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Optimization Design of a Casting System for Sand Casting Steel using DOE Method and Multi-Objective GA Algorithm

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Abstract: Metal Casting is one of the earliest known manufacturing process, industries are suffering from the poor quality of casting because of a large number of parameters are involved in such process. By reducing the defect through optimization of process parameters, the casting quality could be improved. In this paper, the author introduces a new method to design the casting system guide by the DFM system, to do the best for a 'good design' as the start point.
Then the design of experiments (DOE) technology and genetic algorithm (GA) optimization technology was used to evaluate the parameters and design variables, the difference riser, feeders, chills and pouring temperature were selected to check the affection to the final yield ratio and shrinkage porosity. Based on the DOE and simulation result, the riser parameters and feeder parameters were observed to play the major affection to the yield ratio and porosity. Finally, the GA optimization is used for searching the best parameters for the best result. With GA optimization, the front Pareto curve was obtained and the best manufacturing windows was defined.
Keywords: Cast-Designer, DOE, GA, Gravity Sand Casting, Optimization, Porosity, Quality Control, Yield Ratio.

I. INTRODUCTION

In the casting process, due to involvement of number of process parameters foundry industries suffer from poor quality and productivity. The Casting process is also known as process of uncertainty due to the defects in casting is observed. It also challenges explanation about the cause of casting defects. For analysis of casting defects various researchers use techniques like cause-effect diagrams, design of experiments (DoE), casting simulation, if-then rules (expert systems) and artificial neural networks (ANN).

II. PROPOSED WORK

A. Casting Part and Casting System Design

Fig 1 is the casting part which used for ship building and asks a solid sound quality. The casting alloy was steel 1008, with 104Kg of the net part. To ensure the best balance of the quality and costs, our objective is to design a riser and gating system, optimize the casting process, to reduce the casting defects to a minimum also saving the cost of alloy material.DFM Analysis is the first step for part manufacturing. It is the bridge to link the part designer and manufacturing suppliers. Geo-Designer is a powerful upfront Design for Manufacturing (DFM) tools for designers and manufacturing engineers with innovative technology. Geo-Designer can bring very clear benefit to casting part designer and mould supplier, such as the MDI/HDI analysis, slider checking, draft angle and undercut checking, ejection force evaluation, riser and feeder design, cores extraction, cooling system designer etc.

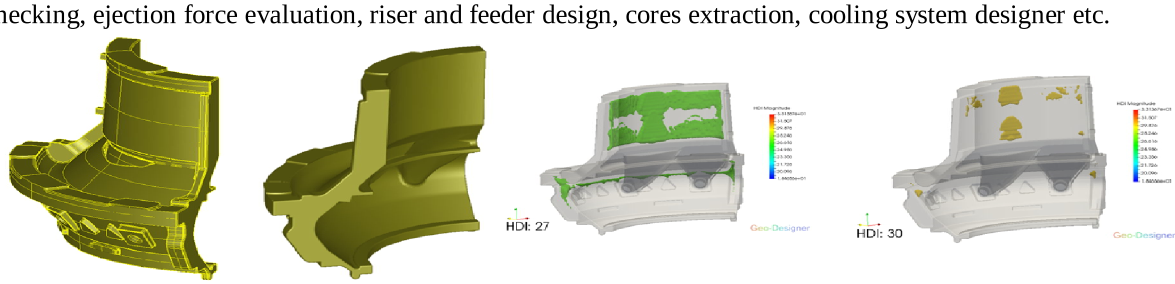


Fig 1 Casting part and Geo-Designer HDI result

The Geo-Designer can analyse the product thickness in ray method and the 3D volume method. More ever, the HDI analysis is very similar the hot spots during the solidification which considering the 3D geometry and the environment heat affection fully, but don't need simulation, so it is faster and flexible than simulation at the early stage.

B. Riser Design

The HDI result can guide the riser and feeder design directly. As the HDI result, we can set two risers on the top surface and two feeders on the side of the casting (Fig 2). The top risers will help compensate the liquid shrinkage of the top region and the side feeders will help compensate the middle region, also the gating system can attach to the feeder to save space.

