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Design for Casting - A New Paradigm for Preventing Potential Problems

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Abstract

Design revisions are expensive and time consuming. Yet, these are inevitable because product designers have limited knowledge about casting processes and have no means to evaluate the influence of design features on castability (costs, quality and productivity). Problems appear much later, at the tooling or manufacturing stage, when it is much more expensive to incorporate changes than at the design stage. Progressive engineering companies therefore rely on design review committees, which include tooling and casting engineers, to suggest early modifications to a product design for ease of manufacture. This paper presents an intelligent design environment to assist product engineers in assessing a part design for castability. The software simulates the way casting engineers decide the casting process, parting line, cores, mold box, feeders, gating system and mold layout, and analyzes each decision to suggest how the design could be modified to improve quality as well as reduce tooling and manufacturing costs. The software also facilitates electronic exchange of information between product, tooling and casting engineers, thus improving the level of communication between them and helping compress the total lead time to complete a project.

Keywords: *Casting, Computer-Aided Design, Concurrent Engineering, Design for Manufacture, Simulation.*

1 Beyond Structural Design

Casting continues to be the most preferred process to create intricate shapes in metal, but is also one of the most difficult to precisely model and control for achieving consistent quality. The range of variation in terms of geometric, material and process characteristics, and their uncharted effects on manufacturability makes every casting project a new challenge. It is no surprise that the foundry industry continues to suffer from poor utilization of material, energy and human resources: the average scrap rate is as high as 7% [1] and the average lead time to produce the first casting for approval is 10-14 weeks [2].

Today, casting engineers have access to a range of software, starting from database management and design calculations to process simulation and computer-integrated manufacturing, in increasing order of difficulty of installation and use (Fig.1). Of these, computer simulation of casting process has emerged as a powerful tool for achieving quality assurance without time consuming trials. Software packages for simulating the solidification of molten metal in the mold enable predicting the location of shrinkage defects and optimizing the design of feeders to improve the yield; more advanced packages perform coupled simulation of mold filling and casting solidification [3]. It has been reported that simulation studies can reduce casting defects, manufacturing costs and lead time by as much as 25% [4]. Already, an estimated 1000 foundries (among 33,500 worldwide) are using simulation software to improve their performance and the number of simulation users is steadily increasing.

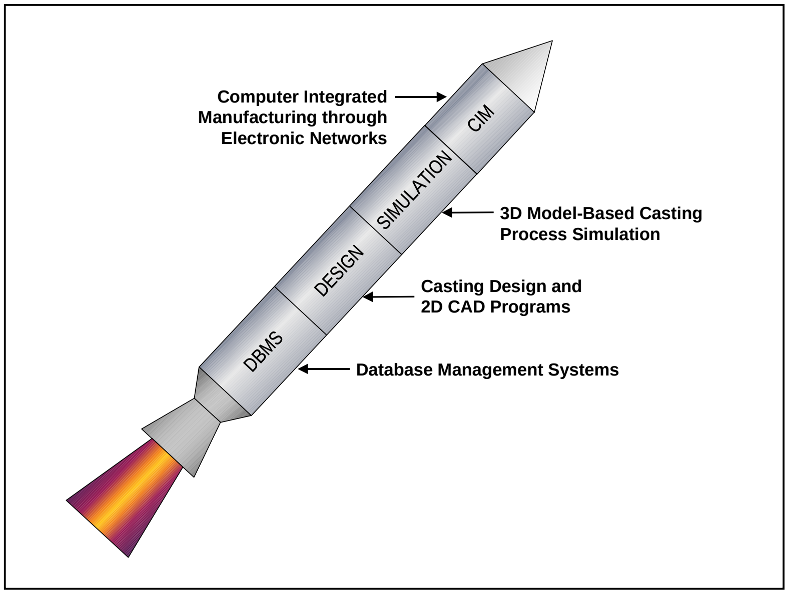

Fig. 1 Range of software tools for casting engineers.

