iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** VIII **Month of publication:** August 2021

DOI: https://doi.org/10.22214/ijraset.2021.37352

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue VIII Aug 2021- Available at www.ijraset.com

Optimization of Shrinkage Porosity in Grinding Media Balls by Casting Design Modification and Simulation Technique

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Abstract: ***Shrinkage porosity or cavity are associated with the solidification of the metal either due to gas/air entrapment or when the shrinkage occurring during solidification is not entirely compensated by the riser. Shrinkage cavities occurring in the casting reduces its strength which leads to unfulfillment of the desired serviceability. In this paper, casting design has been modified using the DISA manual to achieve directional solidification which directly relates to improvement of casting quality. The running of metal from pouring basin into casting along with solidification has been analysed through PROCAST which is a casting simulation software based on Finite Element Method and CAFE (Cellular Automata Finite Element) Model.***

The feeding system of the casting has been modified in terms of shape and volume to minimize air aspiration effect and promote directional solidification. The model used is of grinding media balls casting of high chromium cast iron. The feeding pattern, feeding velocity and solidification with respect to pouring temperature, pouring rate, ambient temperature and film coefficient has been analysed.

The final optimum range of all parameters with corresponding minimum shrinkage porosity in casting was obtained. Main aim was to minimize shrinkage porosity in the main casting, ignoring gating and feeding system. The actual minimization of shrinkage porosity comes out around 56 %.

Keywords: Optimization and Simulation, Shrinkage Porosity, Casting Design, Gravity sand casting, Procast, Solidification.

I. INTRODUCTION

Foundry process involves production of casting right from casting design to testing of casting. Every stage is important for production of sound casting. Every casting produced has different service conditions and different required properties which leads to different optimum conditions depending upon the optimization criterion. In every casting, shrinkage is inevitable, and it badly effects the quality of casting. It results as metal shrinks while solidifying and even after solidification but the later can be compensated by giving contraction allowance. Though, the former can be minimized by using proper design of casting along with altering the parameters which directly or indirectly affects the solidification of casting.[1]

Directional solidification is one of the basic and important parameters to achieve defect-free sound casting. Solidification should start from casting, then moving on to riser, to solidify at last. So, design of gating and feeding (riser) system also plays very important role to provide directional solidification. It can also be modified to achieve sound casting. [2,3]

To study the solidification pattern, a 3-D model of the casting was taken as input along with all the other parameters including material composition, specification, pouring temperature, variation of fluid velocity and other properties with temperature.

II. CASE STUDY AND CASTING COMPONENT

Casting component was taken from one of the leading manufacturers of Grinding Media Balls, to analyse the shrinkage porosity in the final casting.

Grinding media are the medium to crush or grind another material exclusively used in coal grinding, mining, cement palletisation, etc. These can be produced of wide range of sizes and different materials. Grinding media can be of various shapes including: the balls of different diameters; short cylinders — steel circle cut into the size; steel bars (round billet); and truncated cones (cylpebs, ellipsoids). These are produced generally in groups since these are generally smaller in size, rather than producing single component at a time.[5]

A. Casting Part and Casting Process

Casting component is Grinding media balls (spherical shape) with 50 mm diameter being produced by one of the Foundry Unit. Material being used is High Chromium white iron (ASTM 532 Class II). The composition data is collected from the industry producing the component.

Table I- Composition of material

Carbon	2.4-2.8%
Chromium	12.5-13.5%
Manganese	1.0% Max
Silicon	1.0% Max
Sulphur and Phosphorus	0.06% Max

1) *Casting Process*: Sand Mould Gravity Casting is used for production of grinding media balls casting. In this process, liquid alloy flows into the mould in the influence of gravity owing to less turbulence. Sand being used as mould material helps in minimization of stress developed during solidification stage and in escape of gases or air getting trapped. Also, it helps in cost cutting of production as it is inexpensive as compared to other mould materials.
2) *Sand to be used*: Green Sand with bentonite and lustron. The total clay content in the fresh coming silica sand (85-100 mesh) used for moulding, should be below 0.5% preferably.

Table II- Composition of sand

Bentonite	21kg/batch
Lustron	6.5kg/batch
Return sand	900kg/batch
New Silica sand	30kg/batch
Batch	1000kg

III. CASTING DESIGN

To produce the sound casting with the desired quality and optimum cost, the objective is to design a riser and gating system, optimize the casting process, reduce the casting defects to a minimum and also saving the cost of alloy material. The casting design includes designing of gating and feeding system including pouring basin, runner, sprue, gates and riser. All the parts are designed and modified using DISA manual so as to promote directional solidification, minimize turbulence and air aspiration effect, and ensure smooth flow of alloy with optimum pressure and fluid velocity.