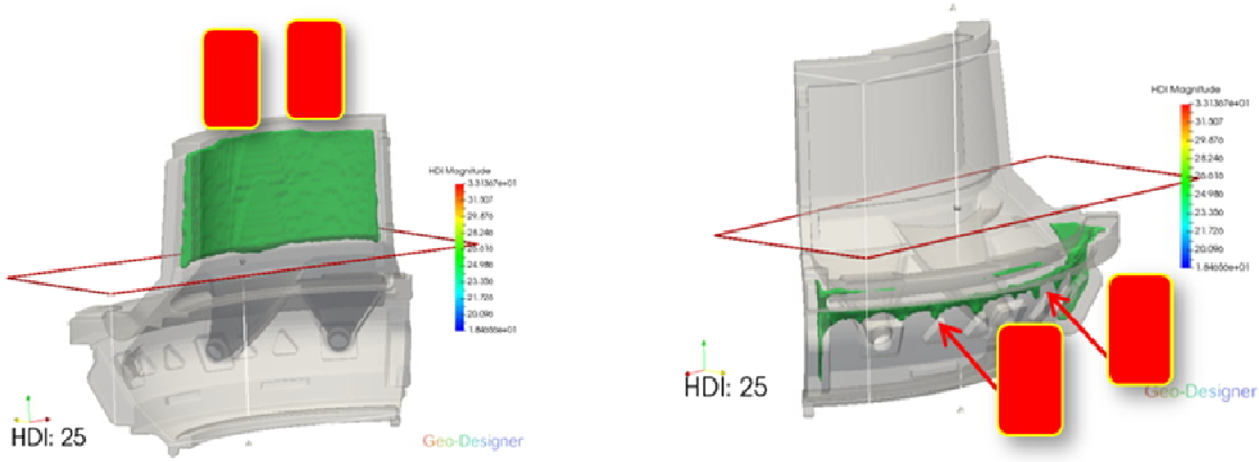


Fig 2 HDI result to design the riser and feeder

Then, we can use Geo-Designer to evaluate the design immediately. With the designed risers and feeder, we can check the new HDI again in Geo-Designer; normally the new HDI value will be bigger than the part only case. In this design, we found the shrinkage compensation was not enough in the top region between the two top risers. Also, there are two hot spots in the middle region, the left and right corner, the feeder is not enough to compensate such shrinkage also. So, we have to revise the riser and feeder design.