However, casting engineers only produce what product engineers design. Designers mainly focus on product function - creating an optimal shape to withstand operating stresses - aided by excellent Finite Element Analysis software available for this purpose. They are largely unaware of the casting processes, their capabilities and limitations [5]. This results in either over design (for example, unnecessary thick ribs leading to heavier castings) or under design (for example, inadequate fillet radius leading to casting defects). Many product features (for example, undercuts) require complex tooling, and others (for example, isolated mass concentration) require additional steps during casting (say, placement of chills). All these mean higher cost, lower quality assurance and longer lead time.

Often, a product design causes severe problems at the casting stage, and the foundry may request the customer to either modify the design or pay a higher price to offset the costs of tooling modification, increased scrap and additional operations (such as heat treatment and machining). Significant design modifications at this stage could mean additional burden of redoing the tooling and planning the process again, besides losing the time and resources already spent on these activities.

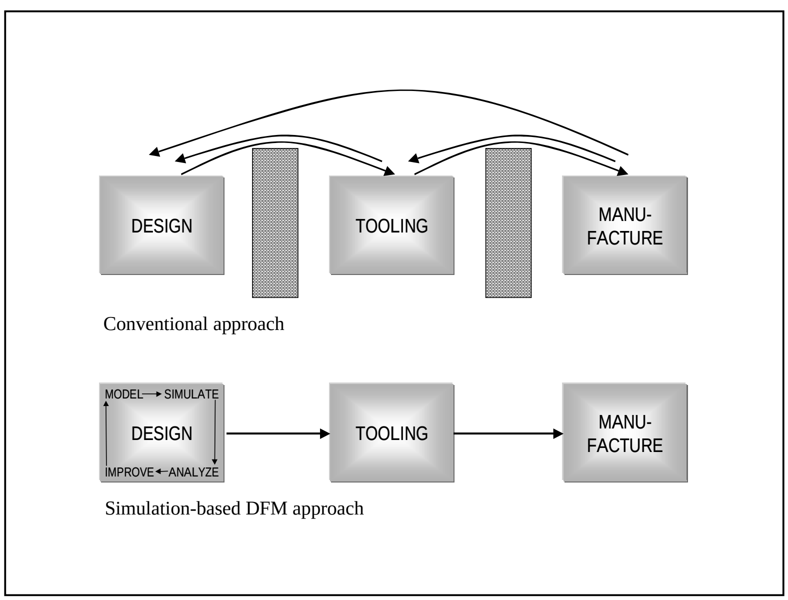

Fig. 2 Design for manufacture versus conventional approach.

Compared to the above, modifying the design of a cast product while it is still on the drawing board is as easy as erasing and redrawing a line. If the ratio of benefit to cost is considered, then it is immediately apparent that dramatic saving of resources can be achieved by predicting potential problems at the design stage itself, and preventing them through suitable changes to product features. This approach is termed Design for Manufacture (Fig.2).

2 Design for Casting

Design for Manufacture (DFM) has caught the attention of both researchers and practicing engineers over the past one decade to bring about dramatic improvements in the ease of manufacture. The most widely practiced form of DFM is through manufacturability guidelines. These are essentially coded rules encapsulating past experience in producing similar products. The guidelines are specific to a manufacturing process; examples of guidelines for casting include minimum wall thickness, aspect ratio of a hole and expected tolerance across mold parting.

Automobile companies were among the first to apply the principles of DFM to simplify product designs, particularly for machined parts, sheet metal parts and assemblies. One of the earliest examples was the Viper car project at Chrysler which was developed from scratch within 3 years and within budget. Gradually this approach has spread to the rest of engineering companies, many of them reporting savings of 20% of costs and 50% of time, besides improved quotations from vendors [6]. However, the guidelines are not always exhaustive nor available (particularly for a radically new design) and they sometimes conflict with each other. Also, new materials and processes have rendered many of these guidelines obsolete. Therefore many companies rely on Concurrent Engineering, in which design review committees comprising of experts in prototyping, tooling, manufacturing, marketing, maintenance and other areas evaluate the design and suggest modifications before it is finalized and released for further action. Design review is however, a *reactive* approach in which designers merely try to confirm the manufacturability of a particular design or improve it slightly. Product engineers need to be *proactive* and take advantage of the range of cast metals and processes available to create a product which best satisfies the final requirements.

