Detailed study for Finding Optimum Values for different Parameters using Simulation and Experimentation for Investment Casting Process

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September, 2019

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Abstract:

Investment casting is a manufacturing process in which a wax pattern is coated with a refractory ceramic material. Once the ceramic material is hardened its internal geometry takes the shape of the casting. Optimization of Investment Casting Process and finding the best possible combination of parameters using simulation in order to get desired results with improved quality and reduced costs is a real challenge which all the investment casting firms are facing these days. The combination of different parameters I am using has not been used before. To find the best value of the variable is not a new concept and considerable research has been carried out in this area while no one has tried combination of variables by changing their values and using simulation technique to find out best possible combination of variables so the area is not been explored yet and has great potential in terms of its impact on the efficiency of the investment casting process. In this research, a combination of optimum values of variables will be presented with the objective of optimizing the overall efficiency and quality. The proposed combination would be Different types of Materials to be used for casting, Metal Pouring Temperature and Different Types of Tree designs.

Table of Contents

Thesis Acceptance Certificate .... **iii**

Declaration .... **iv**

Plagiarism Certificate .... **v**

Copyright Statement .... **vi**

Acknowledgements .... **vii**

Abstract: .... **ix**

List of Figures .... **xii**

List of Tables .... **xviii**

Chapter1: Introduction & Literature Review **1**

- **1.1. The investment casting process- a brief description:** **2**
  - **1.1.1. Creating a Wax Pattern** 2
  - **1.1.2. Wax Tree Assembly** 3
  - **1.1.3. Shell Building** 3
  - **1.1.4. Dewax & Burnout** 3
  - **1.1.5. Metal Pouring** 3
  - **1.1.6. Shell Knock Off** 4
  - **1.1.7. Cut Off** 4
  - **1.1.8. Finishing** 4
- **1.2. Defects in parts produced by investment casting:** **5**
- **1.3. Background & Motivation:** **5**
- **1.4. Literature Review:** **6**
- **1.5. Problem Statement:** **7**

Chapter2: Methodology **9**

- **2.1. Methodology:** **9**
  - **2.1.1. Parameters and Their levels:** 10
  - **2.1.2. Design of Experiments:** 13
- **2.2. Simulation using Inspire Cast:** **15**
- **2.3. Experimentation:** **19**
- **2.4. Summary:** **26**

Chapter3: Results and Analysis **27**

- **3.1. Visual Inspection:** **27**

3.2. Simulation Results: 28
3.3. Microscopy: 57
3.5 ANOVA: 67
3.6 Results Summary: 71
Chapter4: Discussion and Future Work 72
4.1. : Discussion: 72
4.2. : Future Work: 72
Bibliography 73

List of Figures

Figure 1.1: The Investment Casting Process………………………...………………………….5

Figure 2.1: Methodology Flow chart………………………………………………...………9

Figure 2.2: Tree1 SolidWorks Model…………………………………………………….....10

Figure 2.3: Tree2 SolidWorks Model…………………………………………………….....11

Figure 2.4: Tree3 SolidWorks Model………………………………………………………11

Figure 2.5: Importing tree 1 in SolidCast…………………………………………………..…16

Figure 2.7: Importing tree 3 in SolidCast……………………………………………………..17

Figure 2.6: Importing tree 2 in SolidCast…………………………………………………..…17

Figure 2.8: Simulation on software defined mesh size……………………………..………18

Figure 2.9: Wax Pattern………………………………………………………………………….19

Figure 2.10: Wax Sprue…………………………………………………………………………19

Figure 2.11: Wax Tree1………………………………………………………………………….20

Figure 2.12: Wax Tree2………………………………………………………………………….20

Figure 2.13: Wax Tree3………………………………………………………………………….21

Figure 2.14: Trees after coating……………………………………………………………….21

Figure 2.15: Dewaxing Oven………………………………………………………….……....22

Figure 2.16: Burnout oven/ Heating furnace………………………………………………….22

Figure 2.17: Pre heating………………………………………………………………………….23

Figure 2.18: Metal Pouring…………………………..23

Figure 2.19: Trees obtained after pouring………………………………...……………………..24

Figure 2.20: Finished Products……………………………………………………………..…25

Figure 3.1: Parts Produced before this work……………………………………….………………….27

Figure3.2: Parts produced by performing experimentation according to parameters discussed in this work……………………………………………………………………………...…………………..28

