Shrinkage Cavity Analysis in Butterfly Valve Disc Castings

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Abstract

Metal casting is the process of forming metallic objects by melting metal, pouring it into the shaped cavity of a mold and allowing it to solidify. During the development stages of any product, it is a common practice to generate a model and then subject the model to the conditions which the product is likely to face during its functions. Modelling of a butterfly valve disc using Solidworks software was done. Analysis of shrinkage cavity or porosity during metal casting process, which is vital factor in casting process, was done with the help of proper gating system design and the numerical simulation of gray iron butterfly valve disc was done by AutoCAST software. According to the simulation results including hot tear and shrinkage cavity defect distribution, the cavity problems were investigated, results and remedies were listed and then the feasible feeding system was proposed.

Keywords: Butterfly valve disc, Shrinkage cavity, gating design, Solidworks, and AutoCAST.

1. Introduction.

The casting process consists of pouring or injecting molten metal into a mold containing a cavity with the desired shape of the casting. Casting is a solidification process. Therefore, the microstructure can be finely tuned, such as grain structure, phase transformations and precipitation. However, defects such as shrinkage porosity, cracks and segregation are also intimately linked to solidification. These defects can lead to lower mechanical properties. A subsequent heat treatment is often required to reduce residual stresses and optimize mechanical properties. Metal casting process begins by creating a mold, which is the “reverse” shape of the part we need. The metal is heated in an oven until it melts, and the molten metal is poured into the mould cavity. The liquid takes the shape of cavity, which is the shape of the part. It is cooled until it solidifies. Finally, the solidified metal part is removed from the mould.

Under normal conditions, like all metallurgical products, castings also contain certain imperfections which contribute to a normal quality variation. Such imperfections are taken as defects or flaws only when they affect the appearance or the satisfactory functioning of the castings and castings in turn do not come upto the quality and inspection standards being applied. A defect may be the result of a single clearly defined cause or a combination of factors, in which case, necessary preventive measures are more obscure. Shrinkage cavity or shrinkage porosity is one of the major defects in castings. Analysis of shrinkage cavity or porosity is more difficult than the analysis of surface defects. Elimination of shrinkage porosity or cavity helps in producing sound casting. During casting process design, CAD/CAE technology can play important role to avoid macroscopic irregularity, internal defect and assure casting performance. A typical complex design industrially used product, butterfly valve, has been used for this analysis. Butterfly valves are valves with a circular body and a rotary motion disk closure member which is pivotally supported by its stem. A butterfly valve can appear in various styles, including eccentric and high-performance valves. These are normally a type of valve that uses a flat plate to control the flow of water. Casting simulation process can able to overcome these problems. It was observed that various type of simulation softwares have been used in foundry, out of which FEM, DFM, VEM based casting simulations are widely used in foundry. Out of these VEM (Vector Element Method) based software AutoCAST have proved to be highly efficient, less time consuming for detecting the shrinkage cavities in the castings [1].

From literature review, it have been revealed that many software packages such as Magmasoft, Novacast suite of programs, finite difference method software SOLIDCAST, PROCAST which works on the basis of Finite element method, Vector element method software AutoCAST, etc. are used nowadays for the casting simulation and analysis purposes. Many researchers reported that about 90% of the defects in castings are due to wrong design of gating & feeding system and only 10% due to manufacturing problems. Many eminent researchers like Prof. M.N. Srinivasan, Prof. B. Ravi from IIT, Bombay, have contributed a lot to the analysis and casting simulations using different softwares [2]. Dr. B.Ravi have contributed a lot to the development of software AutoCAST, intelligent design of gating, concept of zero defect in castings and there are many other research papers by him [3,4]. Dr. B. Ravi studied on optimization of mold cavities, feeders and gating system of an industrial component by using AutoCAST casting simulation process. They shown that the total time for method design and optimization of the casting reduces to about one hour. It has been predicted the location of shrinkage porosity by casting solidification simulation, and could be corrected by minor modification to part design. Those authors investigated the best values and ratios of junction parameters by using casting simulation software like Auto CAST [5,6,7,8]. Another researcher includes Durgesh Joshi et.al, have contributed a lot to the feedability analysis and optimization techniques, quality and process planning studies[9]. D. Ramesh et.al , a research engineer from IIT, Bombay have carried out various studies on rapid prototyping of castings and prevention of potential problems [10]. The work have been carried out by the authors as a part of B-Tech thesis so as to analyse shrinkage cavity of a complex designed butterfly valve disc using various softwares like Solidworks and AutoCAST.