A. Design of Riser/Feeder

For the proper designing of feeder, the modulus, volume, pressure and feeder neck criterions must be fulfilled according to DISA manual. The theoretical design does not always comply with the practical purpose, so modifications are required. [6,7]

1) *Modulus criterion:* The feeder was designed based on Modulus of casting and feeder. The feeder must have liquid metal in required volume to feed the casting until a certain time has elapsed after pouring. This can also be expressed in terms of the so-called moduli of the casting and the feeder:

$$MF = kM \times MC,$$

which is known as the modulus criterion, and where, MC is the modulus of the casting, normally in cm, kM is a constant determined experimentally and is dependent on the thermal conditions during feeding and the feeding characteristics of the different alloys, MF is the modulus of the feeder, normally in cm. [8]

2) *Cooling time versus Moduli:* The dependence of the cooling time on the modulus of a casting can be expressed in the following equation:

$$tT = kT\,(MC)^2,$$

where, tT is the cooling time, normally in minutes, down to a certain cooling temperature T, normally in °C, kT is a dimensionless constant depending on pouring temperature, cooling temperature, mould material, metal alloy and the units, MC is the modulus of the casting, normally in cm.[8]

3) *Volume Criterion*: The feeder must have sufficient volume of liquid metal to be able to compensate for the contraction in the casting during the cooling from pouring temperature to solidus temperature and the solidification itself. If the feeder does not contain enough liquid metal, the feeder will dry out before the completion of the solidification of the casting, and the resulting shrinkage will extend from the feeder into the casting interior. After combining all the criteria, the chosen two standard feeder shapers are cylinder and sphere with slight modification. In this study, the cylindrical feeder was chosen with some design modifications (Fig 1).

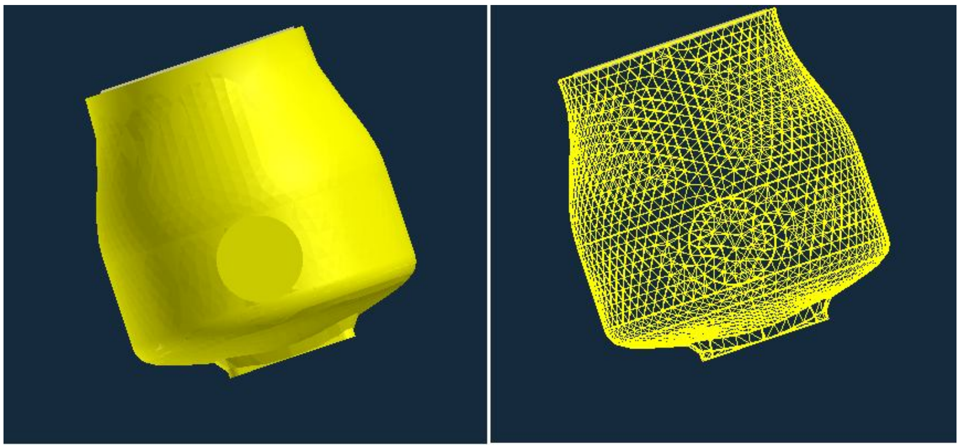

Fig. 1 Modified design of riser

One modification in riser provided, a 40º notch on one side of the parting line. The 40º notch in the feeders creates a "hot spot" in the middle of the feeder. This ensures that this middle will have retarded solidification skin formation and thus maintain the access of atmospheric pressure (mould pressure) on the liquid metal in the feeder open for a longer time.
Another modification is to maintain an angle of 60-120 degrees between the casting contour and the feeder contour depending on the position of the feeder on the casting.[8]

B. Design of Pouring Cup

It is essential for obtaining sound castings that the pouring cup be filled as quickly as possible and kept full during the rest of the pouring operation. If this is not the case, the rest of the gating system will not behave as expected from the gating system calculations. To avoid metal splash / roll out, the anti-roll out pouring cup was developed. As can be seen (Fig 2), the lips counteract turbulence and metal splash / roll out. The dimensions were chosen according to casting weight and respective suggested size according to manual. [8,9]

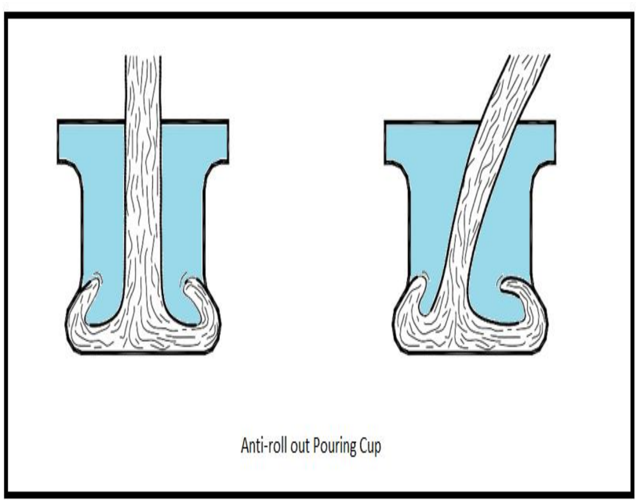

Fig. 2 Anti-roll pouring cups with metal fill-in

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
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C. Design of Runner

Runners are all the channels or passage, which lead the metal from the pouring cup to the ingates. Runners have other functions than just leading the metal, such as preventing slag, oxide, sand and gasses including air from entering the mould cavities. Generally, simple trapezoidal runners are used as vertical runners and slender trapezoidal are used as horizontal runner.