Figure 3.3: Filling Time Aluminium A7075, temp1 and tree 1……………………………………….29

Figure 3.4: Cold shuts Aluminium A7075, temp1 and tree 1…………………………………………29

Figure 3.5: Last Air Aluminium A7075, temp1 and tree 1……………………………………………..30

Figure 3.6: Porosity Aluminium A7075, temp1 and tree 1……………………………………………..30

Figure 3.7: Solidification Time Aluminium A7075, temp1 and tree 1………………………………...31

Figure 3.8: Total Shrinkage Volume Aluminium A7075, temp1 and tree 1…………………………......31

Figure 3.9: Filling Time Aluminium A7075, Temperature 2, Tree2……………………….…………..32

Figure 3.10: Cold shuts Aluminium A7075, Temperature 2, Tree2……………………………….....32

Figure 3.11: Last Air Aluminium A7075, Temperature 2, Tree2…………………………….……….33

Figure 3.12: Porosity Aluminium A7075, Temperature 2, Tree2……………………………..……….33

Figure 3.13: Solidification Time Aluminium A7075, Temperature 2, Tree2……………………………34

Figure 3.14: Total Shrinkage Volume Aluminium A7075, Temperature 2, Tree2…………….…….…34

Figure 3.15: Filling time Aluminium A7075, Temperature 3, Tree 3…………………………..…..…35

Figure 3.16: Cold shuts Aluminium A7075, Temperature 3, Tree 3……………………………..…..35

Figure 3.17: Last Air Aluminium A7075, Temperature 3, Tree 3……………………………………..…36

Figure 3.18: Porosity Aluminium A7075, Temperature 3, Tree 3……………………………………..…36

Figure 3.19: Solidification time Aluminium A7075, Temperature 3, Tree 3……………………..…..37

Figure 3.20: Total Shrinkage Volume Aluminium A7075, Temperature 3, Tree 3………………..……37

Figure 3.21: Filling Time Aluminium available at MRC, Temperature 1, Tree 2…………………..…...38

Figure 3.22: Cold shuts Aluminium available at MRC, Temperature 1, Tree 2………………………..38

Figure 3.23: Last Air Aluminium available at MRC, Temperature 1, Tree 2…………………………..39

Figure 3.24: Porosity Aluminium available at MRC, Temperature 1, Tree 2………………………….39

Figure 3.25: Solidification Time Aluminium available at MRC, Temperature 1, Tree 2…………..….40

Figure 3.26: Total Shrinkage Volume Aluminium available at MRC, Temperature 1, Tree 2…..……40

Figure 3.27: Filling Time Aluminium available at MRC, Temperature 2, Tree 3………..…......41

Figure 3.28: Porosity Aluminium available at MRC, Temperature 2, Tree 3…………………...41

Figure 3.29: Last Air Aluminium available at MRC, Temperature 2, Tree 3…………………...42

Figure 3.30: Porosity Aluminium available at MRC, Temperature 2, Tree 3…………………...42

Figure 3.31: Solidification Time Aluminium available at MRC, Temperature 2, Tree 3……….43

Figure 3.32: Total Shrinkage Volume Aluminium available at MRC, Temperature 2, Tree 3….43

Figure 3.33: Filling Time Aluminium available at MRC, Temperature 3, Tree 1……………....44

Figure 3.34: Cold shuts Aluminium available at MRC, Temperature 3, Tree 1………………...44

Figure 3.35: Last Air Aluminium available at MRC, Temperature 3, Tree 1………………..…45

Figure 3.36: Porosity Aluminium available at MRC, Temperature 3, Tree 1…………………...45

Figure 3.37: Solidification Time Aluminium available at MRC, Temperature 3, Tree 1……….46

Figure 3.38: Total Shrinkage Volume Aluminium available at MRC, Temperature 3, Tree 1….46

