ABSTRACT

Inexplicable patterns of internal defects in diecast parts are often because of borderline optimization of gating and feeding systems. In other words, a particular die design is too sensitive to process parameters such as melt temperature or filling time. A sufficiently robust die design can be determined through extensive (but expensive) die tryouts. Computer simulation programs can replace shop floor trials, but most of the available programs are quite difficult-to-use and computation intensive. To overcome these limitations, we have developed a hybrid approach combining automated design, intelligent analysis and castability health-checks. The design program includes encoded experience to give a good first gating and feeding design and creates their solid models. Intelligent analysis combines physics-based simulation with practical experience to quickly predict internal defects in a casting. The health is assessed and quantified by a set of castability criteria. With this approach, it is possible to complete several virtual tryouts and finalize a sufficiently robust die design in a single day. The system has been successfully used for gravity die cast parts and is being extended to pressure diecasting. It is easily customized for any new metal or process.

Keywords: CAD/CAM, Casting Design, Die Casting, Simulation.

INTRODUCTION

Tooling development is not only the most expensive activity in die casting process, accounting for over 70% of the lead-time to the first article of approval [1], but also significantly influences part quality. Often, die development is a bottleneck in new product development.

For a given component, die development comprises broadly three tasks: design, manufacturing and tryouts. Die design includes cavity (parting, cores, draft, allowances), feeding and gating systems (feeders, feed-aids, sprue, runners, gates, overflows, vents), cooling system and mechanical system (ejection, guiding, housings). Die manufacturing includes process planning (NC tool path generation and verification), electrode manufacturing (for EDM process, if used), machining, die finishing (grinding, polishing, etc.), dimensional inspection (conventional or CMM-based) and die assembly.

Die tryout is usually the most cumbersome and challenging task, involving several iterations of casting, inspection, fault analysis and modification of feeding and/or gating system. Each trial may take 1-2 weeks, and typically 2-4 trials may be required. Some complex castings (such as an engine block) may require 8-10 trials or more. Even then, the yield may be poor or the die may continue to produce occasional defective parts.

In some cases, the gating and feeding design is just correct to get a good casting under normal and controlled conditions. Such a design is sensitive to changes in process variables. This means that even minor and expected variation in metal composition or pouring temperature produce sudden and often unexpected increase in the level of defects. We refer to this as ‘borderline optimization’.
To achieve the goal of zero defects, the casting engineer should *tilt the balance* by slightly over designing the casting, so it is *sufficiently robust* against expected process variations. However, determining the optimal value of each design parameter itself requires a series of trials (especially for new castings) at normal operating conditions. Determining the sufficiently robust value for each design parameter will require even more trials (at expected limits of operating conditions). The material, energy and labor costs for so many trials may not be economically justifiable.

The preferred way to reduce the time and cost of shop floor trials is by virtual tryouts, by creating and simulating a 3D model of the casting, described next.

**VIRTUAL DIE TRYOUTS**

The 3D CAD models of the part and die can be created using solid modeling programs (AutoCAD, CATIA, Cimatron, I-DEAS, Pro-Engineer, SolidWorks, Unigraphics, etc.). A combination of operations such as sweep (linear and rotational) and Boolean (add, subtract, intersect) are used. This enables better visualization, property computation, rapid modification and compact archival. Also, the 3D models can be transferred (through standard DXF, IGES, STEP and STL formats) and used for other activities, including stress analysis, cavity shape modeling, NC tool path generation, automated inspection (by comparing CMM data with original model) and process simulation. Parametric and features-based modelers (Pro-Engineer and SolidWorks) enable modeling in terms of manufacturing features (hole, boss, rib, etc.).

Several researchers and diecasting engineers have encoded their die design experience in terms of equations, tables and graphs, which are available in technical literature and handbooks [2,3,4]. These include equations for determining the ideal filling time (as a function of casting thickness, metal fluidity, die temperature, etc.), pressure head (depending on material and application) and ejection force (with respect to cast metal, surface area and length of core). This knowledge can be incorporated in computer programs, useful for preliminary die design calculations. These can also be interfaced with solid modeling programs to semi-automatically generate 3D CAD models of die elements. The models can be exported to NC tool path generation software for die manufacturing. One such software, Diedifice, for pressure diecasting is being developed by Neilsoft Ltd., Pune.

Simulation technology has emerged as a boon to diecasting engineers to perform virtual trials, predict casting defects and improve the die design without pouring a single shot. This not only eliminates the cost of die modification and material/energy costs, but also provides a better insight into the process and enables exploring more alternative solutions.