2. Solid Modelling

The solid model of a cast product is the backbone for various CAD/CAM programs that help in improving the accuracy and speed of different tasks in casting development. The butterfly valve disc has been modelled using SOLIDWORKS software, and the drawing of the same have been shown in the fig.

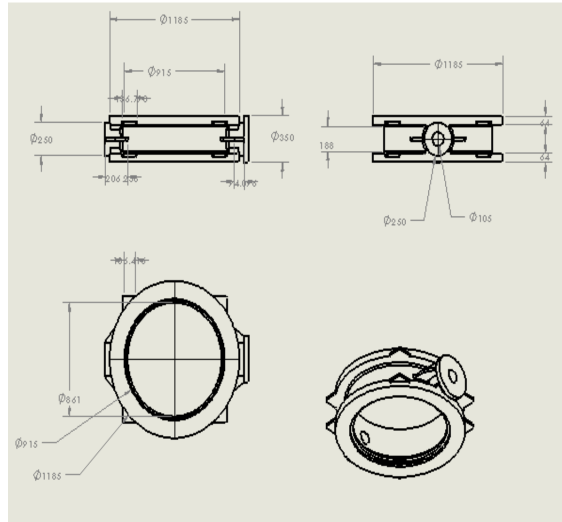

Figure 1. Solidworks drawing of butterfly valve disc casting

The material selected for the butterfly valve disc casting is grey cast iron having grade FG260. Grey cast irons is selected as it exhibits low to moderate strength, low ductility and toughness, low modulus of elasticity, low notch sensitivity, high resistance to wear and seizure, excellent vibration damping capacity, excellent machinability, high thermal conductivity, moderate resistance to thermal shock and most important, excellent fluidity. The grey irons are graded on the basis of their minimum tensile strength in MPa of a test piece machined from a 30 mm diameter test bar cast separately. Major grades include FG150, FG200, FG220, FG260, FG300, FG350 and FG400, with the corresponding tensile strength increasing from 150 Mpa to 400 MPa. The Brinell hardness also increases from 150 HB for FG150 to 250 HB for FG400. The corresponding density is in the range 7050-7300 kg/m3 and specific heat is 490-605 J/(kg K) at 700 C. Thermal conductivity decreases from 49.5 W/(m K) for FG150 to 40 W/(m K) for FG400 at 500 C. Coefficient of thermal expansion is about 12.5 μm/(m K). The modulus of elasticity and wear resistance increases with tensile strength, while machinability, resistance to thermal shock, damping capacity and metal fluidity decrease with increasing tensile strength. The material composition of the grey cast iron of grade FG260 is as follows: Carbon – 3.6%, chromium – 0.05%, iron – 93.93%, magnesium – 0.04%, manganese – 0.21%, molybdenum – 0.05%, nickel – 0.1%, phosphorus – 0.02%, silicon – 2.2%, sulphur – 0.01%. Density of the material is generally 7200 Kg/m3 (here it is taken as 7220 Kg/m3), melting temperature is 1148ºC, specific heat is 605 J/KgK, thermal diffusivity is 12.5 μm/mK, thermal conductivity is 46.8 W/mK, magnetic permeability is 345µH/m, electrical resistance is 0.76µ.ohm.m, tensile strength is 260 MPa, compressive strength is 864 MPa, shear strength is 299 MPa, fatigue limit is 117 MPa, Youngs modulus of elasticity is 120 GPa, rigidity modulus is 51 GPa, coefficient of friction is 0.26, hardness in terms of Brinell Hardness Number (BHN) is 205, solidus temperature is 1148ºC, Liquidus temperature is 1224ºC, pouring temperature is 1324ºC, liquid – solid shrinkage is 1.5%.