Figure 3.39: Filling Time Brass, Temperature 1, Tree 3……………………………………...47

Figure 3.40: Cold shuts Brass, Temperature 1, Tree 3………………………………………..47

Figure 3.41: Last Air Brass, Temperature 1, Tree 3…………………………………………..48

Figure 3.42: Porosity Brass, Temperature 1, Tree 3…………………………………………..48

Figure 3.43: Solidification Time Brass, Temperature 1, Tree 3…………………………………49

Figure 3.44: Total Shrinkage Volume Brass, Temperature 1, Tree 3……………………………49

Figure 3.45: Filling Time Brass, Temperature 2, Tree 1………………………………………...50

Figure 3.46: Cold shuts Brass, Temperature 2, Tree 1……………………………………..….50

Figure 3.47: Last Air Brass, Temperature 2, Tree 1……………………………………………..51

Figure 3.48: Porosity Brass, Temperature 2, Tree 1……………………………………………..51

Figure 3.49: Solidification Time Brass, Temperature 2, Tree 1…………………………………52

Figure 3.50: Total Shrinkage Volume Brass, Temperature 2, Tree 1…………………………....52

Figure 3.51: Filling Time Brass, Temperature 3, Tree 2……………………………………...…53

Figure 3.52: Cold shuts Brass, Temperature 3, Tree 2…………………………………….…53

Figure 3.53: Last Air Brass, Temperature 3, Tree 2…………………………………………..…54

Figure 3.54: Porosity Brass, Temperature 3, Tree 2……………………………………………..54

Figure 3.55: Solidification Time Brass, Temperature 3, Tree 2…………………………………55

Figure 3.56: Total Shrinkage Volume Brass, Temperature 3, Tree 2…………………………....55

Figure 3.57: Microscopy of edge of part obtained from Brass, Temperature 3, Tree 2…………57

Figure 3.58: Microscopy of Shaft of Part obtained from Brass, Temperature 3, Tree 2………...58

Figure 3.59: Using of Imagej to calculate approximate porosity………………………………...58

Figure 3.60: Microscopy of edge of part obtained from Al1, Temperature 1, Tree 1…………...59

Figure 3.61: Microscopy of shaft of part obtained from Al1, Temperature 1, Tree 1…………...59

Figure 3.62: Microscopy of Edge of part obtained from Al1, Temperature 2, Tree 2………..…59

Figure 3.63: Microscopy of shaft of part obtained from Al1, Temperature 2, Tree 2…………...60

Figure 3.64: Microscopy of edge of part obtained from Al1, Temperature 3, Tree 3……...……60

Figure 3.65: Microscopy of shaft of part obtained from Al1, Temperature 3, Tree 3……...……60

Figure 3.66: Microscopy of edge of part obtained from Al2, Temperature 1, Tree 2…….….….61

Figure 3.66: Microscopy of shaft of part obtained from Al2, Temperature 1, Tree 2……….…..61

Figure 3.67: Microscopy of edge of part obtained from Al2, Temperature 2, Tree 3……….…..61

Figure 3.68: Microscopy of shaft of part obtained from Al2, Temperature 2, Tree 3…………...62

Figure 3.69: Microscopy of edge of part obtained from Al2, Temperature 3, Tree 1…………...62

Figure 3.70: Microscopy of shaft of part obtained from Al2, Temperature 3, Tree 1…………...62

Figure 3.71: Microscopy of edge of part obtained from Brass, Temperature 1, Tree 3…………63

Figure 3.72: Microscopy of shaft of part obtained from Brass, Temperature 1, Tree 3…………63

Figure 3.73: Microscopy of edge of part obtained from Brass, Temperature 2, Tree 1…………63

Figure 3.74: Microscopy of shaft of part obtained from Brass, Temperature 2, Tree 1…………64

Figure 3.75: Microscopy of edge of part obtained from Brass, Temperature 3, Tree 2……….....64

Figure 3.76: Microscopy of shaft of part obtained from Brass, Temperature 3, Tree 2……….....64

Figure 3.77: Microscopy of edge of part obtained from MRC…………………………….….65

Figure 3.78: Microscopy of edge of part obtained from MRC……………………………….65

Figure 3.79: Interaction Plot for Porosity in 1st run……………………………………..…68

Figure 3.80: Interaction Plot for Porosity in 2nd run…………………………………………68

Figure 3.81: Interaction Plot for Porosity in 3rd run…………………………………………69

Figure 3.82: Main Effects Plot for Porosity in 1st run……………………………….......69

Figure 3.83: Main Effects Plot for Porosity in 2nd run………………………………………70

Figure 3.84: Main Effects Plot for Porosity in 3rd run……………………………………………..70

Figure 3.85: Main Effects Plot for Means……………………………………………………………71

List of Tables

Table 2.1: E.D.S A7075……………………………………………………………….………12

Table 2.2: E.D.S Al5050…………………………………………………………………………12

Table 2.3: E.D.S Brass…………………………………………………………………...13

Table 2.4: Orthogonal Array of parameters……………………………………………………...15

Table 3.1: Simulation Results………………………………………………….................56

Table 3.2: Porosity in Edge of parts obtained from all experiments…………………………….66

Table 3.3: Porosity in Shaft of parts obtained from all experiments…………………………….66