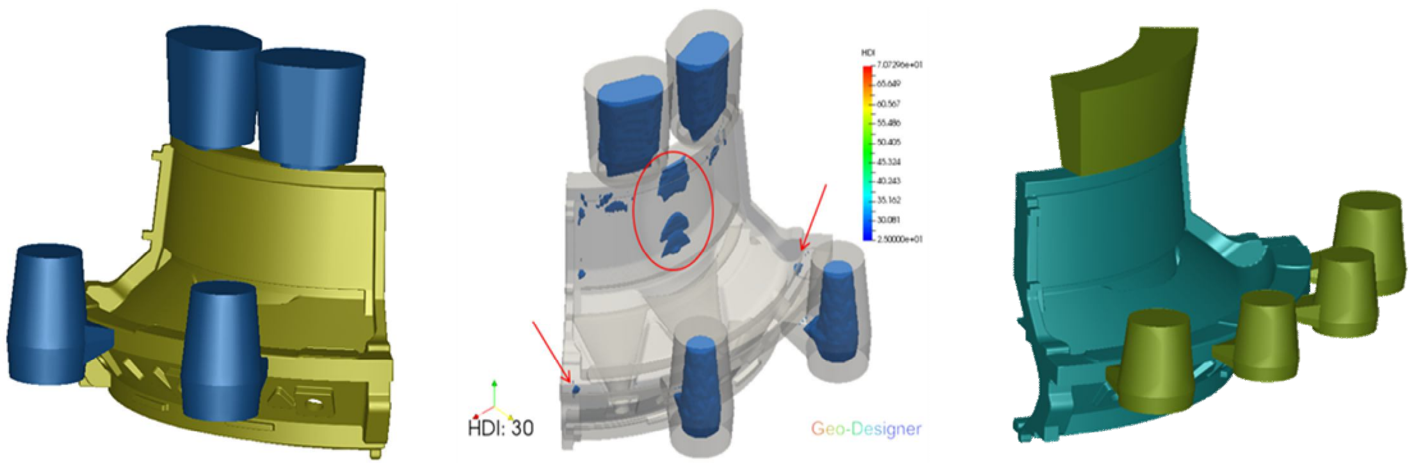


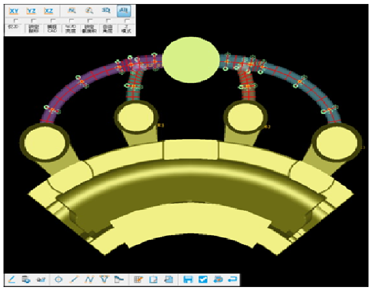
Fig 3 Initial design in new HDI and adjusts the design

As experience, we use the top surface as a riser, this may increase the workload for riser remove in the later but not a big matter; also we add two addition feeders in the parting line of the middle surface, one in left and another in right. Such design will reduce the yield ratio but it can reduce the shrinkage porosity, so it is necessary.

C. Gating System Design

After the riser and feeder design, we continue design the gating system. Cast-Designer provides very strong tools to guide such design, includes gating wizard, free draft gating, chills design etc.

The gating system design wizard can guide designer carries out the gating system design process in a simple way. It also can calculate the final section areas for inner gate, runner and sprue runner. With the 'Free Design' module, design engineers can speed-up the gating system design from hours to minutes; also the design work becomes so interesting and easy. The design process was just like the drafting on the paper. The user drafts the control points and the feature lines of the sprue runner, main runner and gate runner, then drags and moves the control points or feature points in the main view in mouse.



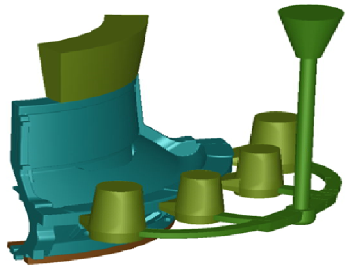


Fig 4 Cast-Designer gating system

While the runner properties and section properties could be defined by the design wizard and KBE system, the user also can modify the whole gating system in a few clicks.

D. DOE Analysis

In this project, we have two major concerns: the shrinkage porosity (quality) and the yield ratio (cost). Lower yield ratio and higher shrinkage porosity is our requirement. However, generally speaking, increase the riser volume can improve the shrinkage porosity but also reduce the yield ratio. So, we have to find the best balance of the quality and cost.

The present research as associated with sand casting process which involves various parameters at different levels and affects the casting quality. The methodology used to achieve optimized process parameters using DoE is given as: A) Select any defect observed due to sand and mould. B) Set the adjusting the process parameters. C) Select the most significant parameters influencing defects in casting by cause effect diagram. D) Select the parameters and their levels. Perform the experiments (trial castings or simulation) as per DOE and collect the data. E) Analyse the data using statistical tools.

An analysis of variance (ANOVA) can be obtained to determine the statistical significance of the parameters. Means plots can be plotted to determine the preferred levels of parameters considered for experimentation.

E. Selection of Parameters & signal levels for DOE Analysis

There are so many factors to affect the final casting result (both quality and cost), such as the riser dimension, feeder dimension, chill setting, and pouring temperature. If we put all the various above with full flexible, then the calculation workload will be huge and not possible to have the result in a reasonable time frame.