After modeling, the following datas were also obtained- Volume of the butterfly valve disc casting, V as 100575307.77 mm^3, Taking density of iron, ρ_{cast} as 7220 Kg/m^3, weight of casting = ρcast * volume = 7220 * 100575307.77 = 726.1 Kg. Surface area of the casting, A, was found to be 4411794.13 mm^3.

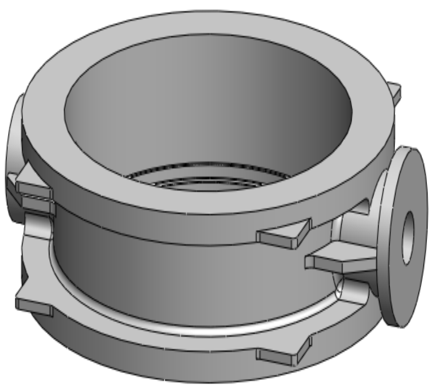

Figure 2. Butterfly valve disc modelled in SolidWorks.

Without favourable thermal gradients no castings poured in an eutectic alloy can be produced free of porosity or shrinkage, even with an adequate riser. Typically in a solid solution alloy, dendrites grow during solidification. When the tips of the growing dendrites meet, they block the passage of liquid metal. Thus, an adverse temperature gradient can render even an adequate riser, with safety factor, incapable of eliminating micro-shrinkage. Feeding systems, consisting of a feeder attached to its casting, must be such, that assuming hot metal is poured through the riser, the solidification starts at the end edge or a chilled region of the casting and then proceeds towards the riser; so that the last metal to solidify is within the riser. A casting (along with feeders) should be designed to achieve controlled progressive solidification, so that it is free of solidification related defects. Progressive solidification refers to solidification in a given cross section of the casting, ideally starting from the mould wall and gradually progressing towards the centre of the cross section. Directional solidification refers to the sequence of solidification of different regions of the casting, ideally starting from the thin regions at one end, followed by adjacent thicker regions, and finally ending at the thickest region (usually the feeder). Inorder to find the appropriate dimensions of the feeder for the butterfly valve disc casting, the following procedure was followed. The whole butterfly valve disc was divided into four regions: bare disc, vertical circular disc, and two extended bosses. The properties like volume, surface area, weight for each region have been found using Solidworks with the help of evaluating mass properties, and assigning material properties and tabulated as shown.

Table 1. Modulus table for each regions

REGION	VOLUME (V) (mm^3)	SURFACE AREA (A) (mm^2)	MODULUS (V/A) (mm)
1.Bare valve disc	82932005.68	3946576.05	21.0136
2.Vertical circular disc	3589642.67	233710.93	15.36
3.Extended boss	7026829.71	115753.575	60.705
4.Extended boss	7026829.71	115753.575	60.705

Hence the order of solidification is 3, 4 – 1 – 2. Thus the end portions (the regions 3, 4) is the last freezing region and requires a suitable feeder, which are the extended portions.