Computer simulation of the manufacturing process would appear to be a good approach to explore new combinations of geometric, material and process parameters. It would seem that designers, who are already familiar with CAD/CAM, including solid modeling and Finite Element Analysis software, would welcome this approach. Indeed, simulation-based DFM is favored by plastics products companies, who usually own the injection molds and therefore willing to spend time and effort in designing the product as well as the tooling so as to minimize overall costs, defects and lead time.

In the case of cast products, a typical DFM iteration involves modeling the part, designing the casting features (including parting, cores, mold, feeders and gating system), creating a solid model of the entire casting, generating the FEM mesh, specifying the boundary conditions (such as heat transfer coefficients and temperature dependent properties of metal and mold), performing the simulation, interpreting the results and deciding further modifications to the design of either the part or the tooling. A number of such design-simulate-analyze iterations are required to optimize the casting design, which could take several days. Thus simulation-based DFM of cast products calls for an in-depth knowledge of the process, as well as significant time and effort for design improvements. For this reason, very few engineering companies perform Design for Casting, including those who have captive foundries.

A combination of simulation-based DFM and Concurrent Engineering has been prescribed for the immediate future. A team of researchers from Concurrent Technologies Corp described how castings will be designed and manufactured in 2000 through electronic exchange of relevant information between designers and foundry engineers who will be using different CAD software specific to their tasks [7]. Virtual prototyping of not only the casting process, but also the entire business has also been proposed [8]. Practical implementation of any such systems has not been reported so far.

Two separate initiatives in 1996 helped understand the needs of casting engineers. The first was the Foundry Benchmarking Survey conducted by the American Metalcasting Consortium and sponsored by the Department of Defense [2]. The survey team was led by Prof. R.C. Creese at the West Virginia University. This study showed that the average lead time for the first article of approval is about 10 weeks for aluminum and steel foundries, 11 weeks for ductile iron and 14 weeks for gray iron foundries. Tooling development emerged as the most important factor, taking up as much as 80% of the total lead time. This showed that significant savings in overall lead time could be achieved by compressing the tool development time alone.

The second initiative was the setting up of a web site called *Casting 2000* at the Concurrent Engineering Research Center in Morgantown, West Virginia during 1996-97. It described a conceptual framework for assisting and linking casting life-cycle engineers (product designers, tool makers, foundry engineers and supply managers) for better and faster decision making. The web site received encouraging feedback from all parts of the world, and the suggestions helped in designing the information backbone of a future software system. A prototype of the system, named AutoCAST, was created and shown to casting engineers [9]. Their suggestions were incorporated in the software to improve it further in terms of features, programs, database structure and user interface. These are described in detail next.

3 Intelligent Design Environment

AutoCAST has been developed as an *intelligent assistant* to casting designers. It simulates the way casting engineers perform various tasks in casting design. The present work integrates the work of the first author in parting line and cores [10], feeding [11], gating [12] and information management [13]. The entire casting design is analyzed using a set of castability criteria [14]. Depending on the results of the analysis, suitable design changes to improve castability are suggested through context sensitive guidelines [15].

The software runs on Pentium computers with Windows-NT or Windows-95/98 systems. It comprises nine integrated programs for various tasks in casting design linked by a casting project database manager. These are briefly described here, before taking up an example of casting design in the next section.

*3.1 Software Features: The **5-I***

<u>Intelligent Routines</u>: The software incorporates a powerful geometric reasoning engine which intelligently suggests good first solutions, while allowing the user to modify the recommendations or impose additional constraints. This minimizes user input to achieve any task in casting design.