Another important aspect in the design of runner is the overlap of vertical to horizontal runner or horizontal to vertical runner to enhance smooth filling of liquid metal or alloy and avoid turbulence at overlap. So, chosen design in this case is slender trapezoidal at overlap region (Fig 3).

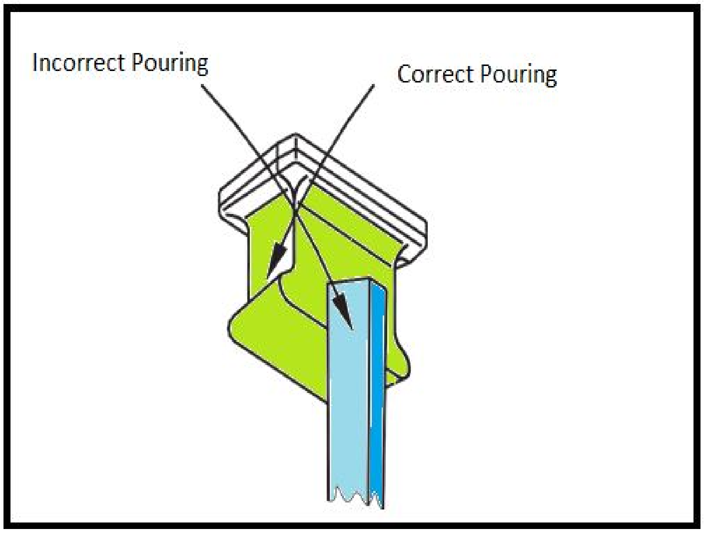

Fig. 3 Pouring cup with trapezoidal runner

D. Final Casting Design

After doing all the calculations and combining all the design features, the final casting design is produced (Fig 4).

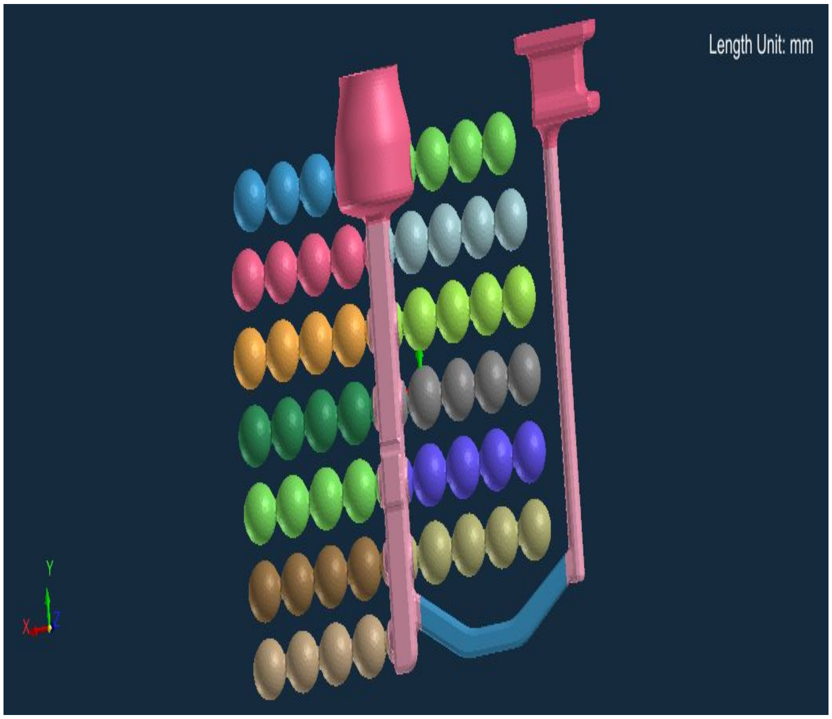

Fig. 4 Casting design along with gating and feeding system

IV. SIMULATION OF CASTING

After finalisation of the design, the next step was to check the design through simulation of casting. The software used for simulation is PROCAST, which is based on Finite Element Method and Cellular Automata Finite Element Model.
The simulation of casting involves three steps including Visual Mesh, Visual Cast, and Visual Viewer.