The solidification time is given by :

$$\sqrt{\tau} = \frac{\rho cast\ [L + Ccast\ (Tpour - Tsol)]}{1.128\sqrt{Kmould\ *\rho mould\ *Cmould}\ (Tint - Tamb)} * (\frac{V}{A})$$

[5], Where, $\rho cast$ = Density of liquid metal = 7220 Kg/m^3, L= Latent heat of metal = 234.7 KJ/Kg, C_{cast} = specific heat of cast metal = 605 J/KgK, T_{pour} = Pouring temperature = 1342ºC, T_{sol} = Solidus temperature = 1148ºC, T_{amb} = ambient temperature = 40ºC, T_{int} =Interface temperature = $0.9*T_{sol}$ =0.9*1148 = 1033.2ºC, P_{mould} = Density of mould material = 1600 Kg/m^3, k_{mould} = Thermal conductivity of mould material = 0.61 J/mKs, C_{mould} = Specific heat of mould material = 1130 J/KgK, V/A = Casting modulus of last freezing region = 60.705 mm, thus the solidification time obtained from the above Chvorinov´s equation, was 4.48 hours.

To design a top feeder for the last freezing region based on modulus principle, feeder height to diameter ratio have been assumed to be 4 : 1 as for large casting, and assumed no heat transfer from the entire bottom face of the feeder. Modulus of feeder, Mf = 0.235Df, where D_f is the diameter of feeder. For grey iron castings, as there is a graphite expansion phase during solidification, the safety factor 0.6 are taken commonly. Taking modulus of feeder = 0.6* Modulus of region around hotspot, feeder diameter is obtained as 150mm and feeder height, neck diameter was obtained as 600mm and 90mm respectively. The above dimensions represent the limiting size of the feeder. The actual dimensions required for a shrinkage free casting may be higher depending on the feed path between the feeder and the hot spot, or may be corrected using feed aids of proper dimensions. The feeder requirement have also been calculated alternatively using graphical method. The modulus of the casting was obtained as 22.7969 mm. The graphite expansion which occurs during solidification of the alloys specifies that grey cast irons do not shrink for the full time during which liquid metal present. The shrinking time (ST) is only a proportion of the total solidification time. This proportion, expressed as a percentage, was determined from the graphs, for 3.35% of carbon content and combined 2.5% of silicon and phosphorus.

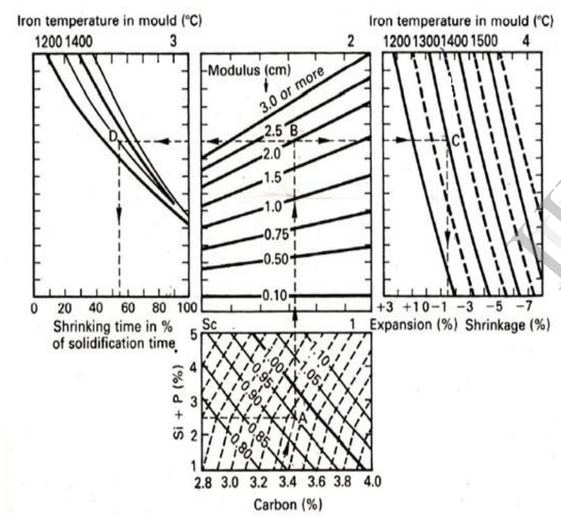

Chart 1. Graph for shrinking time and shrinkage [11].

Using the known carbon content, moving parallel to the carbon line to the appropriate (Si + P) content at point A, a line was drawn vertically until it intersects the casting modulus line at point B. Extending a line horizontally to the left until it intersects at point D with the line representing the estimated temperature of the iron in the mould, shrinkage time (ST) can be found out.

From the graph, casting modulus was obtained as 2 cm, at 1300℃ casting temperature , 1.6% shrinkage and shrinking time as 55% . Effective feeder modulus is given by M (f) = M(c)*1.2*√ (ST/100) and obtained as 20.28 mm. From the modulus & a/b ratio graph, the values of "a" and "b" can be found out, where "a" is radius and "b" is height of the feeder. Assuming a/b ratio of 1:8, the radius of the feeder was obtained as 75mm, that is diameter of the feeder as 150mm, and the height as 600 mm.

