (similar to Figure 10). While reduced inertial effects appear to change the filling pattern slightly with a greater spread of the jet, the effects are minimal. Thus even at a relatively slow gate velocity for conventional die casting (gate velocities typically range from 1,000 cm/sec to 5,000 cm/sec), jetting flow is seen for all gate sizes. A continuous fill pattern with minimal jetting for all gate sizes is however obtained, for a gate velocity of 105 cm/sec as is shown in Figure 12.

As can be seen in these figures at a given gate velocity the filling patterns are nearly identical for all gate sizes. The critical factor in determining whether a continuous fill pattern without jetting and significant air entrapment can be obtained, is the gate velocity and not the overall fill time or the mass flow rate. Thus a mere increase in the fill time (for example in slow injection die casting or squeeze casting) without an increase in gate area to reduce the gate velocity, could still result in jetting flow and consequent air entrapment. This study indicates that the perceived advantages of the squeeze cast or slow injection die cast processes (continuous fill patterns and reduced air entrapment) may not be realized, without an increase in gate size relative to the conventional process, to reduce the inertial effects. These effects appear to hold for a range of gate shapes, sizes, and geometries [Venkatesan and Shivpuri (1993a)], but the results are not reported here for the sake of brevity.

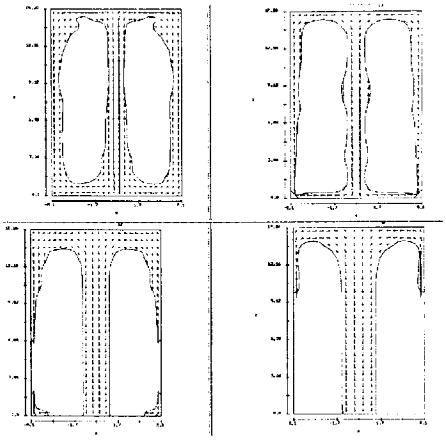

Figure 10 Typical filling pattern at an instant of time for gate sizes of 0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm., for a gate velocity of 1860 cm/sec. As can be seen jetting flow takes place for all gate sizes, and filling patterns are nearly identical.

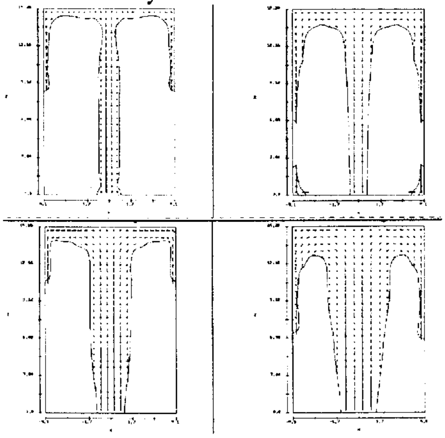

Figure 11 Typical filling pattern at an instant of time for gate sizes of0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm, for a gate velocity of 210 cm/sec. As can be seen jetting flow takes place for all gate sizes, and filling patterns are nearly identical, although the jet spread is more than that seen in Figure 10 (1860 cm/sec).

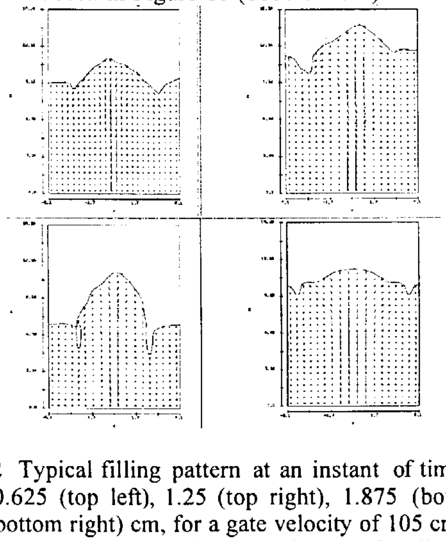

Figure 12 Typical filling pattern at an instant of time for gate sizes of 0.625 (top left), 1.25 (top right), 1.875 (bottom left), and 2.5 (bottom right) cm, for a gate velocity of 105 cm/sec. As can be seen a continuous fill pattern is seen for all gate sizes, and filling patterns are nearly identical.

CONCLUSIONS AND FUTURE WORK

A numerical model based on FLOW-3D, a three dimensional finite difference software based on the SOLA-VOF free surface modeler has been developed, to simulate the transient, inertia dominated and complex cavity filling in high pressure die castings. In order to determine the accuracy of this approach in modeling the complicated flow conditions in die casting, a comparison with experimental filling patterns obtained from water analogy results in the literature was conducted and selected results presented. The comparison of the mold filling patterns from water analogy studies with the results of the numerical simulations, shows that the numerical model appears to simulate the inertia dominated mold filling of die castings very well.

Numerical experiments were then carried out to evaluate the effect of fill times and gate velocities on the filling patterns in dies, at the slower fill times that are increasingly common in the die casting industry, due to the advancement of slow injection die casting and squeeze casting technology. These studies indicate that even at very large fill times relative to conventional die casting (where filling times are typically in milliseconds), jetting and consequent air entrapment is commonly seen. Thus continuous fill patterns with minimal jetting and air entrapment, that is perceived as a significant advantage of slow filling in the die casting industry cannot be attained for all gate sizes and shapes.

These numerical studies also indicate that even at identical fill times (mass flow rates), the tendency toward jetting and consequent air entrapment is different for different gate sizes. The critical factor in determining whether a continuous fill pattern without jetting and significant air entrapment can be obtained, appears to be the gate velocity and not the overall fill time or the mass flow rate. Thus an increase in gate area at identical fill times will result in a reduction in the gate velocity which will result in reduced inertial effects and an increase in the tendency toward continuous fill. This is because the jetting effect, the tendency to back flow and premature sealing of vents are all reduced as the stream inertia is reduced.

This study thus indicates that the reduction in gate velocity required to produce continuous fill patterns with minimal jetting, cannot always be obtained by the reduced flow rates in slow velocity die casting processes that are increasingly gaining popularity in the die casting industry, and that an increase in gate area may be required to further reduce gate velocities.

Studies are currently being conducted to evaluate the effect of fan angles, runner width reduction ratios, tangential gate areas and tapers on the filling patterns of die casting dies. These numerical simulations are being used to study the effect of complex gate shapes on the filling patterns of complex industrial die casting die shapes.

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