

Thermal-Induced Defects and Optimization of Casting Process

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Abstract—A casting process in the general industry is prone to produce varied defective parts, which happens majorly due to the factor of thermal and flow. These factors can cause major quality problems and drop in product performance during operational condition if left untreated. Thus, this paper presents these type of problems encountered in casting by applying analytical technique to forecast the behaviors of inclusions in molten material in a mold, determining the effect of parameter and process change during pouring, and analyze the pattern and provide the best decision in regards to the process of manufacturing. The use of computer-aided tool, also known as Manufacturing Analysis (in this case, an analysis of solidification and fluidity of molten material) technologies, is developed and utilized to enable a study on reduction of thermal-based defects in manufacturing on a casting product. Assessment is made based on temperature distribution, filling and solidification time, and the presence of porosity in a sample product, while optimization is performed on the same product but with different process parameters such as gate size, location, melt temperature and such. The results are varied with improvement in one area, but might worsen in another area. Thus, the final outcome is discussed and measured for its feasibility and possibility for multiple improvement process to be integrated together.

Index Terms—Casting, Casting defect, Casting simulation, Thermal and flow analysis, Casting optimization, Thermal defect.

I. INTRODUCTION

The foundry industry thrives mostly in the automotive and heavy industries, where quality parts made from casting process were required to be produced daily in mass quantities using all means of available technique, technologies and casting materials [1]. Thus, continuous improvement and processes are required to be optimized to achieve the best product design in term of cast effectiveness and high quality from an end user's view [2]. However, despite the convenient way of manufacturing, the method of pouring liquid material into molds present a common problem, widely known as thermal defects. Based on the name, the defects found in casting parts are induced by the manipulation of temperature and other known thermal coefficient and

factor [3]. Some other type of flaws and failures also can and might be caused by other defects; for example, a porosity in completed can lead to blowhole from the trapped gas as shown in Fig. 1 and Fig. 2. In order to counter the thermal factors in quality control, engineers and toolmakers are responsible in predicting changes and compensate for the variations in the mold design. Thus, the application of computer simulation has begun to be integrated with experience based approach by foundries in meeting the demands of high quality parts in a cost effective manner. Simulation software is available not only for thermal and flow modeling, but for calculation of grain structure, porosity, hot tearing, hotspot and solid state transformation [4].

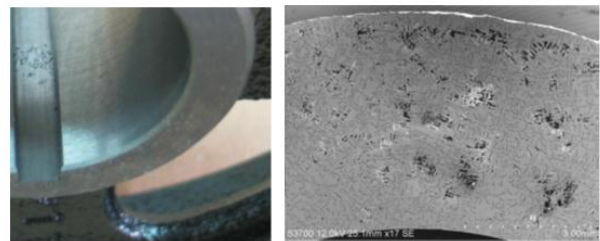


Figure 1. Example of defect by porosity



Figure 2. Example of defect by shrinkage

Proper understanding of the various porosity-type flaw also helps in casting part design. While some of the defects can be fixed through the manufacturing process and technologies, others can be fixed through design changes or even a combination of both. So, by knowing the factors and parameters that are likely to allow to the formation of defects, potential problems can be avoided through multiple means and acceptable tolerance level.

Fig. 2 shows another type of failure function, which is known as shrinkage. Shrinkage is a change in volume of material that occurs when the molten metal solidifies

after being cast into a pattern mold. Most metals, including aluminum, copper, steel and zinc shrink as they solidify. The degree of shrinkage depends on the freezing range of the material. As an example, aluminum shrinks by over 6% during solidification while copper shrinks by nearly 5%. This phenomenon then leads to voids and cavities when there is not enough molten metal to feed the shrinkage when casting.

Hence foundry engineers or related designers are using manufacturing simulation tools to efficiently bridge the gap between design and manufacturing. The introduction of optimization or improved efficiency during the casting and manufacturing cycle leads to major substantial time and cost savings in industries. This is due to the capability to analyze and obtain the info and data for filling (flow velocity, melt temperature, fill time and air entrapment percentage) and solidification (solid temperature, solid-to-liquid fraction, and air entrapment) process is then recorded.

Application of manufacturing simulation helps to understand the cause and effect of adjusting process parameters in metal-casting process. The process of pouring a molten material inside a mold requires adjustment and optimization of many features, such as the gate sizing and shape, injection / pouring condition and initial melt temperature.

II. MODEL DEVELOPMENT

The model using a standard geometrical data of a Globe Valve; obtained from JIS Standard data of 10K-50 as shown in Fig. 3. As a footnote, other samples of data can also be obtained and used in a simulation, provided studies has been done before. In this case, the Globe Valve is checked for its design integrity as a benchmark model through the use of CAD software, CATIA V5.