<u>Integrated Applications</u>: The software has a range of functions useful to casting life-cycle engineers, including product designers, tooling engineers, foundry engineers, quality inspectors and managers. These functions enable the user to design, model, simulate, analyze and improve the casting design without switching between applications.

<u>Information Management</u>: All functions are linked through a casting project database, serving as both input and output. Parts of the database can be notionally owned by a different person, department or organization, and exchanged between them.

<u>Intuitive Interface</u>: The user interface combines database, applications and model display in a clutter-free, pleasant and easy to use environment. All programs have a uniform interface, compatible with Microsoft Windows, and can be learnt easily.

<u>Immediate Response</u>: The software anticipates the needs of the user and positions itself to respond to the next command. Advanced techniques such as software agents, true 32-bit computing, and optimized algorithms enable real-time results.

3.2 Casting Design Programs

AutoCAST comprises a suite of nine programs to perform various tasks associated with casting design (Fig.3). Each program comprises a set of modules for design, solid modeling, simulation, analysis and improvement. The programs are listed below.

<u>Product Design</u>: This program helps in importing a solid model of the part from an external solid modeler through a standard exchange format, followed by computation of geometric properties. Wall thickness, section variation, complexity and other criteria are used for castability analysis, followed by suggestions to improve the design further.

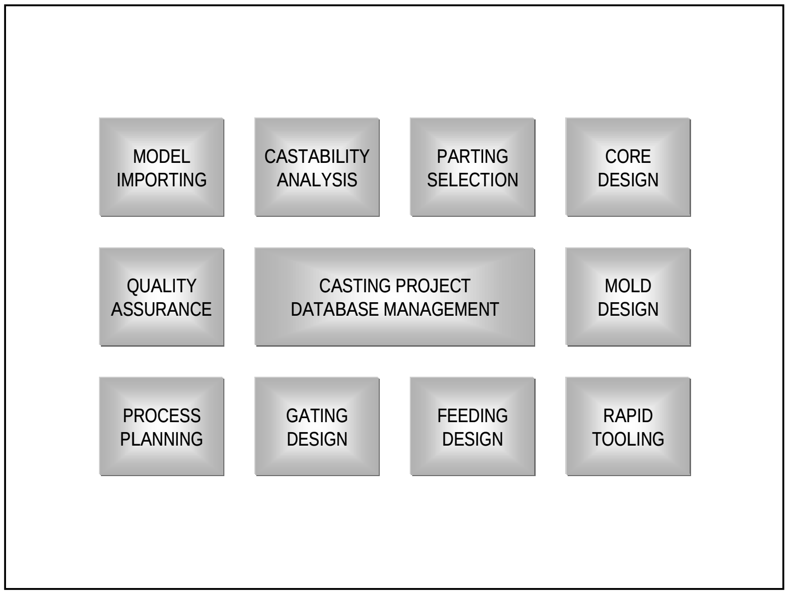

Fig. 3 Casting design programs in AutoCAST.

Parting Design: This program suggests the best orientation of the casting in the mold, generates several parting lines and determines the best alternative, aligns the parting line with the mold parting plane, and finally analyzes the current parting in terms of flatness, draw distance, draft volume, dimensional stability, etc. to suggest improvements.

Core Design: This program first identifies cored features in the part model: through holes, deep pockets and undercuts. For each cored feature, it designs the core print and creates a solid model of the entire core. Finally, it analyzes the cored feature for failure, venting and other criteria, based on which guidelines for design improvement are presented.

Mold Design: This program selects the most appropriate mold box to enclose the casting, determines the optimal number of cavities and displays the cavity layout. The mold design is analyzed in terms of metal to sand ratio, cavity shape and other criteria, based on which guidelines for design improvement are displayed.

Rapid Tooling: This program suggests an appropriate route for producing master pattern, master mold, regular pattern, regular mold, master core, core box and regular core using a sequence of rapid prototyping, rapid tooling and conventional methods. It also suggests the best orientation for minimizing the fabrication time using the above techniques.