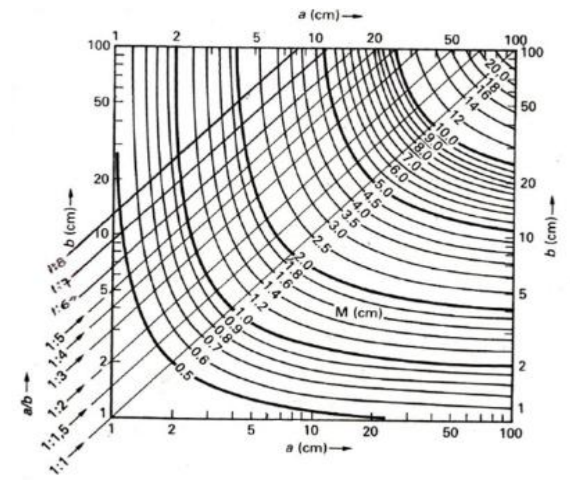

Chart 2. Modulus versus dimensions graph [11].

The gating dimensions have been found at by proper gating design. In general, fluidity of pure metals is higher than alloys. Within alloys, eutectics have higher fluidity than non – eutectics . The fluidity of grey iron ranges between 0.5 and 1 m, and can be estimated by the empirical equation : Lf = (14.9 CE + 0.05 Tp – 155) * 25.4 mm, where, CE is carbon equivalent given by, CE = % C + 0.25 % Si + 0.5% P, and Tp is the pouring temperature in Fahrenheit, = 1324ºC = 2415.2ºF. By applying continuity equation between top and bottom exit of sprue, (A1*V1 = A2*V2), sprue top area, A1 = A2*V2/ V1 = A2 * $\sqrt{2 * g * H2}$ / $\sqrt{2 * g * H1}$, where, H_1 is the metallostatic pressure which is the sum of mould height (H_2) and pouring height, the diameter of sprue at top and bottom was found to be 150 mm and 121 mm respectively. Sprue well arrests the free all of molten metal through the sprue and turns it by a right angle towards the runner. It must be designed to minimize turbulence and air aspiration. The recommended shape of the sprue well is cylindrical, with diameter twice that of sprue exit and depth 1.5 times that of runner. The main function of the runner is to slow down the molten metal, which speeds up during its free fall through the sprue, and take it to all the ingates. This implies that total cross sectional area of runner must be greater than the sprue exit. For gating ratio 1:2:0.3, the dimensions of ingate for rectangular tapered cross section was (90/106)*33. According to the gating dimensions, the butterfly valve disc was modelled along with the gating design using SOLIDWORKS software.

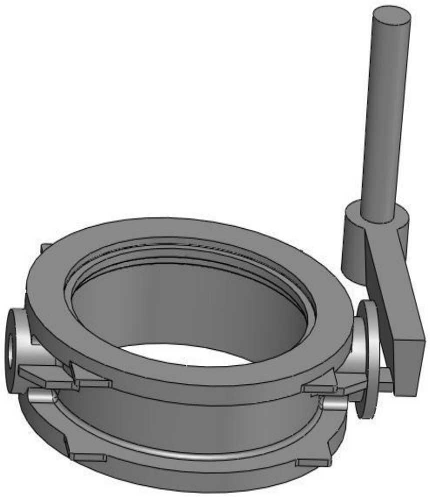

Figure 3. Solid modeling done after gating design.

3. Results And Discussions

The modelled valve disc along with the designed gating system have been converted into STL format and exported to AutoCAST software, which is a vector element method. This method is based on determining the feed path passing through any point inside the casting and following the path back to the local hot spot. The feed path is assumed to lie along the maximum thermal gradient. The casting volume is divided into a number of pyramidal sectors originating from the given point, each with a small solid angle. For each sector, the heat content (proportional to volume) and cooling surface area is determined to compute the flux vector. The method is robust compared to FEM, since minor errors in computing the flux vector at any point (arising due to lack of accurate thermo-physical data) are automatically corrected in subsequent iterations. The VEM has also proved to be much more efficient (lower memory requirement and 10 -100 times faster) than FEM, for identifying hot spots in even complex shaped castings.

