Using Flow Analysis Software to Optimize Piston Velocity for an HPDC Process

- A 3D study of the shot-sleeve velocity profile uncovers some surprising operational parameters

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Introduction

High pressure die casting (HPDC) is one of the most complex processes in the foundry world due to the large number of simultaneous, inter-related physical phenomena involved and their variations across a short span of time. Technicians soon find that changing just a single aspect of the process produces secondary changes that affect the final product, sometimes in a distinctive and undesirable manner.

Today's HPDC machines are essentially small computers that let the user customize and control every set-up parameter from the temperature of the chamber to the motion of the piston during the shot process. This gained "freedom" brings with it some new and non-trivial problems, as the user must combine the best values to produce an excellent product. Human experience provides a good foundation for some of the numbers, but finding just the right combination to quickly and cheaply create the perfect result may be a non-intuitive process.

A particular challenge involves optimizing the run of the piston in the shot sleeve to inject the metal inside the mold. This seemingly straightforward operation is not an easy task due to generally conflicting operations. If the user moves the piston through the sleeve as quickly as possible to simultaneously reduce the cooling of the metal, the process time, and the oxidation, then the molten metal develops a high surface breaking effect and air entrainment will result. By contrast, a slow fill velocity minimizes wave breaking but lengthens the process time, which requires a higher pouring temperature and therefore increases costs. In addition, waves reflect off the opposite end of the shot sleeve and travel back toward the input port, interacting with the bulk metal flow.

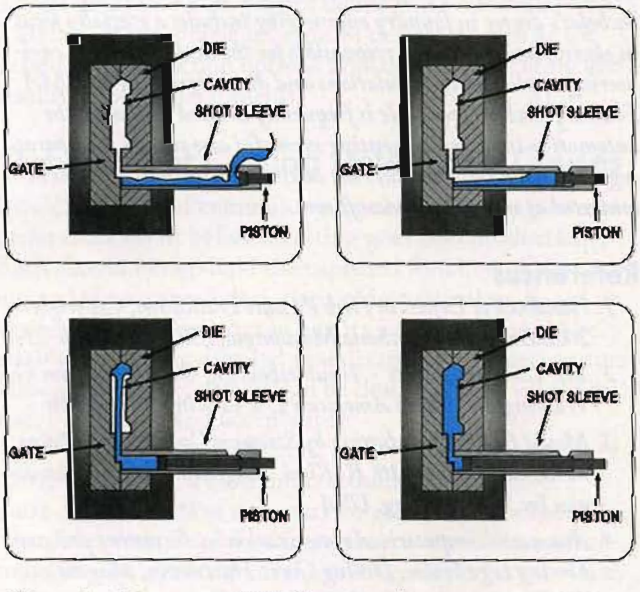

Figure 1 - Schematic of a high pressure die casting filling process.

In the past, users have taken a number of different software-based approaches, ranging from simple to complex, to analyze this travelling wave motion. The results identified operational parameters that might generate a best fill-velocity profile for creating unbroken, in-phase waves. However, all have been limited to modeling the geometry in either one or two dimensions. XC Engineering tackled this problem using the full three-dimensional, time-varying capabilities of FLOW-3D, a fluid-dynamics solver from Flow Science, Inc. and IOSO NM, an adaptive non-linear optimization tool from Sigma Technology.

Case Study

The goal was to achieve the shortest possible sleeve fill-time while minimizing both surface breaking and air entrainment. To evaluate and optimize the operating settings necessary to produce these results, a three-step, iterative work-flow was designed. First, a trial was created with a detailed velocity profile versus time, using the software to simulate the resulting 3D turbulent metal behavior. Key output quality parameters became inputs for the optimization tool, which interpreted the results and suggested directions for changing the input values. The software then ran each time with the new velocity profile to optimize the end-product properties.