Feeding Design: This program first simulates the solidification of the casting to determine the location of hot spots and suggests an appropriate location for the feeder. It also calculates the feeder dimensions, creates its solid model and attaches it to the casting. Feeding aids such as chills, insulating sleeves and exothermic covers can be modeled. The feeding design is further verified by progressive solidification plots on a section and directional solidification vectors (feed metal flow paths) inside the casting. Yield, feeding efficiency and ease of fettling are computed to compare different layouts.

Gating Design: This program suggests the connection points for ingates and the location of sprue, followed by the layout of runners. It determines the optimal pouring time, designs the entire gating system and creates its solid model. Mold filling simulation is performed to determine the actual filling time, and to identify gating related defects. The gating design is analyzed in terms of yield, ease of fettling and other criteria based on which suggestions for design improvement are presented.

Process Planning: This program suggests an appropriate casting process for producing the part (given its metal, weight, lot size, quality specifications, etc.). It plans the requirement of cast metal, mold sand, core sand and other materials. An activity based approach is used for analyzing the lead time and costs for producing the casting.

Quality Assurance: This program helps in casting inspection in two ways. It assists in setting up reference dimensions between specified locations on the casting surface and determines the ideal distance between them. It also simulates radiography to produce the radiograph of a defect-free casting, which can be compared with actual radiographs to identify internal defects in the casting.

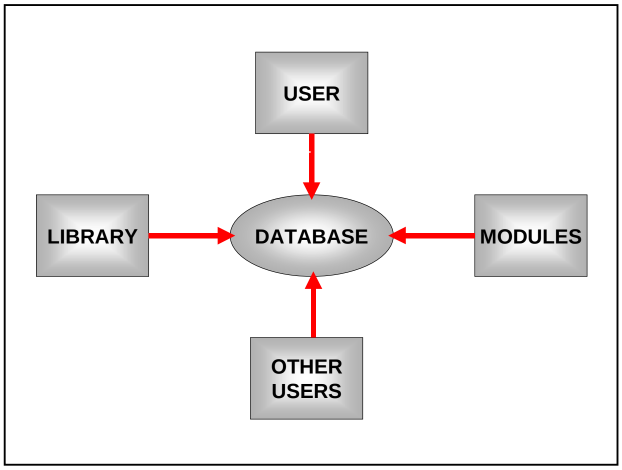

Fig. 4 Casting project database acts as the exchange medium.

3.3 Casting Project Database

AutoCAST treats the design and manufacture of each individual cast component as a separate project. The casting project database acts like a medium of exchange (Fig.4) and serves the following objectives:

- Provide a transparent window to the user to view the data related to the casting.
- Enable user input required for some modules and to allow 'what-if' explorations.
- Reuse of data between different functions of the software without repetitive entry.
- Exchange of selected data between different users through email over a network.

The database is primarily stored as a casting PROJECT, which in turn has six children: ADMIN, PRODUCT, TOOLING, PROCESS, MATERIAL and QUALITY. Each of these blocks contains information related to a specific aspect, and is notionally 'owned' by the corresponding person, department or organization in charge. The child blocks are arranged in a hierarchical tree structure (parent-child-grandchild). Each block in the casting project database has a set of lines, each line containing the name of a field and its value. Most values are integers, real numbers or character strings (ex. names, date and time). Some fields are references to other blocks and some blocks are linked to geometric models (part, feeder, parting line, etc.).

The user can edit a value or its units by clicking inside the box containing the value. Even new units can be typed, and the software will automatically convert the value according to the units. Coordinate values can be modified by directly clicking on solid models.

Library data files (cast metal, mold boxes, etc.) can be viewed and copied to the current casting project database. The casting design guidelines are also stored in the library directory as bitmap files showing a pair of figures and an explanation of the problem/solution.

3.4 User Interface

AutoCAST has a Windows-based graphical user interface. The screen area, referred to as the desktop, is divided into 4 zones: program menu (top), casting database (middle left), model display (middle right) and system feedback (bottom), providing simultaneous access to all these. The entire desktop can be resized.