The butterfly valve analyzed using AutoCAST software was processed under different operations. Processing under different instructions, the colour discriminates the perfect and imperfect castings. The mold size of 1850.0 x 1750.0 x 1300.0 mm, 688 mm and 282 mm of part height of cope and drag respectively, with horizontal parting were selected.

After processing using AutoCAST, certain portions of the intense area show various colour changes. In this the “white” colour shows, a large amount of shrinkage cavity; “yellow” colour indicates some imperfections like small cavities or porosities, and “red” colour shows perfect casting without porosity. The X,Y,Z directions in mold design are represented by R,G,B (red, blue, green colours) respectively and Z direction is the pouring direction.

Initially just after processing, some portions showed reddish yellow. In those portions, it seems there would be possibility of formation of cavities while casting the product. In some portions, red colour could be seen, which implies that solidification of molten metal in those portions will be perfect and all the portions should be made correct by properly designed feeders or risers, and feedaids.

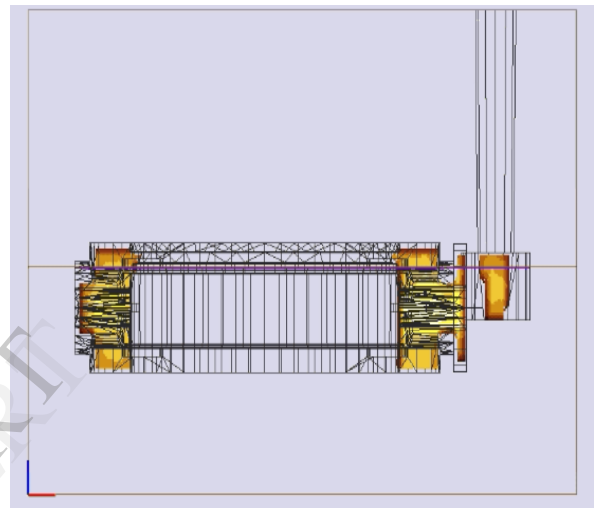

Figure 4. Front view after processing of butterfly valve disc

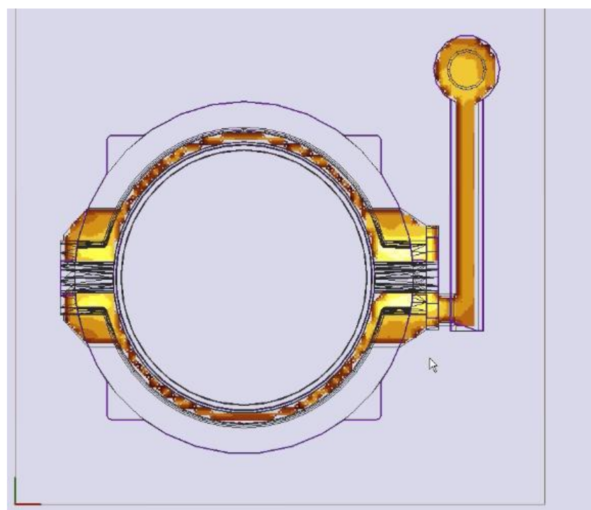

Figure 5. Top view after processing

Proper feeders have to be introduced for rectifying the problems arising during the analysis. After designing the proper feeder, the required dimensions like diameter and height of the feeder is entered as program instructions. The proper feeder will clear all the shrinkage cavities that will occur in those portions. Risers, also known as feeders, are the most common way of providing directional solidification. It supplies liquid metal to the solidifying casting to compensate for solidification shrinkage. For a riser to work properly, the riser must solidify after the casting product, otherwise it cannot supply liquid metal to shrinkage within the casting. Risers add cost to the casting as it lowers the yield of each casting; that is, more metal is lost as scrap or waste for each casting.

