Optimization of Casting Process Parameters through Simulation

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***Abstract*— Casting simulation helps visualize mold filling and casting solidification; predict related defects like cold shut, shrinkage porosity and hard spots; and optimize the casting design to achieve the desired quality with high yield. Flow and solidification of molten metals is however, a very complex phenomenon that is difficult to simulate correctly by conventional computational techniques, especially when the part geometry is intricate and the required inputs ((like thermo-physical properties and heat transfer coefficients) are not available. For industrial application, we need alternate approaches that are fast, reliable and user-friendly. Key benefits and best practices, based on studies of industrial cases of casting defect prediction and feeding system optimization, are presented. Current research directions include integration of basic and advanced simulation techniques, useful for large foundries; and cloud-based simulation, useful for SME foundries. Optimization plays vital role in business. It is an effort towards making the things run smoothly with efficient utilization of available resources. Optimization is the philosophy of life. When applied to the engineering sector, that too to foundry it saves unnecessary wastage of resources. This leads to the noticeable savings in terms of cost. In this paper new method of casting defect analysis is proposed and studied.**

***Index Terms*— Casting Design, Casting Defect, Simulation, Optimization, Analysis**

I.INTRODUCTION

Metal casting is one of the direct methods of manufacturing the desired geometry of component. The method is also called as near net shape process. It is one of the primary processes for several years and one of important process even today in the 21st century. Early applications of casting are in making jewellery items and golden idols. Today, casting applications include automotive components, spacecraft components and many industrial & domestic components, apart from the art and jewellery items.

Casting Defect Analysis

Casting defects analysis is process of finding the root cause of occurrence of defects in the rejection of casting and taking necessary steps to reduce the defects and to improve the casting yield. Techniques like cause-effect diagrams, design of experiments (DoE), casting simulation, if-then rules (expert systems) and artificial neural networks (ANN) are used by various researchers for analysis of casting defects. Casting defects result in increased unit cost and lower morale of shop floor personnel. The defects need to be diagnosed correctly for appropriate remedial measures; otherwise new defects may be introduced. Unfortunately, this is not an easy task, since casting process involves complex interactions among various parameters and operations related to metal composition, methods design, molding, melting, pouring, shake-out, fettling and machining. For example, if shrinkage porosity is identified as gas porosity, and the pouring temperature is lowered to reduce the same, it may lead to another defect, namely cold shut. So far, casting defect analysis has been carried out using techniques like cause-effect diagrams, casting simulation, design of experiments, if-then rules (expert systems), and artificial neural networks. Most of the previous work is focused on finding process-related causes for individual defects, and optimizing the parameter values to reduce the defects. This is not sufficient for completely eliminating the defects, since parameters related to part, tooling and methods design also affect casting quality, and these are not considered in conventional defect analysis approaches. In this work, we present a 3-step approach to casting defect identification, analysis and rectification. The defects are classified in terms of their appearance, size, location, consistency, discovery stage and inspection method. This helps in correct identification of the defects. For defect analysis, the possible causes are grouped into design, material and process parameters. The effect of suspected cause parameters on casting quality is ascertained through simulation. We trace the history of such approaches, starting from the Modulus Concentration Method in recent Gradient Vector Method in 2012, as well as their incorporation in software programs for casting design and simulation [1].

II.METHODOLOGY

In this proposed method of casting defect analysis, computer aided casting simulation technique is used for methoding, filling and solidification related defects such as shrinkage porosity, hot tears, etc. the DoE whereas (Taguchi method) is used for analysis of sand and mould related defects such as sand drop, bad mould, blow holes, cuts and washes, etc.

Casting Simulation for Casting Defects Analysis

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. It has been reported that simulation studies can reduce casting defects, manufacturing costs and lead time by as much as 25%. 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.

Methods design is usually carried out manually on the part to be cast. The tooling is then fabricated, trial castings are produced in the foundry in trial run in small batches, and inspected. If these castings contain defects, then the methoding is modified and the process is repeated. Each such iteration can take up several days which delays delivery schedule, is lead time and hence the customer is dissatisfied. After a few iterations, the foundry may find the best alternative for the methoding which may help to solve the problems stated earlier. It may also help to increase yield, reduce the rejection rates This is especially true in the case of large castings, where the cost of a trial or repair can be prohibitive [2].