We use DOE method to check the major affection factor at first. In this studying, five parameters are selected for experimentation which is Riser, Feeder 1, Feeder 2, Chills and Pouring Temperature. Metal composition and other parameters are not taking because of some limitation. Parameters are described below:

1) *Riser:* 3 type risers were designed with different dimension and volumes, sorted as smaller, middle and big.
2) *Feeder 1 and Feeder 2:* same as riser, three type feeder were also designed in different size. Feeder 1 and feeder 2 was different also.
3) *Chills:* we set three type chill at the bottom surface of the casting. The three types are no chills, one chill and two chills in different region.
4) *Pouring Temperature:* The temperature range in this case is from 1540 to 1580 degree. The aim is to define a range of temperature which gives minimum porosity.

The selections of signal levels are done for shop floor Experiments which are in Fig 5 and the following table.

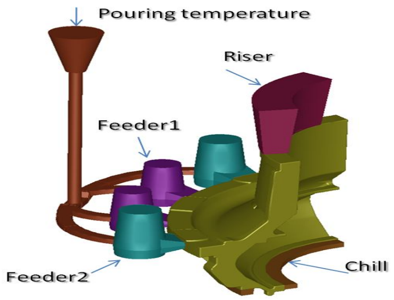


Fig 5 Cast Designer DOE Analysis

Variables	Start	End	Step
Riser	1	3	1
Feeder 1	1	3	1
Feeder 2	1	3	1
Chill	1	3	1
Pouring Temperature	1540	1580	40

Table 1 Cast Designer DOE Analysis

Cast-Designer has several DOE methods, one is the full combines, and one is Taguchi method. One of the advantages of Cast-Designer DOE is, it is possible to assign the user's condition to reduce the calculation array, and this is very useful for the complex project. For example, in this model, if a model with very smaller feeder1, but very big feeder 2, it was not realistic and we can eliminate it from the array.

The literature review indicates that the Taguchi method is one of the best option for design of experiments when number of process parameter are involved in the process. Taguchi approach is suitable in experimental design for designing and developing robust products or processes irrespective of variation in process parameter (within set limits) and or variation in environmental conditions. However, if the user does not have enough experience of the variables of the project, then Taguchi method may fail.

Since we have almost no idea of the inputs, Taguchi method may miss right result, so we trend to use the full combine with user boundary condition, the whole runs will be 120 runs After optimize the simulation model, such as using a good meshing, solidification only simulation, we can control the CPU time of each simulation within 30 minutes only.

Cast-Designer can run job in parallel optimization mode also. This means it can run several projects on the same time and the system will collect the result automatically, with such technology, the CPU time can reduce 5 to 6 times depends on the computing resource. We run such DOE analysis in 5 parallel jobs, so the total CPU time of such analysis could be controlled within 12 hours. This time frame is quite reasonable.

F. GA Optimization

In DOE analysis, all inputs were assigned from the user and the system search the best result from such dataset. However, it is very often, the best input dataset may not exist in the user input. To find such 'best' condition, we have to use the automatic optimization method. Cast-Designer Optimizer is a software package opening up new opportunities for the market of "complex" practical problems. The software also enables lower research expenditures and shorter implementation time. Before use the full automatic optimization, some core technology must be applied, such as:

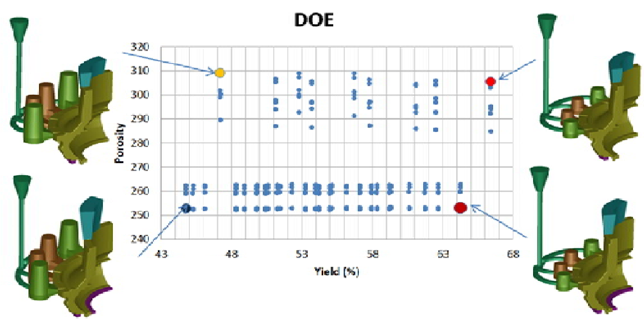
1) The full parametric design of the casting system, including the riser, the gating system, the riser, feeder and chills;
2) Automatic meshing generation and mesh assembly technology;
3) Automatic CAE model generation includes the parameters setting and performs CAE simulation;
4) Automatic result analysis techniques. In the case without programming, the user can extract and analysis the various results, as more as possible. The results analysis should also contain a degree of logical analysis;
5) Automatic optimization techniques to search and analyze the simulation results, and make decision for the next step automatically. At present, the mature optimization techniques include genetic algorithm, particle swarm optimization, artificial neural network, multi-objective optimization, fuzzy mathematics and so on.