Optimization Set-up

For this project, XC Engineering partnered with Swiss company, Bühler Consultancy, a global specialist in a number of plant services including casting machine manufacturing. Bühler supplied data from an actual HPDC machine for reference, loading it with a typical level of metal and measuring the transition time between the first and second phase runs to define the shot-sleeve filling time. Users can program the machine to have up to 20 different locations where the piston velocity can be changed, though in the first shot phase only four such change points are commonly used.

The optimization software varied the relative velocity of the metal flow at six locations along the sleeve. Two of these locations, the initial and final run points, were fixed so that a total of 10 design variables were completely independent: the ranges of six sets of velocity values (in m/s at the six locations) and the spread of values defining the four possible locations (in mm along the run). (Figure 2)

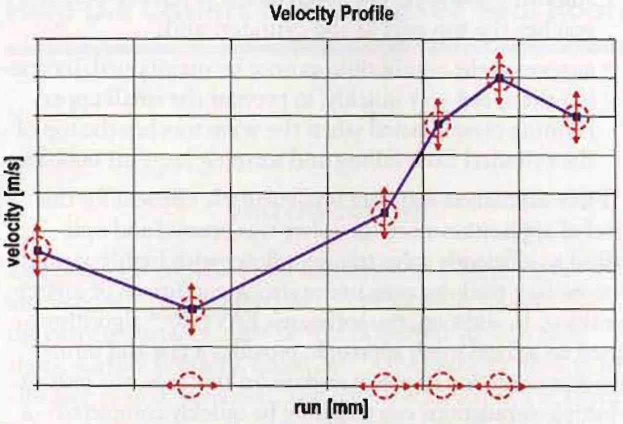

Figure 2 - Set of design variables defining fill velocity and location, as analyzed for shot sleeve filling analysis.

The analysis team felt that the objectives should be minimal yet sufficient to adequately describe the physics and the quality of the filling. Two concurrent objectives were chosen: minimize the time required for the first phase stage and minimize the "air entrainment" variable given during the entire simulation – a useful index for the turbulence and surface-breaking of the metal.

Note that the two objectives are not only equally important but also reciprocally contrasting. Therefore, it was clear the optimal solution would not be a single solution, but a curve of solutions (Pareto curve) giving the best compromise between elapsed time and air entrained. The end-user will have to choose, according to his experience, the point that best satisfies his needs.

Results

After several initial iterations to evaluate the molten surface response, the optimization tool started to produce the Pareto curve and to break at some interesting optimal points. The software worked for a long time (four days) on a typical desktop computer, even though very good solutions were found after just one day (500 cycles) of processing. Figure 3 shows the resulting Pareto curve at the end of the optimization task.