Casting simulation can overcome the above problems: virtual trials do not involve wastage of material, energy and labour, and do not hold up regular production. However, most of the simulation programs available today are not easy-to-use, take as much time as real trials, and their accuracy is affected by material properties and boundary conditions specified by users. The biggest problem is the preparation of 3D model of the casting along with mold, cores, feeders, gating, etc., which requires CAD skills and takes considerable time for even simple parts. Methoding is an important task in casting production, directly affecting casting quality and yield. It involves several decisions, such as the size of mold box and number of cavities, orientation. Casting simulation is used to modify such method and to get best alternative of process.

Need of Optimization during Casting Process

Optimization is the process of finding the best way of using your resources, at the same time not violating any of the constraints that are imposed. By "best" we usually mean highest profit, or lowest cost. Even after spending significant resources (man-hours, materials, machine overheads and energy) for casting development, one of the following situations may arise during regular production.

1. **Under design**: Resulting in high percentage of defective castings. This usually happens when the number or size of feeders and gating elements are inadequate, or their placement is incorrect. Sometimes the cause is an undersized neck or a thin intermediate casting section, which prevents feed metal flow from the feeder to the hot spot inside the casting.
2. **Over design**: Leading to acceptable quality level, but poor yield and thereby higher cost. In this case, the number and/or size of feeders and gating elements is much higher than their respective optimal values. This situation usually arises because of lack of time or resources to fine-tune the methoding solution or to try other alternative solutions.
3. **Borderline design**: Irregular defect levels during regular production, although sample castings are defect-free. This happens when the methoding solution is just optimal (perhaps by accident), which will produce good castings only under controlled conditions. This is difficult to expect in practice, especially with manual molding and pouring [3].

Fig.1 shows 2-D model of bracket chasis which is a one of the casting component from which determination of general outline of casting component takes place.

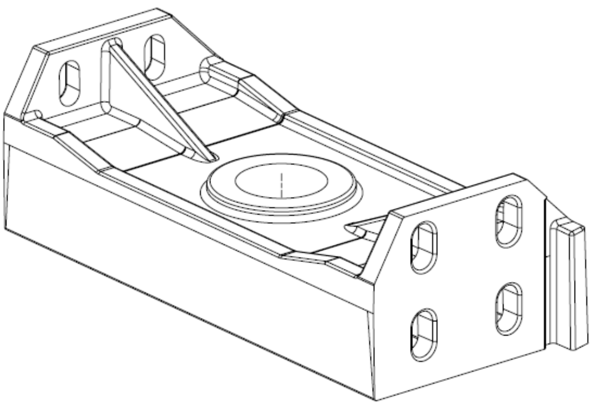

Fig.1: 2-D model of bracket chasis

Optimization of Parameters by Casting Simulation Technique

A simulation model is, in general, used in order to study real life systems which do not currently exist. In particular, one is interested in quantifying the performance of a system under study for various values of its input parameters. Such quantified measures of performance can be very useful in the managerial decision process. The cost concerns of the metal casting company focus on the extra time and energy spent in changing the setup configurations in the manufacturing system. The need for changing the machine set-up is due to the various customer orders that vary in material type, make and dimension. The objective is to design the methoding system, optimize it with the help of simulation and minimize the cumulative total cost incurred in changing of machine set-up. The simulation model is built to assess the set-up cost of every possible combination of the orders. It is necessary to describe briefly the Computer Applications in Simulation of Metal Casting Process, AutoCAST software for simulation and its features and methoding for Green Sand Molded C. I. Casting for different components using simulation software.

Casting Simulation Programs

The casting simulation programs are used for analyzing:

1. Mould filling
2. Casting solidification
3. Internal stresses and distortion
4. Microstructure and mechanical properties

The simulation programs are based on Finite Element Analysis of 3D models of castings and involve sophisticated functions for user interface, computation and display. The casting model (with feeders and gates) has to be created using a solid modeling system and imported into the simulation program. In addition, material properties (density, thermal conductivity, specific heat, latent heat, etc.) and process parameters (pouring time, pouring temperature, casting-to mold heat transfer coefficient) have to be provided by the user. The latter may require extensive experimentation to customize the software databases for a particular organization. After executing the simulation routine, the results can be post-processed to view color-coded temperature profile, velocity vectors or residual stresses. This enables predicting the probable location of defects. The results are reliable if the input data is complete and accurate. The casting design software developed at IITB named AutoCAST is getting popular because of the key features of it such as

- Part volume, weight, surface area
- Part dimensions, as well as its height in cope and drag
- Wall thickness: minimum, average
- Significant modulus around a hot spot
- Casting orientation in the mold
- Suitable position of the parting line
- Suitable location of feeder and gates.