A. Step 1- Visual Mesh

In this step, the casting design is meshed by breaking individual part of casting into number of elements so that entire volume of the casting can be covered. Both surface and volume mesh are created for every part of the casting. Generally, the size of mesh of main casting part is kept smaller so that entire volume can be covered. Since, in this study, the size of the casting component is very small (50mm diameter ball), so the mesh size for casting is kept as 10 for surface mesh. The gating and feeding mesh size can be different but the transition should be smooth. Since mould box is not a part of casting, its meshing size is kept quite larger as 35.
Once the surface mesh has been created, then volume meshing is done so that entire volume is covered during the simulation. Both surface and volume mesh generation are very critical, as any departure from following the exact contour of casting will not yield actual result. The transition in the mesh size can be seen in Fig 5.

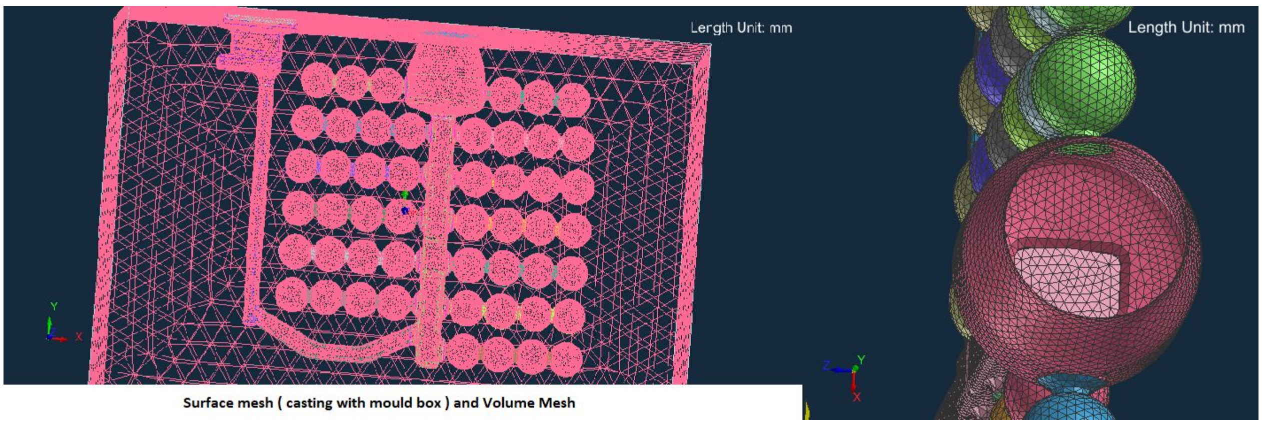

Fig. 5 Generated surface and volume mesh

B. Step 2- Visual Cast

In this step, all the casting parameters are to be defined as type of casting process, material of casting and mould, pouring temperature, ambient temperature, pouring time or metal flow rate, inlet area etc.

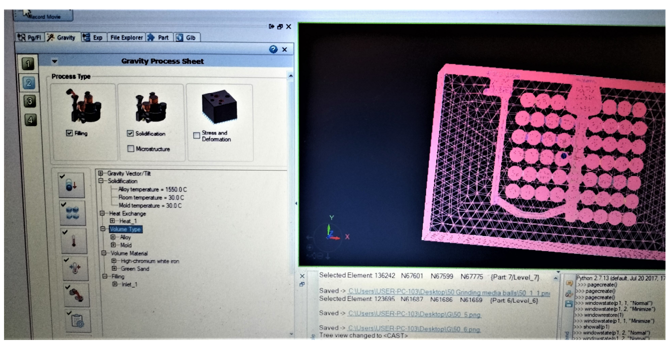

Fig. 6 Input parameters to define the process for simulation

All these data were gathered from one of the leading manufacturers of grinding media balls casting so that the actual condition can be analysed.
After defining all the parameters, the simulation was run to analyse the resulting solidification, shrinkage porosity, fluid velocity, solid fraction, void fill, etc (Fig 6).

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C. Step 3- Visual Viewer

The simulation result shown in Fig 7 depicts the filling of liquid alloy in the mould and the solidification progress.

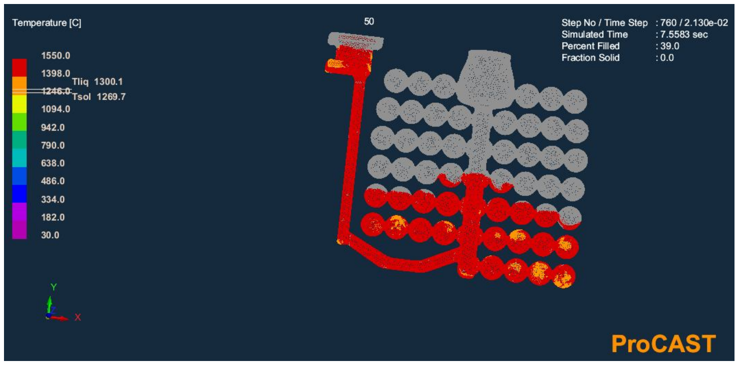

Fig. 7 Variation of temperature with percent filling of alloy in mould

The design of casting is good at achieving directional solidification as seen on the Fig 8. The riser is able to compensate for the shrinkage occurring during solidification as the cavity can be seen on the upper part of the riser (grey colour). The colour variation in Fig 8 shows that how solidification proceeds towards the riser. The variation of temperature from 1550 °C to 30 °C is shown with different temperature and simulation shows how the whole casting is getting solidified.