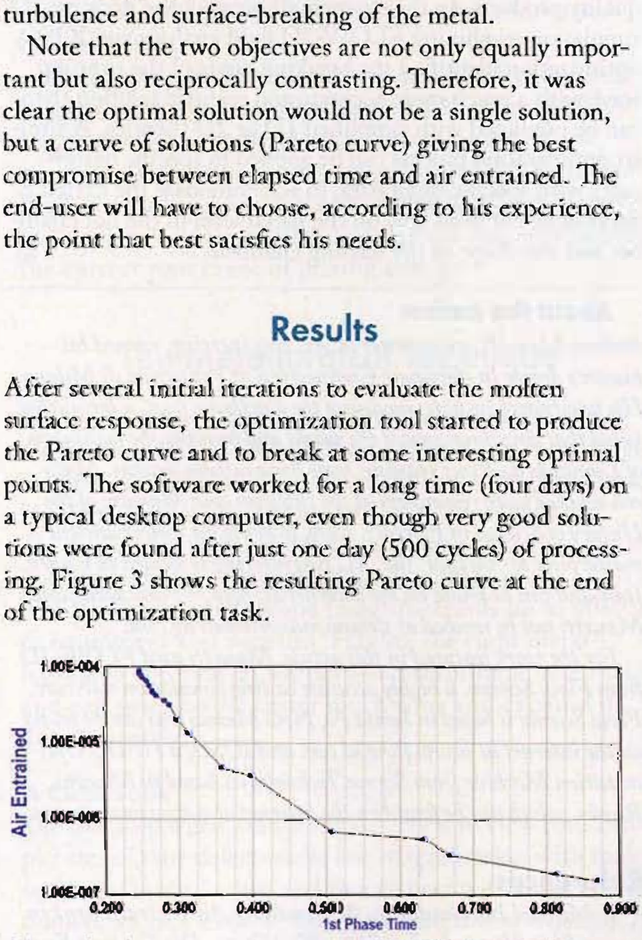

Figure 3 - Comparison of predicted entrained air amounts versus length of first phase time taken, as analyzed with fluid analysis software and optimization software.

This curve displays some interesting aspects: first, it covers a wide range of values, with the two extremes being quite robust. This latter aspect is particularly important in an optimization process because it is commonly required that the solution must be reliable and usable even if there is some uncertainty in the parameters.

Secondly, for all cases, the maximum time spent in the first phase stage is less than 0.9 seconds. This value represents a process about 30% faster than what is commonly used to prevent surface breaking, and therefore a lower cost; yet provides even higher than normal quality.

Every point of the Pareto curve is an optimal solution, representing the best velocity profile to use for the piston for that particular compromise between fill time and air entrained. However, one particular point at the right of Figure 3, corresponding to the slowest process (0.9 seconds), shows that practically zero associated air is entrained. Since plants place great value on having both a smooth surface and minimum wave breaking, users may choose to set up their machine based on the rightmost solution point.

The velocity profile connected with this latter solution point is shown in Figure 4; as previously stated, it has an air entrained value very close to zero. The details of the simulated velocity profile associated with this point, among all the infinitely possible combinations of accelerations and decelerations, show a surprising characteristic. They are very similar to those actually used on the die casting machines, based on experience: an initial slow and long acceleration, then a constant step, and lastly a final steep acceleration. This velocity profile then not only follows human logic, but is also the best profile among all the similar ones.

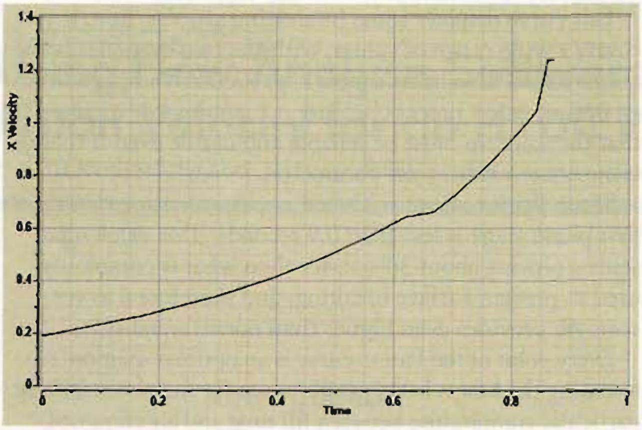

Figure 4- Details of velocity profile versus time for a shot sleeve fill time of 0.9 seconds.