Most of the die filling and solidification simulation programs available today are based on Finite Element Method [5]. The main input is a 3D CAD model of the part and die, created using a solid modeling program. This model has to be *meshed*, that is, broken down into a number of simple elements (cubes or tetrahedrons). A smaller mesh size gives slower but more reliable results. Adaptive meshing (finer in
critical regions and coarse elsewhere) gives faster results without compromising on accuracy, but requires expertise in mesh generation. After meshing, material properties (density, thermal conductivity and specific heat at different temperatures, and latent heat of cast metal) and process variables have to be either selected from a library or specified interactively. Then the boundary conditions have to be specified, in terms of heat transfer rates from different regions of the die, which is influenced by the properties of the die material and the variable air gap between the part and die, besides process variables.

Simulation programs give accurate results if the CAD model, FEM mesh, material properties and boundary conditions are correct (otherwise: garbage in, garbage out). Material property and boundary conditions data usually have to be determined and fine-tuned through experimentation. This may take several weeks, which is beyond the scope of most small and medium companies. Second, these programs require engineers with higher academic qualifications, CAD/CAM skills and die casting experience to conduct the simulation and interpret the results properly. Third, the programs are computation intensive, and require powerful engineering workstations. Even then, a single iteration of CAD model creation, mesh generation, boundary condition specification, simulation and visualization can take 2-5 days for a complex part. Thus it may take several days to arrive at an optimal die design.

To slash the total die development time, it is important to minimize the time taken for die design, casting simulation and analysis of results. This is possible by adapting an integrated approach for the above three tasks. An automated die design program, which incorporates casting domain knowledge, will quickly give a good first design. An intelligent simulation program, which does not require cumbersome user inputs, will reduce the time for virtual trials. Finally, automated interpretation of the results will point out directions of improvement and reduce the number of design iterations. Such an integrated approach, based on an intelligent casting design system, called AutoCAST, has been developed. This is described next.

INTELLIGENT DESIGN ASSISTANT

The AutoCAST software provides a single integrated environment for casting design, modeling, simulation, analysis and project data management. Advanced geometric reasoning and knowledge-based functions have been incorporated in the software, making it work like an intelligent assistant to casting engineers. The methodology for casting design (mainly feeding and gating systems), process simulation, castability analysis and optimization is explained here with the help of a case study.

The product is an Aluminum alloy (LM4) compressor cover casting produced by permanent mold (gravity die casting) process. The largest dimension of the part is 186 mm, minimum wall thickness is 4 mm and the weight is 1.2 kg.

The part is modeled using AutoCAD 2000 and exported to a file in the standard STL format. The STL file is then imported into AutoCAST software. The part model is oriented along a vertical parting line, as per the current practice. The program suggests the mold size and after confirmation from the user, creates the mold model around the part model. Both models can be visualized (Fig.4).

A preliminary simulation of casting solidification was carried out. The program automatically generates the mesh, sets the boundary conditions (based on metal and process), computes the progress of solidification, post processes the results and displays the location and extent of shrinkage porosity (Fig.5). All this took less than 15 minutes on a Pentium computer.
To increase the heat transfer rate near the porosity zone, a chill is modeled in the center (Fig.6). This involves specifying the chill type, location, shape and size. The software automatically models the chill and considers its effect on casting solidification. Simulation shows that porosity is reduced, but not completely eliminated (Fig.7).

The layout is then changed to horizontal. For this, the part model is turned in the mold, the parting is set to horizontal and the mold is remodeled. The feeder location is specified by selecting the connection point on the part surface. The program automatically computes the significant modulus (ratio of volume to cooling surface area) around the hot spot in the part, and designs the feeder dimensions to ensure that its solidification time is longer than the hot spot. After user confirmation, the feeder model is created automatically. Again, simulation shows that the feeder alone is unable to eliminate porosity, and a chill is also modeled (as described earlier) at the bottom of the casting.

The gating layout is also created by the program semi-automatically. The user only specifies the ingate connection points on the part surface. The program automatically suggests the sprue location and the runner path, which can be modified by the user if necessary. The ideal filling time is computed based on the metal, process, weight, wall thickness and pouring temperature, for confirmation or modification by the user. Then the dimensions of all gating elements are automatically computed, and a solid model of the gating system is created.