The main menu lists various programs (Database, Product, etc.). Clicking on any one of these displays a pull-down menu with sub-options. Clicking on the sub-option launches the particular routine and the results of the computation are shown in the updated database and/or the displayed solid model.

Icon buttons to manipulate the model display, arranged on a vertical bar on the right side of the desktop, include: entity selection, hide/display model, wireframe view, shaded view, move left, move right, move up, move down, turn left, turn right, tilt up, tilt down, zoom up, zoom down, zoom to fit, clean display, top view, front view, side view and isometric view. The database has its own buttons which include: view library options, view top block, view previous sibling, view next sibling, view previous page and view next page. The parent of the currently displayed block is shown as the title button. In addition, most blocks have child blocks which can be accessed by clicking on buttons labeled DETAILS next to their names.

A 3-dimensional model of the cast product is an important input for design and analysis functions in AutoCAST. The user may get the model from the customer, contract the part modeling task to a service bureau, or create the part model using a solid modeling software. Part models can be imported into AutoCAST through a data exchange interface using the industry standard STL format.

Other solid models: mold, cores, feeders, feedaids and gating channels are created by internal functions based on the data created during casting design. Thus the user need not switch between modeling and analysis programs once the part model is available, considerably saving time and effort. Different colors are used to visually distinguish between the various models. Any solid model can be selectively hidden or shown as a wireframe or shaded image. It can also be shifted or rotated relative to others. The three orthogonal coordinate axes are shown along the mold body, in three separate colors.

On-line help is available by clicking Help in the main menu. This includes a quick round-up of all the features, detailed information on any module and description of the database structure and related functions.

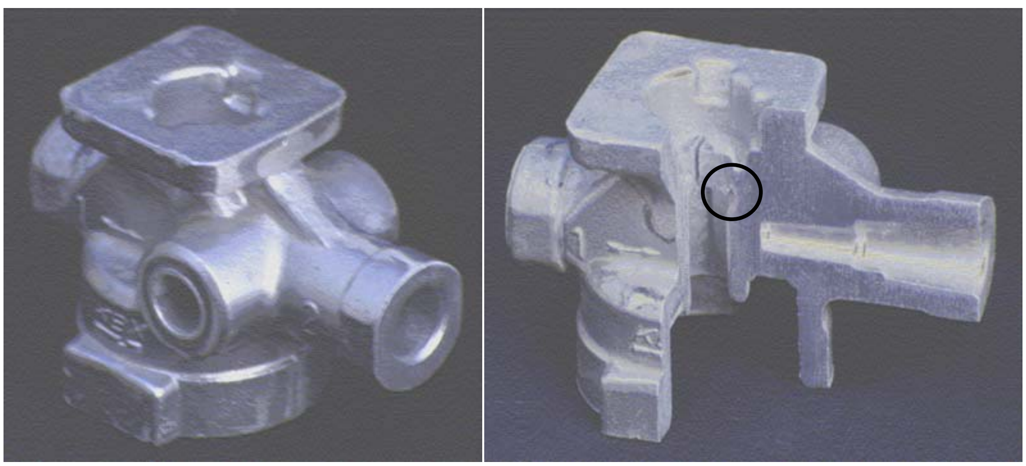

Fig. 5 Test casting and its section showing shrinkage defect.

4 Casting Design - An Example

An example session of casting design and analysis using AutoCAST is given here. The casting is an aluminum alloy unloader valve (Fig.5). The valve was first modeled using Pro-Engineer software (from Parametric Technologies Corp, USA) and exported as a standard exchange file in STL format. A new casting project was started in AutoCAST with preset default values. The part STL model was imported and the alloy properties were copied from the library. An appropriate mold box was selected and modeled.

The part is displayed as a shaded image inside a transparent mold in the main window and the computed properties are shown in the database window (Fig.6). The program suggested gravity die casting as the most appropriate process for the given casting alloy, geometric characteristics, quality specifications and lot size. Based on the capabilities of the process, the part features were analyzed. The criteria for complexity and wall thickness returned poor assessments and the guideline suggested increasing the minimum wall thickness (Fig.7). The casting orientation and parting line suggested by the program were accepted. Cored features were extracted and solid modeled (Fig.8). Minimum core diameter was found to be adequate during the analysis of cores.