Fig. 8 Temperature variation with fraction solid

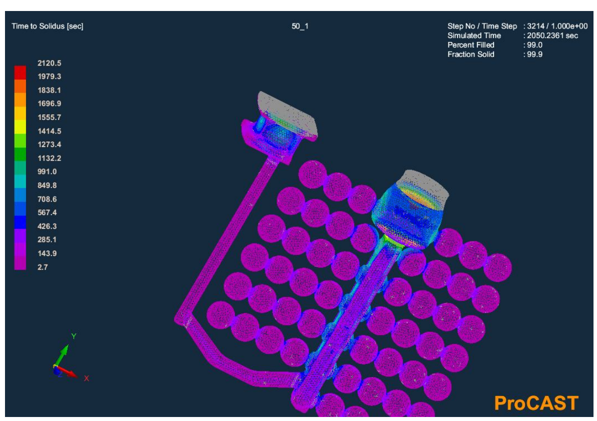

Fig.9 Total time to solidus with fraction solid

The part of casting to solidify at last can be analysed using fraction solid variation (Fig 9). The red coloured regions show 0 to 0.25 fraction solid means regions having red colour to solidify at last. Movement of solidification front can also be seen towards the runner, leading to the riser (Fig 10). The grey part signifies that the part has been solidified while other colour shows how much fraction of casting is turning solid.

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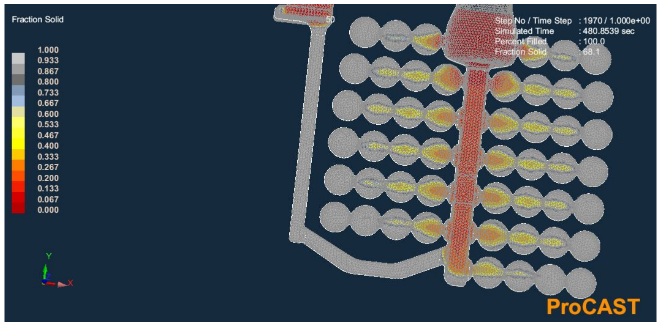

Fig. 10 Fraction solid of whole casting

The variation of fluid velocity inside the casting can also be analysed and the mould hardness corresponding to high velocity regions must be maintained to avoid casting defects occuring due to mould erosion, high stresses regions. In this case, the maximum velocity region (2.019m/sec) is the overlap zone of vertical and horizontal runner which is not the part of the casting component, so mould cavity is safe from any unwanted departure in shape (Fig 11).

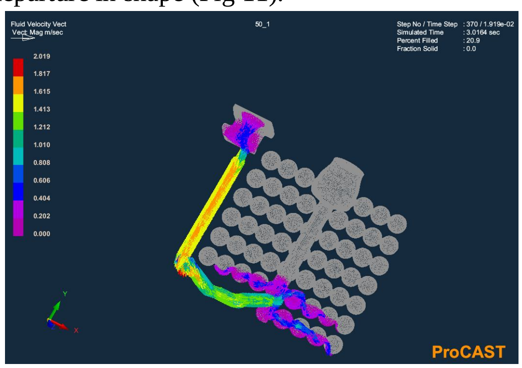

Fig. 11 Fluid velocity variation in the mould

The resulting shrinkage porosity in percentage can be seen in Fig 12 and the location of shrinkage porosity along with percentage can be analysed.

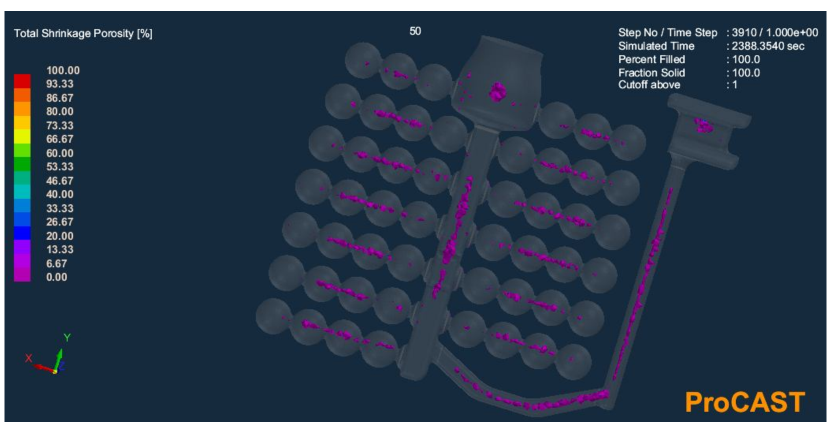

Fig. 12 Total shrinkage porosity

V. OPTIMIZATION

The various parameters which effect the occurrence of shrinkage porosity includes design of casting parts, pouring temperature, ambient temperature, mass flow rate, film coefficient, etc. [13]