Therefore, in order to achieve the above objectives, not only single CAD design software or single CAE simulation software can be achieved, and a full solution from the design to analysis to optimize is strongly required. At this moment, very few software can achieve this, but the Cast-Designer of C3P software is one good example.

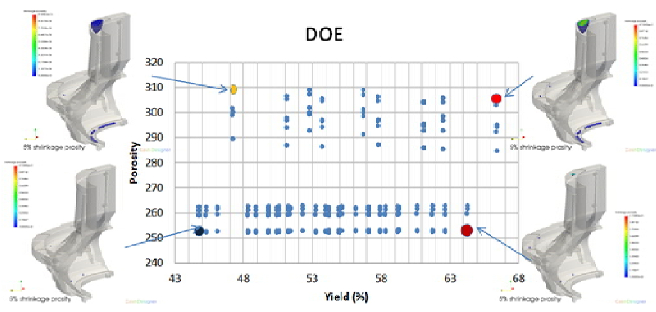
III.RESULT

A. DOE Result

The responses of experiments are recorded for the optimization. The optimization of research parameters is done in the Cast-Designer software through Design of Experiments Technique. In this research, the focus is on a single defect which is shrinkage porosity so while inspection there is the only single defect is considered in the results.



(a)



(b)

Fig 6 (a) DOE analysis result (casting yield vs. porosity) & (b) DOE analysis result (casting yield vs. porosity, show porosity)

Fig 6 (a) shows the DOE analysis result with different yield ratio and porosity. The different object color shows the different input variables. All simulation results were plotted in one graph. The four corner's models were displayed to show different yield ratio. The yield ratio is the casting volume divided by the whole alloy volume (casting + gating + riser & feeder), so a bigger value is better. The left two models are with bigger riser and feeder, and lower yield ratio, while the right one with smaller riser and feeder, and higher yield ratio. The bottom two models are smaller shrinkage porosity and better for quality. It is clear, for the same porosity, the yield ratio was quite different, so optimization is absolutely necessary.

Fig 6 (b) shows the same model as Fig 6 (a) but the shrinkage porosity result. The down-right corner is the best result with the higher yield ratio and lower porosity. The top model with big porosity, it may caused by too small riser. To continue the more detail study; we need address the main affection factor from the DOE analysis result. There are many methods and software tools to help analysis the DOE result. However, the simplest way is the parallel coordinate plot. With such data analysis tools, Cast-Designer allows you to display column-based data sets with many parameters in just one single chart and helps you to extract the most relevant information on cause/effect relationships with just a few clicks.

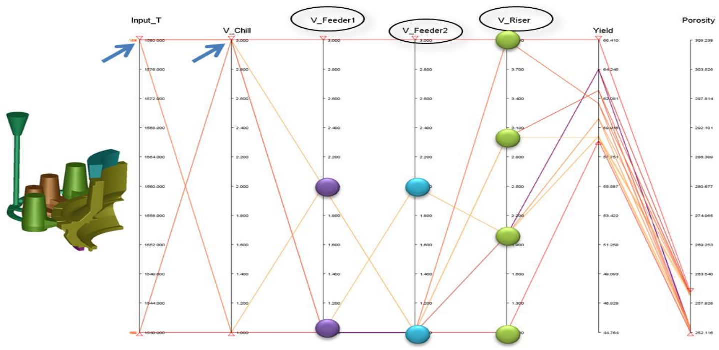


Fig 7 DOE analysis result (parallel coordinate plot in Cast-Designer)

Fig 7 is the parallel coordinate plot of the DOE analysis. Each of the parameters is represented by one vertical axis (black lines). The parameter title is shown on top of each axis. Each design is represented by a line that crosses the axes at the ordinates corresponding to the values observed for their respective parameter in that design. The user can drag the mouse and only designs that cross the axis between its filters are displayed.