Fig.2 shows input for the AutoCAST which is 3-D geometric model of bracket chasis created in the CATIA software. This model is imported in the AutoCAST as the .stl format [4].

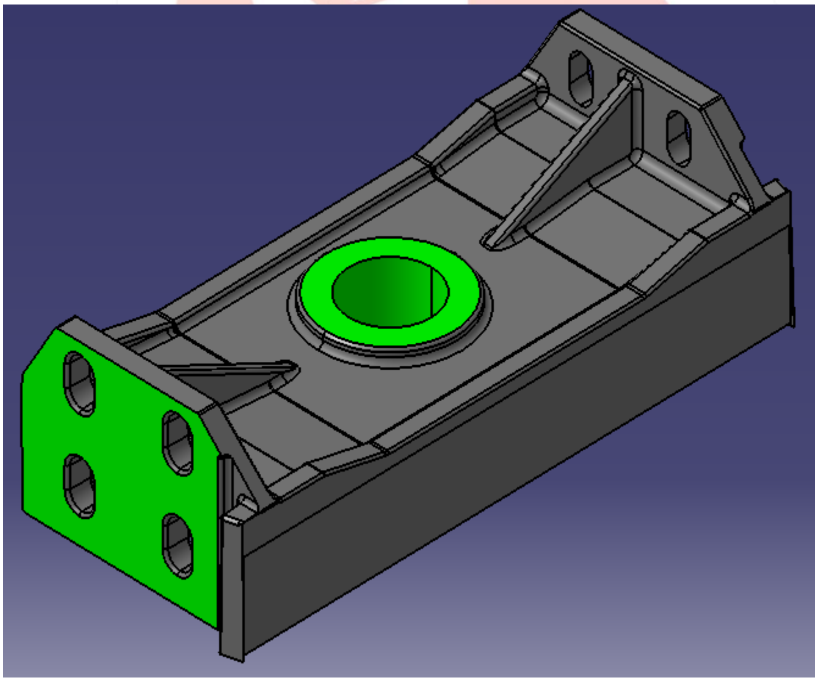

Fig.2: 3-D model of bracket chasis

III. Necessity of Optimization using Simulation

B.ravi et al. have studied survey of 215 foundries all over India2 revealed that use of CAD/CAM and simulation reduced the average lead time for first good sample casting by 30%: from 10 weeks to 7 weeks, and halved the average rejection rate: from 8.6% to 4.1%. Other reported benefits included higher yield, cost reduction and customer satisfaction. Casting simulation can, however, be an agonizing experience for novices. The program may not accept the user inputs, other data may not be comprehensible or available, the computer can hang up or take a very long time to produce the results, and the results may not match shop floor observations. Even regular consultants sometimes experience such problems. A poor knowledge of solidification physics and inadequate training in simulation technology becomes a handicap in successful utilization of simulation technology.

Thus a foundry setting up a simulation facility may end up only showcasing it to visitors. This sets a poor example for others, who delay their learning curve of exploring this important tool. As the simulation programs get more sophisticated every year, it becomes even more difficult to adopt and adapt the technology in their foundries. In this paper, we present guidelines and the best practices for effective implementation and efficient utilization of casting simulation technology. This is based on our experience of guiding over 50 foundries in implementing casting simulation, and supervising over 200 casting simulation projects for others *(Fig. 2)*. Another rich source of knowledge is from interactions with 1200 senior and middle-level foundry engineers who attended our professional course on 'casting design and simulation 'every September since 2000, and ten casting simulation clinics conducted all over India during 2008-2009. We first outline situations which necessitate simulation (not all castings need to be simulated). Then guidelines for establishing a casting simulation facility are presented.

The simulation protocol (step-by-step procedure) is described next, highlighting all important inputs required along the way. Best practices for obtaining accurate results, minimizing the total lead time, We first outline situations which necessitate simulation (not all castings need to be simulated). Then guidelines for establishing a casting simulation facility are presented. The simulation protocol (step-by-step procedure) is described next, highlighting all important inputs required along the way. Best practices for obtaining accurate results, minimizing the total lead time, and ensuring data security are presented. We conclude with future developments in this area, and how foundries can prepare themselves to benefit from the same. Although most of our experience is with AutoCAST, the casting methods design and simulation software developed at IIT Bombay, the guidelines have been generalized to cover all simulation programs, metals, processes, casting shapes and sizes[5].