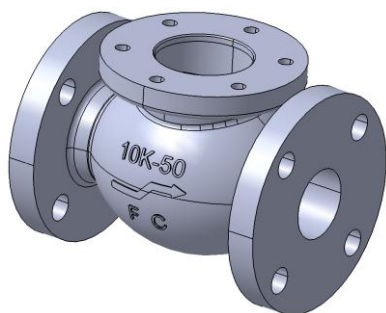


Figure 3. Globe Valve 20 JIS 10K-50

Some feature modifications were done to prepare the valve model for manufacturing analysis. The modifications include:

- Deleting engraving and symbols of valve size and specification
- Eliminate mounting holes and other machining-process features

The modified product, as shown in Fig. 4, is then saved and exported into a suitable CAD format of .stl (Standard Triangle / Tessellation Language) for pre-processing activity in Click2Cast casting simulation software.

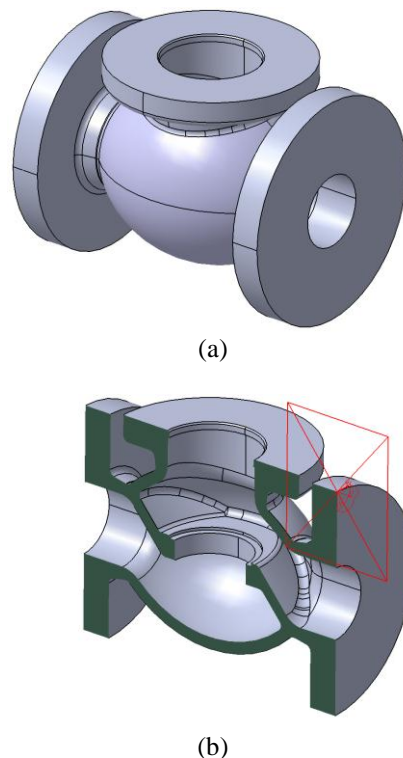


Figure 4. Modified CAD data of Valve for Manufacturing Analysis

Similarly, the original CAD model of Globe Valve 20 JIS 10K-50 is also modified to accommodate the requirements and assessment for performance analysis. However, features that were adjusted were only the engraving and symbols on the outer surface of the globe valve itself. Three main cases of performance analysis done is:

- Modal (Normal Modes) analysis is done to check the rigidity and natural frequency (termed as Mode Shape) of the product in its assembled condition. The acceptance value for passing is to obtain frequency of more than 30.0 Hz.
- Pressure loading test is done to check the resultant stresses during operation. The resultant stress is required to be lower than yield limit of applied material and ensured to have minimal / zero element strain as possible. Factor of safety is also included in assessing the pressure loading test.
- Operating Free-Flow analysis is also done to check acceptable margin of output velocity compared to input, against the shearing stresses during contact with valve body. Minor or zero loss is required to be achieved.

The mesh, or also known as Finite Element (FE) model must be prepared for all cases. The size is defined as 5mm tria + quad element. Software has been used in this analysis is;

- **Pre-processing:** Hypermesh v14.0
- **Solver:** OptiStruct v14.0 and AcuSolve 14.0
- **Post-processing:** Hyperview v14.0

Another important aspect in every performance test is the boundary condition. Due to the requirement and needs for a product to be tested as per assembly condition, the geometrical model or mesh needs to be constrained by its

degree-of-freedom (DOF). The range of DOF is 1-6, with the DOFs 1, 2, and 3 are x, y and z translation degrees of freedom, and DOFs 4, 5, and 6 are x, y and z rotational degrees of freedom. For both normal mode and pressure loading assessment, all mounting points are constrained with 1-3 DOF as shown in Fig.5.

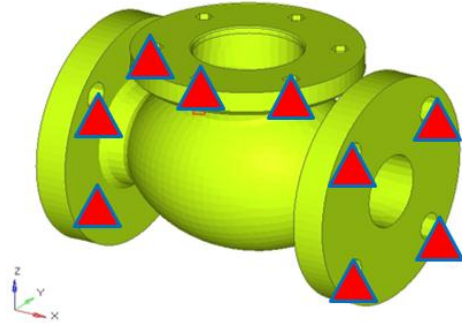


Figure 5. DOF's for normal mode and pressure loading

III. PROCESS ANALYSIS AND OPTIMIZATION

The application of manufacturing simulation studies enables the assessment of manufacturability of a base model, and defects that might occur based on any process parameters. Example of process parameters include gating size and shape, number of material inlet, melt and mold material, and corresponding temperatures. From these process parameters, multiple results can be obtained.