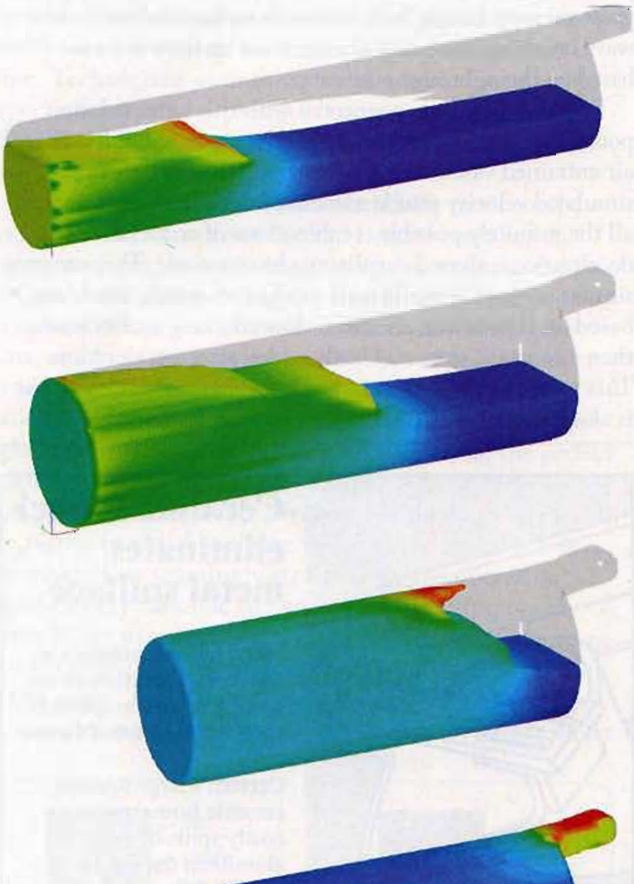

Figure 5- Time lapse sequence of shot sleeve filling, progressing from left to right, showing beginnings of wave formation. Colors represent velocities, with blue the slowest; the min/max scale is relative for each image. With this timing, the sleeve completely fills before the upper leading wave edge can actually break the surface.

Building upon mono-dimensional theories and a technical report[1] on minimizing air entrainment during the slow shot phase, the analyses produced the following explanation: the optimal piston velocity profile is the one that catches up with the starting wave without giving it the time to reflect or break. In fact, an animation of the simulation (Figure 5) shows exactly this behavior.

The motion of the piston controls the wave inside the domain by:

- increasing the metal height at the piston face (increasing the steepness without breaking the leading edge);
- smoothly reducing the acceleration when the height reaches the top part of the cylinder; and,
- as soon as the equilibrium cannot be maintained, increasing the speed very quickly, to prevent the small upper running crest (created when the wave touches the top of the cylinder) from falling and forming large air bubbles.

Flow simulation software is particularly efficient for this kind of application since the solver was created and optimized to efficiently solve transient flows with highly accurate free-surface tracking even under strong conditions of surface breaking. In addition, the software's FAVOR™ algorithm, based on a fixed mesh approach, provides a fast and intuitive representation of object motion (in this case, the piston). Multiple simulations can therefore be quickly completed – a critical aspect for a highly iterative optimization process.

Conclusion

Since HPDC machines are now more programmable, user choices in their operational settings have become more complicated. At the same time, these choices create the possibility of achieving optimal processes and the highest quality products. In the example illustrated, the iterative 3D simulation combining FLOW-3D fluid analysis and IOSO optimization identified the breaking angle of the running wave with a much more accurate and realistic solution than can be predicted with simplified 1D or 2D theories. A similar optimization process can be applied to specific design cases with specific input data, to accommodate the extreme dependency of fluid flow on the metal level in the hot chamber and the shape of the feeding channels. ●

About the Author

Stefano Mascetti, an engineer at XC Engineering, earned his master's degree in Aerospace Engineering at Politecnico di Milano. His latest work includes modeling the Earthrace boat, a bio-fueled vessel that circumnavigated the world and proving the feasibility of Leonardo da Vinci's famous huge horse casting designs. Mascetti worked with researchers at the Institute and Museum of the History of Science in Florence, Italy, to bring da Vinci's ancient masterpiece to "virtual" life. XC Engineering is located in Cantu, Italy and can be found on the internet at: http://www.xceng.com. Mascetti can be reached at stefano.mascetti@xceng.com.

For the work featured in this article, Mascetti used FLOW-3D from Flow Science, a highly accurate casting simulation software. Flow Science is based in Santa Fe, New Mexico and can be found on the internet at www.flow3d.com and IOSO, a HPDC Optimization Machine from Sigma Technologies based in Moscow, Russia, which can be found on the internet at www.iosotech.com.

References

1. *Michael Barkhudarov, Minimizing Air Entrainment in a Shot Sleeve during Slow-Shot Stage, Die Casting Engineer (The North American Die Casting Association ISSN 0012-253X), May 2009.*