Richard W Heine and Carl R Loper et al. investigated that simulation model is used in order to study reallife systems which do not currently exist. In particular, one is interested in quantifying the performance of a system understudy for various values of its input parameters. Such quantified measures of performance can be very useful inthe managerial decision process. The cost concerns of the metal casting company focus on the extra time and energy spent in changing the setup configurations in the manufacturing system. The need for changing the machine set-up is due to the various customer orders that vary in material type, make and dimension. The objective is to design the methoding system, optimize it with the help of simulation and minimize the cumulative total cost incurred in changing of machine set-up. The simulation model is built to assess the set-up cost of every possible combination of the orders. It is necessary to describe briefly the computer applications in simulation of metal casting process, AutoCAST software for simulation and its features and methoding for Green Sand Molded C. I. Casting for different components using simulation software.

Necessity of Simulation

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. It has been reported that simulation studies can reduce casting defects, manufacturing costs and lead time by as much as 25%. 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 [6].

B. Ravi and R. C. Creese et al. investigated that casting simulation should be used when it can be economically justified for at least one of the following three reasons:

- **Quality enhancement** by predicting and eliminating internal defects like porosity.
- **Yield improvement** by reducing the volume of feeders and gating channels per casting.
- **Rapid development** of a new casting by reducing the number of foundry trials. The corresponding cost benefits can be estimated.
- **Quality improvement** reduces the (avoidable) costs associated with producing defective castings, including their transport, and warranty or penalties.
- **Yield improvement** reduces the effective melting cost per casting, and increases the net production capacity of the foundry (without adding melting or moulding units).
- **Faster development** of castings through virtual trials eliminates the wastage of production resources, and improves the rate of conversion from enquiries to orders, giving foundries an opportunity to select higher value orders.

Not all defects can be accurately simulated. Solidification shrinkage defects (macro, micro and centerline shrinkage) can be predicted fairly accurately. Flow-related defects (cold shuts and blow holes) can be simulated but may not always match actual observations. Cooling stress related defects (cracks), micro-structure and mechanical properties are difficult to simulate, and extensive calibration experiments may be needed for practical use. From the above it is clear that it is advisable to start with solidification simulation, which requires relatively less inputs, gives fairly reliable results, has a high impact on quality (shrinkage accounts for nearly half of all defects) as well as yield (feeder size optimization), and thus gives a high benefit to cost ratio. There are at least three other secondary (long term) benefits, which accrue after using simulation for some time (few months to years). The corresponding cost benefits are relatively more difficult to estimate, and these reasons are not normally used for justifying setting up simulation facility.

- Manufacturability improvement by part re-design in consultation with OEM
- Methods knowledge management by re-using simulation projects
- Brand image enhancement by using the simulation facility as a marketing tool

High capacity foundries (over 5,000 tonnes/year) with a large number of jobbing orders (more than 100 per year) require in-house casting simulation facilities, preferably one for each foundry unit. Two or more medium capacity foundries, who have fewer jobbing orders, can share common facilities. Small foundries with less than ten new projects per year should set up co-operative simulation centers in their cluster, or approach casting simulation consultants. There are different types of users associated with casting simulation which are shown in fig.3 [7].

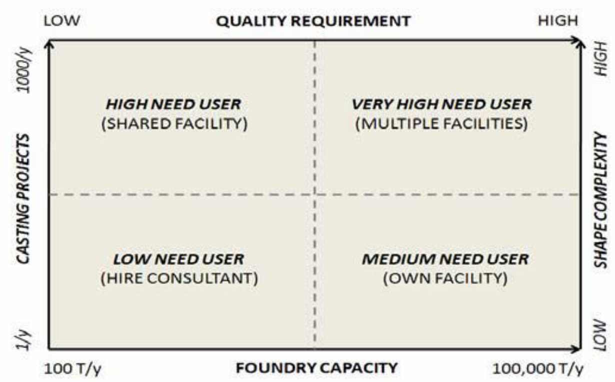

Fig.3: Types of Casting Simulation Users Based on Various Factors

B. Ravi and M. Srinivasan have studied the phenomenon of casting solidification, accompanies by volumetric contraction, leads to several major defects in casting including shrinkage porosity, cracks and distortion. In short freezing range alloys, especially those poured in permanent molds, the shrinkage tends to concentrate at the hot spots. In long freezing range alloys, especially those poured in sand molds, the shrinkage tends to be distributed all over the casting, though more of it still appears around hot spots. The location and extent of shrinkage porosity can be predicted by identifying regions of high temperature (hot spots) and low gradients (short feeding distance). Unfortunately, castings can be of complex shapes, and the heat transfer from all faces of the mold may not be uniform. Other factors, such as air gap formation at the metal-mold interface, convection in liquid metal, application of feedaids, presence of cores, gating system design and pouring parameters also affect the location of shrinkage porosity, making its prediction difficult, if not impossible, manually[8].