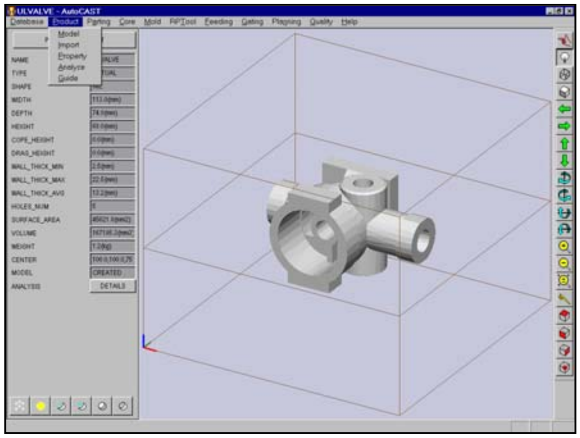

Fig. 6 Casting and mold models in AutoCAST.

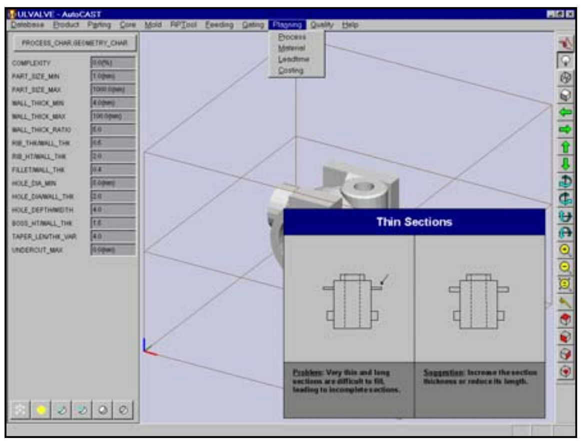

Fig. 7 Design analysis points out a problem with wall thickness.

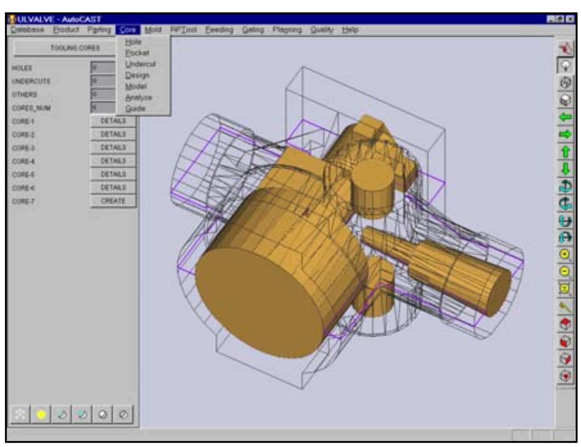

Fig. 8 Parting line and cored features for the casting.

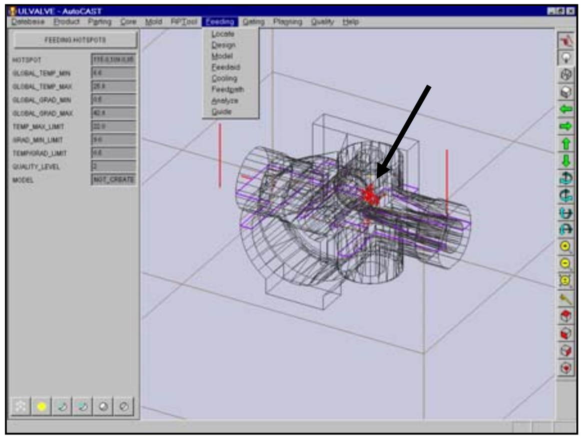

Fig. 9 Solidification simulation shows shrinkage cavities.