Since we need the maximum yield ratio and minimum shrinkage porosity, so we drag the mouse in the yield axis (the bigger value side) and porosity axis (the smaller value side), then we found,

1) Feeder1 and Feeder 2 play a main affection to the final result, the data regions are the lower side;
2) Pouring temperature and chills don't play a major role in the analysis, so both of them are minor factors
3) Riser also not a major affection factor as the DOE result, but it affects the yield ratio and shrinkage porosity directly, so we wish to have a more detail study.

B. GA Modelling and Result

As the DOE analysis result, we select the following parameters for the GA optimization:

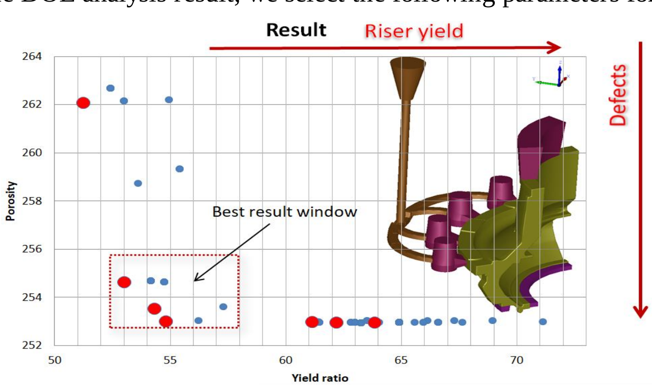


Fig 8 Cast Designer GA Optimization result

	From	To	Step
Height of Riser (mm)	120	160	10
Riser Angle (degree)	60	64	2
Feeders diameter (mm)	90	110	5
Feeder height/Feeder diameter	1.0	1.5	0.1

Table 2 GA Optimization parameters

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Then setup the automatic optimization model and performance optimization. Parallel optimization in 5 runs each time also used for this project. Fig 8 is the GA optimization result, there is 52 runs in total then system come to converge. In automatic optimization, because we used the minimum method to search the result, so the yield ratio should be different from the above DOE plot. In Fig 9
Yield ratio = 100 – Casting volume / (volume of casting+ riser & feeder + gating)
So the smaller Yield ratio in Fig 8 is better. The red points were the front Pareto points; there are the best results as the given condition. For this project, the best result window was marked in Fig 9.

C. GA Result Discussion

Now, we select a few key points to discuss the result.

1) The best result with higher casting yield ratio and shrinkage porosity result

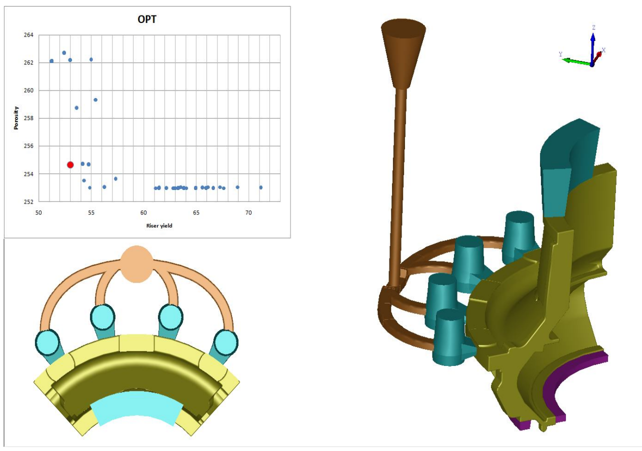


Fig 9 Cast Designer GA Optimization result (best window result)

Height of Riser (mm)	Riser Angle (degree)	Feeder diameter (mm)	Feeder height/Feeder diameter
130	62	90	1.0
Riser Yield %	Casting Yield %	Porosity Volume	
53.01	71.3	254.64	

Table 3 GA Optimization parameter

The red point in Fig 9 and the near region could be considered as the best result of the optimization with given porosity. In this point and near region, the whole system can have the best quality and yield ratio.