The solid models of the feeder, chill and gating system, along with the part model, are displayed for visual feedback (Fig.8). The size of feeder and chill are optimized through several iterations of design-model-simulate-analyze until simulation predicts zero porosity defects even for the highest quality requirements (Fig.9).
Finally, castability health-checks assess the casting design on a scale of 0-100. A value of zero implies impossible to cast and 100 implies ideal castability. The actual values usually lie in-between. The Fettling criterion, for example, is assessed by comparing the casting wall thickness (connected portion) to thickness of feeder neck or ingate. Weights are attached to each criterion, and the weighted sum of assessment of individual criteria indicates the overall health of the feeding or gating design. The weights may be different for each project, depending on customer requirements and production constraints, and can be changed by the user. The weighted assessment is not only useful as an absolute measure, but also for comparing the relative health of two different casting designs. Table 1 shows the assessment of the final layout of the compressor cover casting. The weighted assessments of feeding and gating criteria are above average, but can be improved further by part design for castability.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder Yield</td>
<td>50.0%</td>
<td>63.7%</td>
</tr>
<tr>
<td>Feed Efficiency</td>
<td>30.0%</td>
<td>02.6%</td>
</tr>
<tr>
<td>Feeder Fettling</td>
<td>20.0%</td>
<td>98.0%</td>
</tr>
<tr>
<td>Weighted Assessment</td>
<td></td>
<td>52.2%</td>
</tr>
<tr>
<td>Filling Time</td>
<td>20.0%</td>
<td>62.5%</td>
</tr>
<tr>
<td>Choke Velocity</td>
<td>30.0%</td>
<td>33.3%</td>
</tr>
<tr>
<td>Gating Yield</td>
<td>20.0%</td>
<td>54.5%</td>
</tr>
<tr>
<td>Gating Fettling</td>
<td>30.0%</td>
<td>65.3%</td>
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<tr>
<td>Weighted Assessment</td>
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<td>53.0%</td>
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</tbody>
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**LEVERAGING DOMAIN KNOWLEDGE**

We are also using AutoCAST as a platform to capture and leverage specialized domain knowledge of a particular organization, for even better and faster decision support. There are two areas of focus: (1) improved design calculations to obtain a good first design of feeding and gating systems, and (2) more accurate simulation results for improved matching between predictions and actual observations.

To improve the results of design calculations, various equations are being generalized and their coefficients made accessible to the user, who can easily change them. For example, ideal pouring time calculation is based on three parameters (weight, thickness and fluidity), and six factors, as follows:

\[
POUR_{\text{TIME\_IDEAL}} = POURTIME_{\text{FACTOR}} \times \text{FLUIDITY}_{\text{FACTOR}} \times \frac{\text{fluidity}/1000 \times (\text{SIZE}_{\text{FACTOR}} + (\text{THICK}_{\text{FACTOR}} \times \text{thickness}/20))^{\text{WEIGHT}_{\text{POW}}}}{\text{WEIGHT}_{\text{FACTOR}} \times \text{weight}},
\]

The POURTIME_FACTOR is an overall correction factor for ideal filling time and can be modified if there is a consistent difference between suggested and practical values (always higher or always lower). The SIZE_FACTOR accounts for the casting size and is taken from a table of values against casting size ranges. Similarly, the THICK_FACTOR accounts for the average wall thickness of the casting. A particular company may have its own knowledge base of ideal pouring time for a family of castings (size, shape, wall thickness) of a particular metal produced by a particular process. This knowledge can be incorporated in the library of metal-specific process characteristics to match the suggested ideal pouring time with the values used in practice.

The second application is fine-tuning the results of solidification simulation for an existing or a new combination of metal and process. This is really useful when accurate values of the thermo-physical properties (density, thermal conductivity, specific heat, etc.) of the casting metal or mold material are not available and the boundary conditions (metal-mold interface air gap thickness, heat transfer coefficient,
etc.) are unknown. For example, the FR_RANGE_FACTOR interprets the results of solidification simulation to map the extent (spread) of shrinkage porosity from the hot spot, depending on the quality level desired. This factor can be adjusted to match the prediction with observed results. For this purpose, several simulation runs are carried out, each with a slightly different value of the factor, until the matching is perfect. The factor is then incorporated in the database for automatic application when the same combination of metal and process is used in another casting project.

In a recent project, the software was customized (in a single day) for a high-Mg aluminum alloy ASTM tensile bar casting, produced by gravity die casting. The solidification analysis parameters were fine-tuned for one layout (Fig.10), and then used to analyze a different layout (Fig.11). The predictions perfectly matched the known results for the second layout.

**CONCLUSION**

To ensure zero defect castings, it is necessary to correctly optimize the casting design (feeding and gating). We have shown how this can be achieved by combining automated design, intelligent simulation and castability health-checks. By integrating all three in a single environment, the design-simulate-analyze cycle time has been reduced to less than one hour. This makes it possible to optimize even complex castings in a single day. We have also shown how the system can be customized to leverage the specialized domain knowledge of a particular company for reuse on new projects. This will ensure better casting design decisions, faster than ever before.

**ACKNOWLEDGEMENTS**

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**REFERENCES**