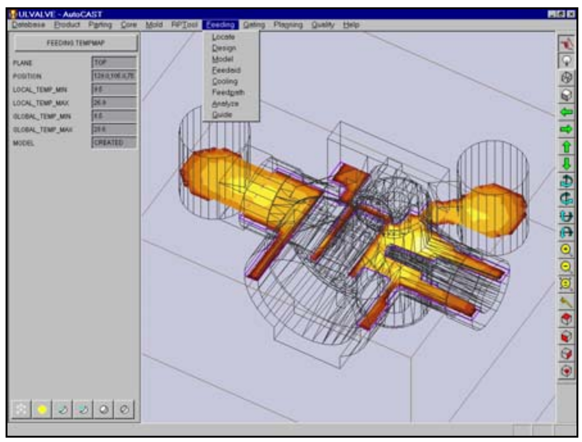

Fig.10 Solidification profile shows that the problem persists.

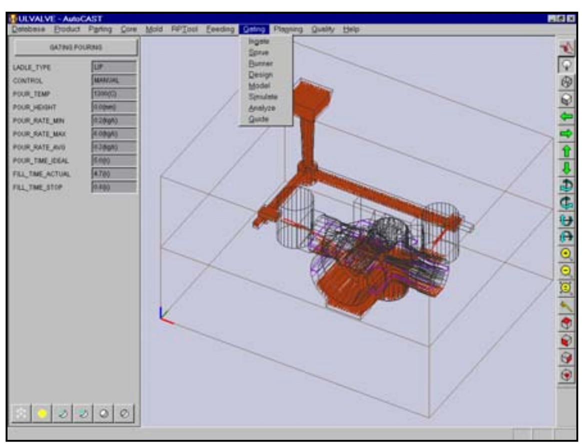

Fig.11 Gating design and mold filling simulation.

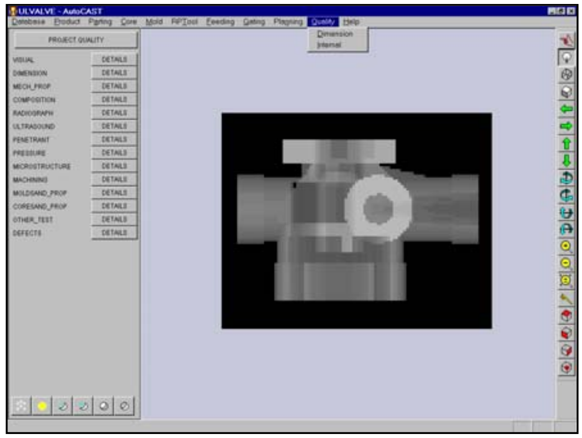

Fig.12 Simulated radiograph of the casting.

Solidification simulation revealed two isolated hot spots inside the casting (Fig.9). After feeder design and modeling, it was found that one of the hot spots is difficult to remove even with a large sized feeder (Fig.10). The actual casting experienced severe shrinkage defects at the same location. Since the hot spot is caused at the junction of thick sections and cores, coupled with the difficulty in reaching the defect region to apply either feeders or feedaids, modifications to part design may be necessary. The gating design was done as suggested by the program; the filling simulation showed the sequence of filling the mold and a narrow difference between the optimal (designed) and actual filling time (Fig.11). Finally, a radiography simulation was performed to produce the image of an ideal radiograph (Fig.12), useful for comparing with actual radiographs during inspection.

5 Conclusion

Design for Manufacture (DFM) has been successfully applied to machined, sheet metal and plastics parts to significantly reduce manufacturing costs and lead time. So far, it did not find wide acceptance in the casting sector owing to a lack of suitable software tool for this purpose. The AutoCAST software described in this paper aims to fill this gap. Early benchmarking results and beta tests have shown that it can be easily used by design engineers, who have limited knowledge of the casting process, to improve the design for ease of casting. This will enable product engineers to design more cost-effective parts through a better appreciation of the problems faced by casting engineers. It will also improve the level of communication between product, tooling and foundry engineers, leading to better and faster decision-making.

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