2) The bad casting yield ratio and good shrinkage porosity result

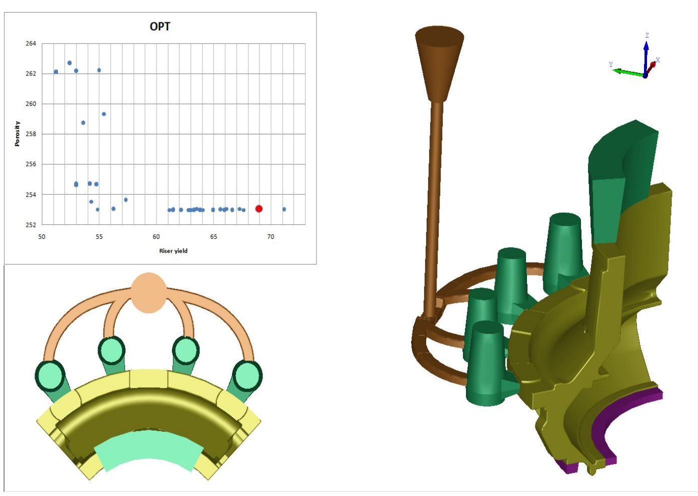


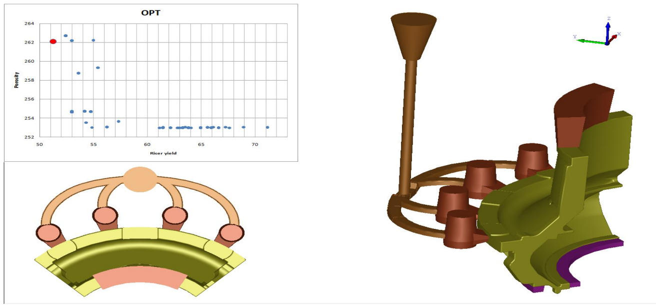
Fig 10 Cast Designer GA Optimization result (lower yield ratio, good porosity)

Height of Riser (mm)	Riser Angle (degree)	Feeder diameter (mm)	Feeder height/Feeder diameter
104	60	100	1.4
Riser Yield %	Casting Yield %	Porosity Volume	
68.96	63.8	253.04	

Table 4 GA Optimization parameters

The red point in Fig 10 and the near region could be considered as good shrinkage porosity but bad yield ratio means it waste material. In fact, this result is bad, because there are many points in the left with the same porosity but much better yield ratio. It must avoid.

3) The good yield ratio and bad shrinkage porosity result



Height of Riser (mm)	Riser Angle (degree)	Feeder diameter (mm)	Feeder height/Feeder diameter
120	62	90	1.0
Riser Yield %	Casting Yield %	Porosity Volume	
51.25	72.2	262.09	

Fig 11 Cast Designer GA Optimization result (higher yield ratio, good porosity) Table 5 GA Optimization parameters

The red point in Fig 11 and the near region show another case, it is good yield ratio but bad shrinkage porosity. Compared with result in a), the yield ratio improved a little but shrinkage porosity was not good

IV. CONCLUSIONS

A new method of casting system design and defect analysis is proposed and studied which is a combination of design of experiments method and GA optimization technique for analysis of casting yield ratio and shrinkage porosity. DFM analysis is useful for casting part checking and riser & feeder design. The Cast-Designer solution provides a whole solution for casting industrial from DFM, casting system design, simulation and optimization. Design of experiments method can be efficiently applied for deciding the optimum settings of process parameters to have minimum rejection due to defects for a new casting as well as for analysis of defects in existing casting. For analysis of defect like shrinkage porosities, the GA optimization technique is the most efficient and accurate method. The quality and yield of the casting can be efficiently improved by computer assisted casting simulation technique in shortest possible time and without carrying out the actual trials on foundry shop floor. Today's optimization is no longer limited to simple parameters and simple shape optimization, but can be applied to any CAD changes; while the optimization of the study point is no longer simple direct mathematical variables, but more representatives of the actual physical phenomena of casting, such as shrinkage porosity, flow imbalance, gas entrapment and other factors.