The other parameters include MACROFS (macro fraction solid), PIPEFS (pipe fraction solid), FEEDLEN (feeding length). By varying these, macro- and microporosity pattern can be changed.[14]

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According to the simulation result, the design is good at smooth filling of alloy in mould and achieving directional solidification. So, for optimization of shrinkage porosity, a suitable combination of all the parameters is required, otherwise focusing on only one or two parameters, the other parameters might lead to deviation from the required result.

For optimization, the *Adaptive Response Surface Method (ARSM)* is selected. ARSM approach defines design space to get the global optimization values of objective function. The initial conditions were already defined during VISUAL CAST. The recommended range for all the parameters were selected by combining the data of literature survey and actual experimental values being gathered from company. The range of parameters opted for performing iterations is defined in Fig. 13. After numerous iterations, the best point with minimum shrinkage porosity in the casing part was generated as a result.

VI. RESULT

For each set of designing variables (combination of pouring temperature, mass flow rate, ambient temperature, film coefficient, macro fraction solid, pipe fraction solid, and feeding length) , the cut off of objective function i.e., shrinkage porosity was set as 0.01 (1% maximum). The ARSM performs numerous iteration to keep the value of actual objective function at the optimum. The value of parameters are chosen only if it fulfills the objective function condition. After each design iteration, the design space is reduced according to the defined objective function. The result of all iterations were analysed to find optimum value of shrinkage porosity.

Table III- Value of shrinkage porosity ($cm^{3)}$ and respective design variables

FilmCoeffic	Ambient Te	Inlet Flow	Inlet Temp	MACROFS	PIPEFS	FEEDLENGT	MOLDRIGII	OBJECTIVE
10	30	2.0308	1550	0.7	0.3	0.005	1	2.12072
10.8	27.6	2.19326	1400	0.644	0.324	0.0046	1.08	3.32401
9.2	27.6	2.19326	1600	0.644	0.324	0.0054	1.08	2.11303
9.2	27.6	1.86834	1400	0.756	0.276	0.0046	1.08	5.91844
10.8	32.4	2.19326	1600	0.644	0.324	0.0046	0.92	2.17725
10.8	32.4	1.86834	1400	0.756	0.276	0.0054	0.92	6.04394
10.8	27.6	2.19326	1600	0.756	0.276	0.0054	0.92	6.66092
10.8	27.6	1.86834	1600	0.644	0.276	0.0046	1.08	7.93375
9.2	32.4	2.19326	1400	0.756	0.276	0.0046	0.92	5.79446
9.2	32.4	1.86834	1400	0.644	0.324	0.0046	1.08	3.31408
9.2	27.6	1.86834	1400	0.644	0.324	0.0054	0.92	3.46456
9.2	32.4	1.86834	1600	0.644	0.276	0.0054	0.92	7.26926
10.8	32.4	2.19326	1400	0.756	0.324	0.0054	1.08	1.84455
10.4	31.2	2.11203	1600	0.672	0.312	0.0052	1.04	1.65266
9.6	31.2	1.94957	1600	0.728	0.288	0.0052	1.04	5.31176
10.4	28.8	1.94957	1500	0.672	0.288	0.0052	0.96	5.72832
10.4	31.2	1.94957	1500	0.728	0.312	0.0048	0.96	1.39494
9.6	28.8	2.11203	1600	0.728	0.312	0.0048	0.96	1.31943
10.4	31.2	2.19326	1590	0.728	0.324	0.0046	1.04	1.01259
10.8	30	2.11203	1540	0.756	0.312	0.0046	1.08	1.27209
10	32.4	2.19326	1540	0.7	0.324	0.0048	1.08	1.5599
10	30	2.19326	1540	0.756	0.324	0.0048	1	1.2453
10.8	32.4	2.19326	1540	0.756	0.312	0.0046	1	1.24701
10	30	2.19326	1600	0.756	0.312	0.0046	1.08	1.27479
10.8	32.4	2.11203	1600	0.7	0.312	0.0046	1.08	1.41154
10.8	30	2.19326	1600	0.7	0.324	0.0046	1	1.07199
10.8	32.4	2.11203	1600	0.756	0.324	0.0048	1.08	0.979931
10.4	32.4	2.11203	1600	0.756	0.324	0.0046	1	0.966809
9.6	32.4	2.19326	1550	0.728	0.312	0.0046	0.96	1.29666
9.6	32.4	2.19326	1550	0.756	0.312	0.0048	1.04	1.31355
9.6	32.4	2.19326	1600	0.756	0.324	0.0048	0.96	0.971041
9.6	31.2	2.0308	1600	0.728	0.324	0.0046	0.96	1.20265
10.4	32.4	2.0308	1600	0.756	0.312	0.0048	0.96	1.30057
9.6	31.2	2.0308	1600	0.756	0.312	0.0046	1.04	1.27897
9.6	32.4	2.0308	1550	0.756	0.312	0.0046	0.96	1.28368
9.6	32.4	2.0308	1550	0.728	0.324	0.0048	1.04	1.05374
10	32.4	2.11203	1600	0.756	0.324	0.0046	1	0.931754
10	32.4	2.19326	1600	0.756	0.324	0.0046	1	0.941856
9.6	31.2	2.19326	1600	0.756	0.324	0.0048	1.08	0.977318
9.6	32.4	2.19326	1550	0.728	0.312	0.0046	1.08	1.29666
10.4	32.4	2.0308	1550	0.728	0.312	0.0046	1.08	1.26595
9.6	32.4	2.0308	1600	0.756	0.312	0.0048	1.08	1.28794
10.4	31.2	2.0308	1550	0.756	0.324	0.0048	1.08	1.01055
10	32.4	2.11203	1600	0.756	0.324	0.0046	1.04	0.931754