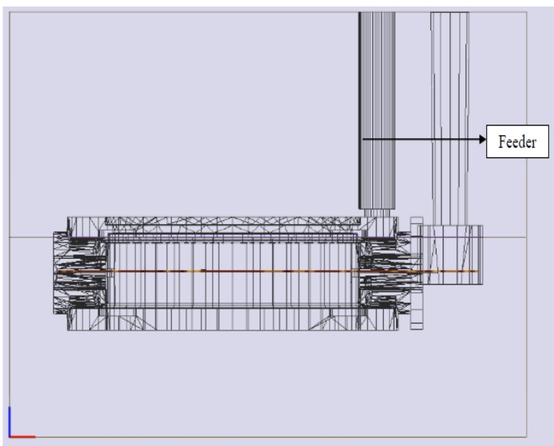

Figure 6. Introducing feeder to the casting

Another way to promote directional solidification is by adding chills to the mold. A chill is any material which will conduct heat away from the casting more rapidly that the material used for molding. Feeder aids or riser aids are items used to assist risers in creating directional solidification or reducing the number of risers required. One of these item chills which accelerate cooling in a certain part of the mold. Insulating sleeves and toppings may also be installed around the riser cavity to slow the solidification of the riser. Heater coils may also be installed around or above the riser cavity to slow solidification. By the addition of feeder also, a slight percentage of shrinkage cavity was found which is undesirable. Inorder to avoid this problem, an exothermic feedaid of 15 mm thickness, obtained using trial and error method, was included around the feeder. Sleeves of the correct dimensions were set on the individual pattern in the predetermined location and the mould would be rammed around the sleeves in practical applications. It was ensured that the base of the feedaid should not come into direct contact with the casting but be set on a sand step at least 10 mm thick.

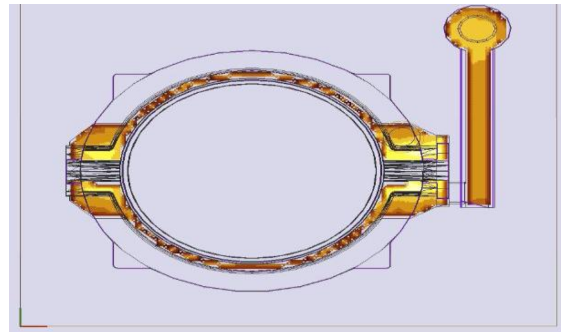

Figure 7. Corrected casting using proper feeder and feedaid

By properly locating the feeder and feed aid, the colour has changed to almost red in most parts of the casting. Feeder and feedaid is positioned in those places where more molten metal is needed. The solidification of metal in feeders will taken place only after reaching the molten metal in every portions of the casting product. Thus shrinkage cavities can be considerably reduced using this analysis. Due to abrupt changes in cross sections, the possibility of shrinkage cavity is somehow higher, even if the region is closer to the gating system.

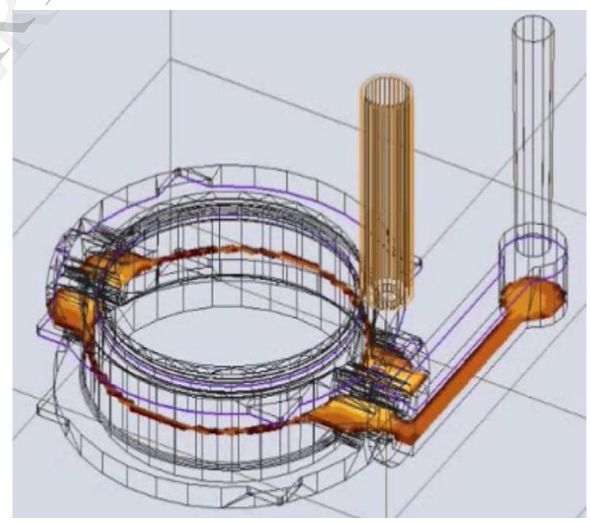

Figure 8. Three Dimensional view of the product after feeder and feedaid design.