V. ACKNOWLEDGMENT

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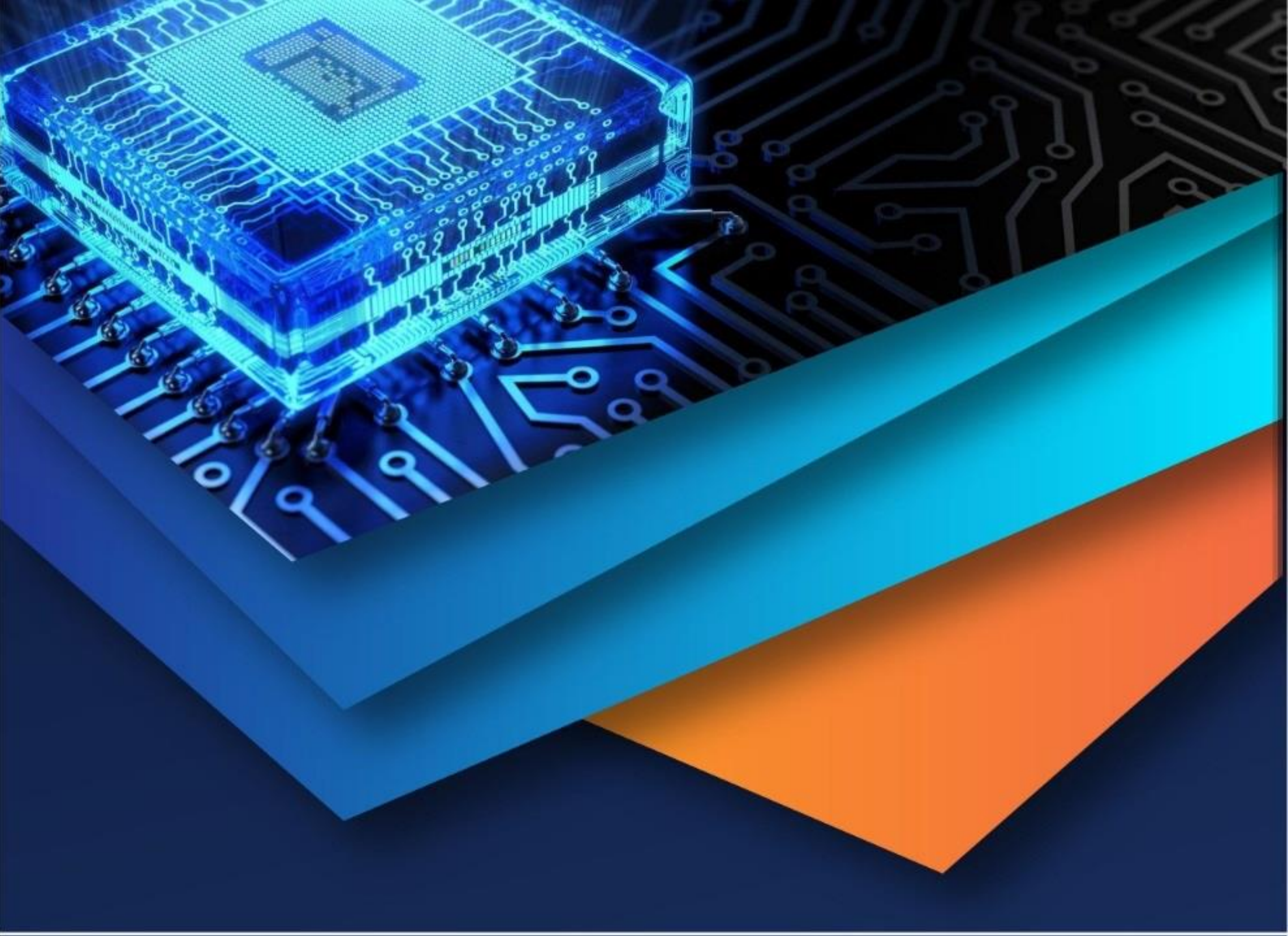

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