IV. EXPERIMENTAL WORK

Data regarding to bracket chasis in which all sand related data which is required for casting i.e sand preparation data, permeability of sand, moisture content of sand, green compressive strength of sand is present. All this data have shown in table 1.

Table-1: Data Regarding Bracket Chasis Component

Sr. No	Specific operation	Characteristic	Value	Equipment
1	Sand Preparation	Permeability	110-150	Permeability Meter
		Moisture Content	3.5-4.2%	Moisture Tester
		Green Compressive Strength	1000-1500 gm/cm^2	Compressive Strength Tester
		Mulling Time	2-3min	Timer
		Bentonite	3-4Kg	Weighing
2	Metal pouring	Tapping Temp.	1480-1520 ºC	Pyrometer
		Pouring Temp.	1320-1420 ºC	Pyrometer
		Pouring Time	8-10 sec	Stop Watch
		Inoculation	350gm	Measuring Cup

Then I prepared 3-D model of bracket chasis component and converted into .stl format by using website of E-foundry for the simulation purpose on AutoCAST-X software. This .stl file imported in AutoCAST-X software. Figure 6.2 shows imported .stl file of bracket chasis in AutoCAST software.

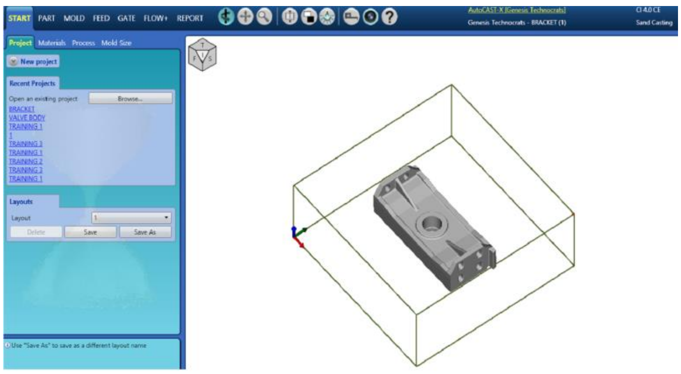

Fig.4: File of Bracket Chasis in AutoCAST-X Software

After that all the steps are carried out required for simulation in AutoCAST-X software. The methods design involves cores, feeders and gating system. Holes in the part model are automatically identified for core design. Even intricate holes can be identified by specifying their openings. The print length is computed based on the core diameter and length (the user can change these if required), and the entire core model is automatically created. The program suggests the number of cavities depending on the mold size (selected from a foundry-specific library), considering both cavity-cavity and cavity-wall gaps. Then the part model is automatically duplicated in the correct locations as per the desired cavity layout. Fig.5 shows major stages in casting simulation and optimization [9].

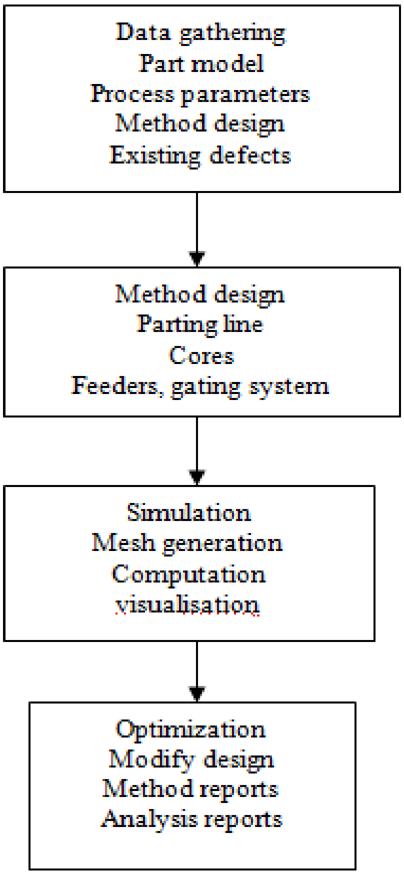

Fig.5: Major stages in Casting Simulation and Optimization

First simulation of old feeding and gating system of bracket chasis component is carried out. Due to that, hot spots are detected. Hence we got shrinkage porosity defect caused by old gating system. Fig.6 shows areas of hot spot in bracket chasis component while simulation of old gating system is carried out.