The best range of parameters was obtained by comparing respective value of shrinkage porosities resulting with pre-defined parameters (Table III & Fig 16). Table IV shows the value of best point from ARSM resulting with minimum shrinkage porosity.

Table IV – Recommended Input Values for Minimum Shrinkage Porosity

Film Coefficient	10.8 W/m^{2}K
Ambient Temperature	32.4℃
Mass Flow Rate	2.11203 kg/sec
Pouring Temperature	1600℃
Macro Fraction Solid	0.756
Pipe Fraction Solid	0.324
Feeding Length	0.0046 m
Mould Rigidity	1 GPa

The optimized value of *resulted shrinkage porosity* is ***0.931754 cm^3*** which is much lesser than ***2.12072 cm^3*** that resulted with initial parameters. The *percentage reduction of shrinkage porosity* with new set of values is around ***56%***, which directly implies to comparatively better quality of casting.

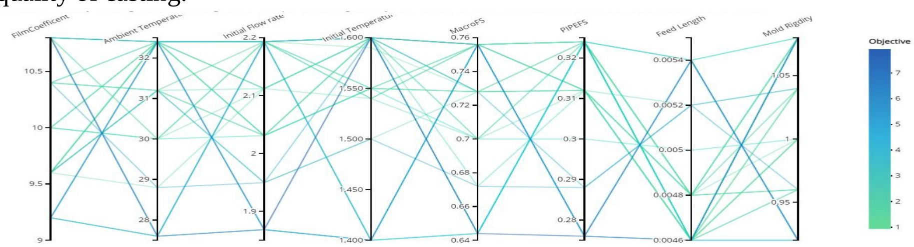

Fig. 13 Parallel coordinates with all input parameters for ARSM and resulting objective function

Fig 13. shows the combination of input parameters used in ARSM, leading to the resulting value of shrinkage porosity. The bar on the right states the value of shrinkage porosity in cm^3 . A particular colour contrast shows the combination of all parameters resulting to the shrinkage porosity of same colour contrast.

The simulation was run with the best range of parameters and result is shown in Fig 14. The casting shows much reduced shrinkage porosity.

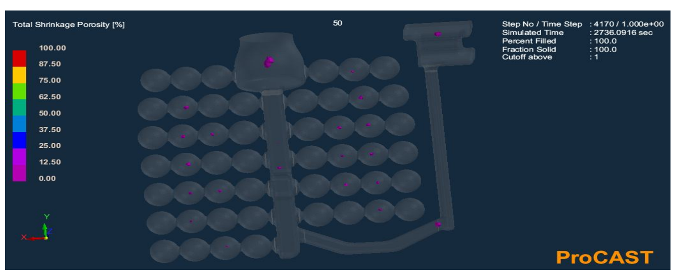

Fig 14. Optimized shrinkage porosity with recommended value of parameters

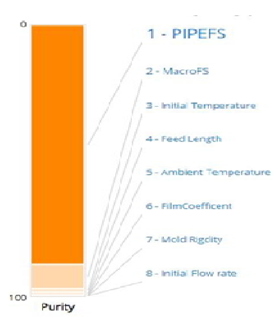

Fig 15. Importance Column for all studied parameters

The importance column in Fig 15, shows the most important input parameter at top and the colors are fading down from the first (and most important) column to the lesser ones, each one of which adds more ability to predict the target in a cumulative fashion.

VII. CONCLUSION

Casting defect like shrinkage porosity can result in the rejection of casting as it leads to failure of serviceability of castings. So, the factors leading to occurrence of shrinkage porosity can be altered and exact values for optimization can be known.