As a part of reducing the scrap obtained through feeding and gating system, to increase the feeder efficiency further, the inherent capability to develop the gating and sprue arrangement by AutoCAST has been exploited. The product to be analysed was exported to the software devoid of gating system.

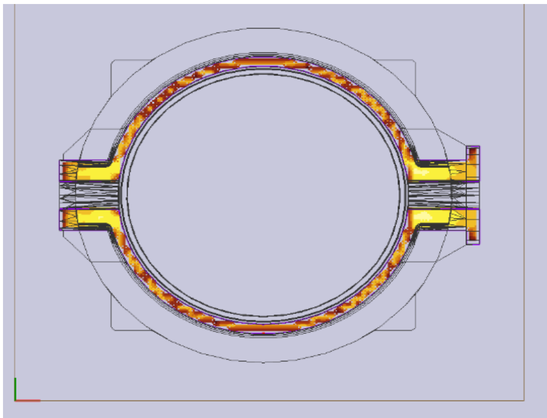

Figure 9. Processing using AutoCAST without gating system

An optimum gating design with gating ratio of 2.03:1.52:1.00, top and bottom sprue diameter of 40 mm and 22 mm respectively, runner section of 15.0 x 19.0 mm and ingate section of 17.0 x 11.0 mm was found by trial and error method using the software. Taking under manufacturing considerations of the desired product, the optimum gating dimensions plays a vital role which makes the casting a perfect one. At the intense joint portions, there are possibilities of formation of cavities as shown by yellow colour during analysis. Feeders and feedaids have been placed in certain locations where the colour change has been found, changing from yellowish to reddish colour, proving casting without shrinkage cavity. Two side feeders with 540 mm feeder height, 150 mm feeder diameter and exothermic feedaids with thickness 24mm were added to the system so that a sound cast would be obtained.

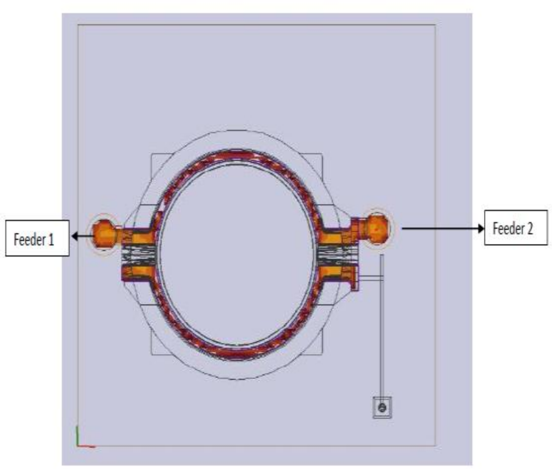

Figure 10. Perfect casting obtained with two side feeders.

4. Conclusion

Analysis of casting products is a major concern in the foundry industries. Among these, shrinkage cavities are the most possible casting defects, so the analysis of shrinkage cavities have a major significance in those industries. By the usage of Solidworks and AutoCAST softwares, this problem has been sorted out. The proper designing and the analysis of the gating and feeding system will contributes for better casting products. A similarity in positioning of feeder between the theoretically predicted design and through simulation was noticed and a new paradigm design with an optimum gating and feeder design was found to produce defect free casting. The design and analysis phases are very significant phases in the foundry industries and those phases have been undergone by computing the gating and feeder designs and Software processing. Completing the processes in the software, it enables the system to identify the places where the feeders or risers had to be positioned, so that more molten metal would be allowed to flow through those portions where defects were identified. So the casting product (butterfly valve disc) hence if manufactured would be having only negligible defects and the casting will possess a long life. Proceeding in this approach, the manufacturer or industrialist does not need to waste time and money on doing testing methods like destructive and non-destructive methods , as the software is possessing much higher accuracies, and even zero defect concept is possible producing sound castings.

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