Using Cast Iron material of GGG-50 as baseline material and sample, an initial study is done based on the specification on study and industrial processes. The details of a process parameters for initial – hence termed as baseline results are:

- 2 gating is defined (20x20), +y-direction
- Mesh element size 4mm. Total number of tetrahedral, tria and nodes will be displayed. Estimated duration for full run is 1 hour.
- Define melt material as Cast Iron - GGG-50 with temperature of 1580 °C
- Define mold as Green Sand, with temperature of 20 °C
- Gravity direction is set to Y-direction
- Ingate velocity is 5.0 m/s

From these process parameters, multiple results can be obtained. However, the objective of defect analysis and detection will require careful observation and assessment of results obtained. All information obtained is then used to compare the process set up and parameter to benchmark information and for optimization purpose. The relevant results will be based on either material flow condition and material solidification process, and able to be detailed out as follows:

- Material Flow – Flow Filling Time, Temperature Plot and Nodal Graph, Pressure Contour
- Material Solidification – Temperature Plot and Graph, Solidification Time, and Porosity Size and Percentage

However, the objective of defect analysis and detection will require careful observation and assessment of results obtained. All information obtained is then used to

compare the process set up and parameter to benchmark information and for optimization purpose. The relevant results are based on either material flow condition and material solidification process. The results of initial analysis of benchmark product in terms of material flow and fill, which shows distribution of time, temperature and pressure, and material solidification in terms of temperature, time and defect detection analysis. These are shown in Fig. 6, Fig. 7 and Fig. 8.

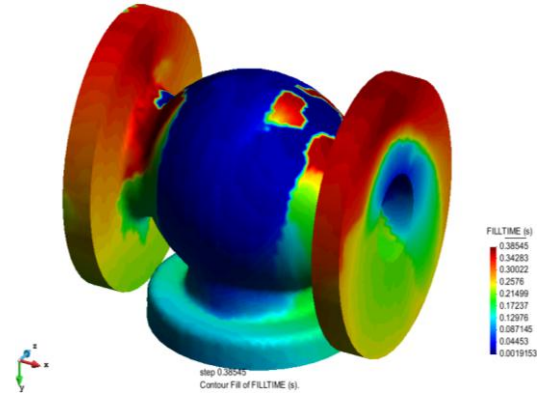


Figure 6. Total Time for Mold Filling

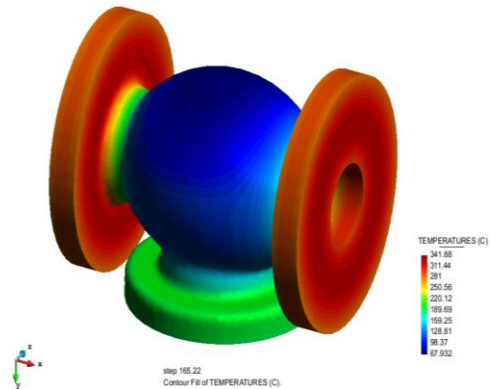


Figure 7. Final Temperature of Melt Solidification

Based on the results for initial assessment of manufacturing analysis, optimization is recommended to be carried out. One of the simplest definitions for optimization is “doing the most with the least”. Lockhart and Johnson define optimization as “the process of finding the most effective or favorable value or condition” [5].

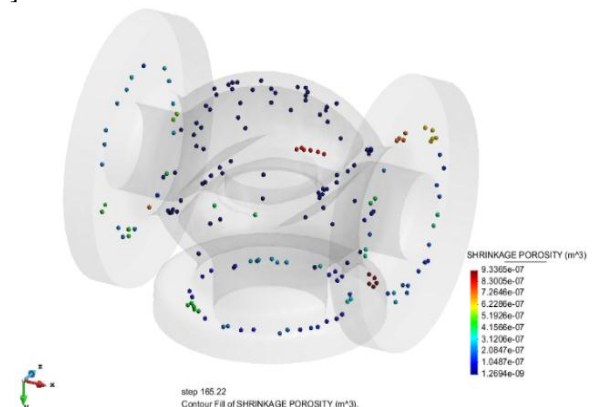


Figure 8. Porosity Volume at Final Time of Solidification

Seven (7) cases have been carried out and assessed in order to determine the best possible optimization plan for product manufacturability through casting process. The cases covered as stated below:

- Case01 - Melt temperature. The molten metal temperature will be varied to be one step lower and higher than the current temperature of 1580 °C. The purpose is to study on the filling and solidification time to reduce shrinkage and porosity issue.
- Case02 - Mold temperature. Mold temperature plays the part of boundary layer temperature to avoid solidification takes place too soon before melt is cooled down.
- Case03 - Ingate shape. The shape of the ingate will determine the amount of material flow rate, hence optimizing filling and solidification time.
- Case04 - Ingate sizes. Similar with Case03, it can be used to provide the best filling and solidification time.
- Case05 - Melt flow velocity. Able to be optimized due to similar cases of Case03 and Case04 by controlling flow rate of material.
- Case06 – Material. Different materials have different properties. These properties include the cooling rate, thermal expansion coefficient and other factors that could greatly affect the defect reduction function.
- Case 07 - Number of ingate. Reduced or extra number of ingate could provide a solution of optimized material flow to reduce porosity in certain areas.

Thus, based on the results of initial analysis, several optimization plan is being put into motion in order to achieve thermal-based defect reduction. Such plan includes melt and mold temperature, gate shape and size, material used and number of gate. The results are shown in Table 1. It shows that Case06 and Case07 are considered as optimum sample with good quality casting product.

TABLE 1. SUMMARY OF RESULT FORM BENCHMARK AND OPTIMIZED ANALYSIS

Case	Melt Fill Time (s)	Melt Solidify Time (s)	Porosity	
			Sizes (m ³)	Percentage (%)
Benchmark	0.3855	82.07	9.34e-7	1.87
Case01-1	0.3979	68.41	9.08e-7	2.41
Case01-2	0.3839	86.47	8.19e-7	2.01
Case02	0.399	82.19	1.07e-6	1.94
Case03	0.4473	82.07	7.56e-7	1.90
Case04-1	0.7427	81.27	8.00e-7	2.02
Case04-2	0.2538	82.09	1.61e-6	1.77

Case05-1	0.1995	82.02	8.44e-7	1.82
Case05-2	0.7592	81.23	7.09e-7	1.98
Case06-1	0.3834	60.43	1.03e-6	1.78
Case06-2	0.3854	66.47	1.40e-6	1.79
Case07	0.2118	61.97	5.67e-5	1.63

The objective of optimization process in engineering is to achieve the “best and optimum” concept, usually fixed in parallel to a set of prioritized criteria or constraints. These criteria include fully maximizing factors such as process efficiency, productivity, strength, reliability, longevity and concept utilization [6] [7]. Engineering optimization are often used to find a few appropriate design solutions and then decide which one best applied in terms of time, cost and feasibility.

Finally, based on the optimization case studies, it is found that there are significant of differences of product output quality due to process and material change. The results are summarized below:

- Not all purposed cases have the best output (some has the best time but increase in defects, and vice versa), such as melt temperature adjustment.
- Several other cases have the best outcome (reduced time and defects). This include studies on gate sizing and material change.
- Based on the results, some best cases can be combined to achieve better effect. The best optimization that can be proposed is to add another gating system to the mold, which effectively reduce production time and defects in product.

Additionally, product performance test is done to check whether the product design is according to operating conditions, and concluded that all test passed with acceptable level. Weight and material optimization is essential due to industry’s demand for cost reduction for one period of cycle (increase profit without affecting product quality), and needed to be considered fully for best possible outcome.

IV. CONCLUSION

It can be observed that casting products are still being applied in all major industries worldwide. Thus, it is essential to get along with the latest adaptation of technology for best and optimum product manufacturing. By this method, material flow in casting can be optimized in terms of filling, solidification time and defect detection.

This optimization can be done by modifying and adjusting process parameters and dimensional configuration (such as gate sizing). Thus, the best and most efficient process can be utilized to reduce defects to an acceptable margin. The findings from this research showed that Casting Case06 and Casting Case07 were considered having optimum parameters with good quality product. The benefits obtained can be helpful in reducing material, cost, lead time and defect detection/reduction.

Basically, design optimization for manufactured data are recommended and required to be discussed in detail, especially with the production team. Current technology is recommended to be implemented and applied by all level of engineering process. The benefits obtained can be helpful in reducing cost, lead time and defect detection / reduction. However, more thorough investigation is required to optimize process parameters, such as material impurities, thermal coefficient differences between spec and actual material, and external factors affecting process.

Product performance tests have been done to check whether the product design is according to operating conditions. All test passed with acceptable level. Weight, cycle time and material optimization is essential due to industry's demand for cost reduction for one period (increase profit without affecting product quality).

ACKNOWLEDGMENT

The authors would like to thanks to all staff of the Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia UPM Serdang, Selangor Malaysia for their supports and laboratory facility. This work was financially supported by Fundamental Research Grant Scheme (FRGS) from Ministry of Education (MOHE), Malaysia.

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