Directional solidification also plays very important role in the occurrence of shrinkage porosity. Since, the design of casting (including gating and feeding) is directly related to solidification, it also affects the quality of casting. As seen, slight modification in the traditional shapes have resulted in achieving directional solidification which directly affects shrinkage porosity. The other important parameters should be changed to values stated in result to minimize shrinkage porosity in grinding media balls casting of 50 mm diameter with high chrome white iron material.

3-D Modelling and simulation software helps in analysing the actual casting process with all the practical conditions without much loss of time, power and money. PROCAST is a powerful tool to study the effect of parameters on the quality of casting along with digital analysis of parameters like fluid velocity, solid fraction within the casting, which is not feasible practically. Also, casting simulation helps in analysing the defect along with its location and in finding the best solution for optimization.

VIII. ACKNOWLEDGEMENT

The author gratefully acknowledges BSMPL (India) for their aid in understanding actual production process of grinding media balls casting and collection of experimental data.

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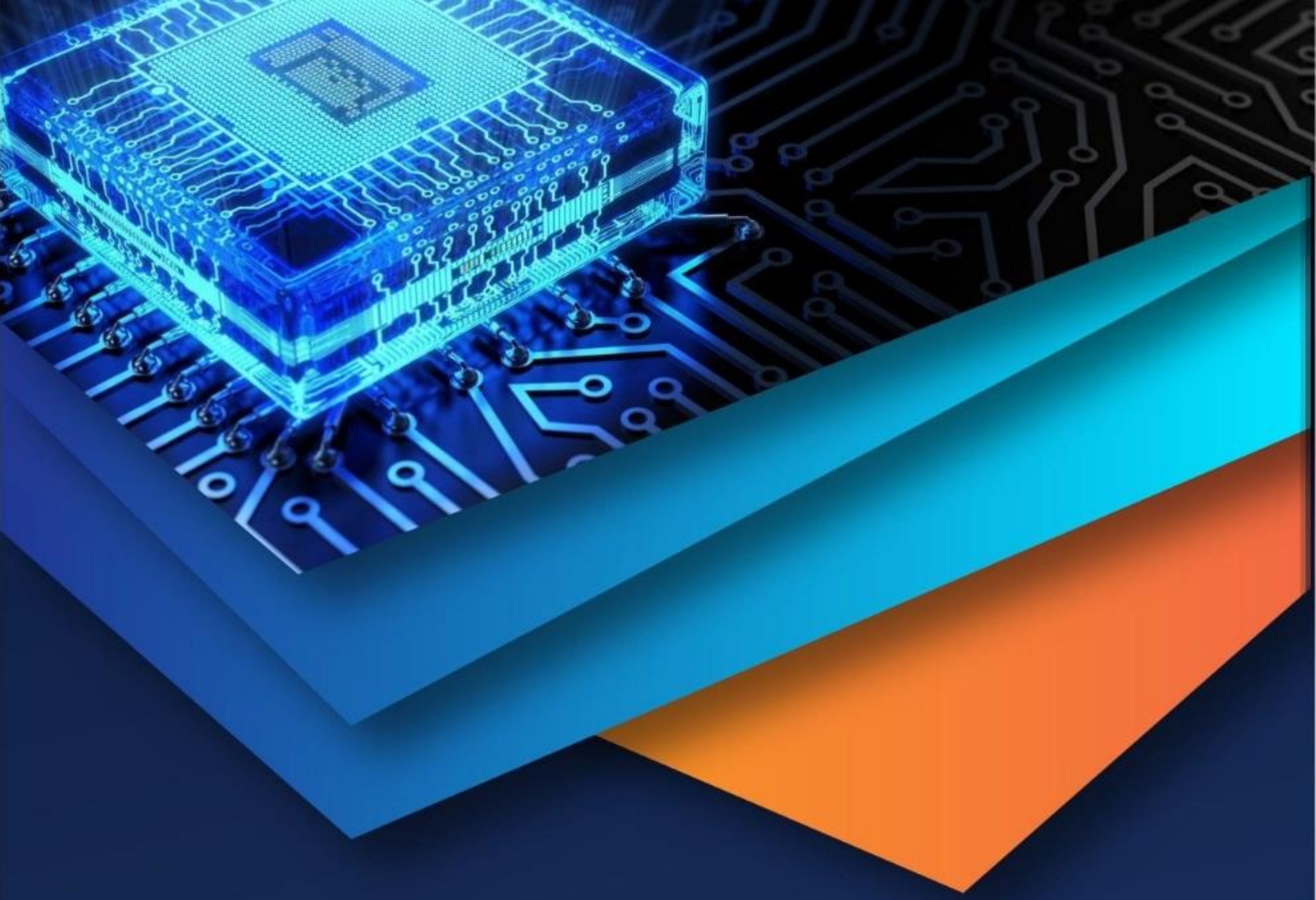

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