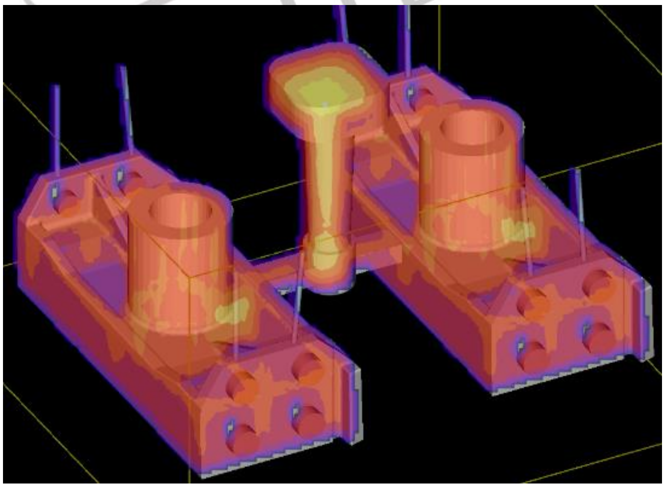

Fig.6: Hot Spot Areas in Bracket Chasis Component

New feeding and gating system is developed to eliminate porosity defect and after that simulation of new gating system is carried out. Fig.7 shows simulation of new gating system in which hot spots get eliminated.

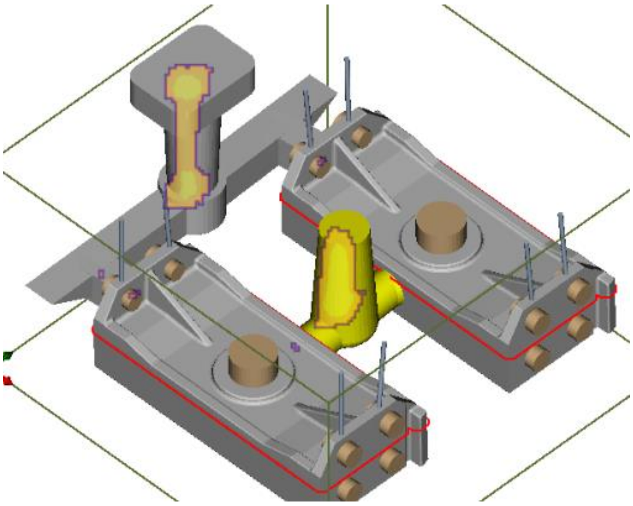

Fig.7: Hot Spots in New Gating System

V. RESULTS

The following advantages we gained by using AutoCAST software for the design of methoding for casting.

1. The time required is very less as compared to the conventional method of design of methoding.
2. Number of options were made available to suitably select the same.
3. The cost was much lower as compared to the conventional trial and error method.
4. Visualization of mold filling phenomenon makes the process easy to understand to the user.
5. Hot spots were easily located where probable chance of occurrence of defect was more.
6. The key parameters of the process were identified easily.
7. The rejection due to the defects arising out of methoding design was reduced to some extent.

The results also included-

- Improved casting quality
- Reduction in rejection
- Reduced cost of rejection
- Reduced lead time
- Increased efficiency
- Increased yield

Along with the above advantages following points [6] are important which add to the merit.

- Product designers can evaluate castability and improve part designs before releasing for manufacture, leading to overall quality and cost improvement.
- Foundry engineers can optimize methoding and process parameters to achieve high quality and yield without expensive shop floor trials.
- Engineering teachers can set up virtual casting labs for students to gain a better understanding of metal casting.

VI. CONCLUSION

Computer simulation modeling is a well-established technology. Initial applications demonstrated the validity and utility of modeling, but further progress was hampered by the primitive state of technology and the expense of building and running the models. Although vast improvements in technology over the past 10 years have greatly reduced the cost of simulation, there are still costs associated with data collection, model building, and validation. To us, these costs seem small in relation to the benefits that can be gained by routinely applying computer simulation modeling to improve metal casting process.

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