Table 3.4: ANOVA of 1st run…………………………………………………………....67

Table 3.5: ANOVA of 2nd run……………………………………………………………..67

Table 3.6: ANOVA of 3rd run………………………………………………………..…67

Table 3.7: S/N ratio of the experimentation……………………………………………………...67

Table 3.8: Simulation and Experimentation results comparison……………………………..….71

Chapter1: Introduction & Literature Review

From centuries casting is used to obtain parts having desired shapes in which molten metal is poured into moulds having desired shape and then allowing it to solidify to get the final part. Using that traditional method the products produced were not of good quality and very simple in design and shape. Later with enhancements in technology Lost Was Process was introduced for the manufacturing of complex shapes and designs along with other types of casting. Lost wax process is also known as investment casting process in which wax-patterns are attached on wax tree which is then coated with ceramic shell. After setting of ceramic shell was is removed out by burning the ceramic shell inside dewaxing oven which leaves behind the net shape we want to manufacture. After that ceramic shells are baked inside baking oven for hardening. Before molten metal is poured inside shells they are preheated at a specific temperature to ensure proper flow of molten metal in every cavity before solidification. And then molten metal is poured in the shell to get the desired inner cavity or shape of shell. After solidification parts are being taken out by breaking the shell. Parts having complex geometries and cast features and good surface finish can be produced using this process without the necessity of extensive machining or finishing work. This process is used extensively for production in bulk and products cover a vast variety and its processes are diverse. Dental fixtures, ratchets, jewelry, turbine blades, gears, cams, machinery components and other parts of complex geometries can be produced using Investment Casting. Since 1950s Investment Casting process is being used for production of components for aero-industry due to its ability to produce complex parts with excellent surface finish and tolerances. Manufacturing processes are also becoming complex with the increasing demand and of more complex, intricate and light weight components. Also to lower fuel and power consumption light weight components are preferred. The production of light weight components will help to reduce the production cost along with improving the efficiency of engineering systems resulting in less fuel consumption and make it environment friendly by reducing amount of hazard gasses emission. In order to investigate the ability of alloys to be casted in thin-walled geometries, the mechanism behind fluidity is very important to understand. Fluidity in case of casting is the molten metal's ability to flow and fill the mould. The fluidity of molten metal depends upon number of material properties. Some important properties are:

- Pouring temperature
- Composition of metal used
- Tree structure
- Mode of solidification
- Molten metal’s viscosity
- Rate of flow of molten metal
- Thermal conductivity of shell along with molten metal
- Heat of fusion
- Surface tension

Fluidity can be categorized into two sub categories i.e. flowability and fillability. Flowability is the ability of molten metal to flow inside mould. Flowability usually depends on molten metal properties and cooling conditions, for example, viscosity, heat transfer rate composition of alloy, etc. Fillability on the other hand is the ability of molten metal to fill all the cavities of mould and it depends on the surface tension between flowing liquid and adjacent mould material [1]. When metal solidifies pre-maturely due to heat losses and flow rate flowability limits the fluidity whereas due to lack of hydrostatic pressure to overcome surface tension and friction between walls of mould and molten metal fillability limits the fluidity to restrict molten metal to reach the fine details. Several parameters related to pouring temperature, shell system, and alloys affect the ability to fill a thin section. Increasing super heat, mould temperature, tree structure, change in composition of alloy used or pressure head will improve fluidity. Shell permeability and flow rate are also important parameters to improve fluidity.

1.1.The investment casting process- a brief description:

Following are the steps of investment casting process:

1.1.1. Creating a Wax Pattern

After the manufacturing of metal die (usually made of aluminium) having the shape of part to be made, wax patterns are then made by pouring molten wax into die and if there are internal cavities urea cores are made first using the same method used for making wax patterns. Cores are placed in metal die in place of cavities then molten wax is poured in the die and after solidification patterns are placed in water to remove urea and get the desired shaped pattern.

Stearic acid is added in wax to improve its hardening capacity. Plastic cores could also be made but due to easily melting option wax is mostly used.

1.1.2. Wax Tree Assembly

It isn't economical to make one small part at a time, so number of wax patterns are attached to a wax-sprue forming wax tree assembly. The sprue serves two purposes.

- Provides a surface for mounting and assembly of multiple wax patterns on a single mold, in which molten metal would be filled.
- Helps the molten metal to reach every cavity/void produced by wax patterns. That's why for better fluidity it is very important to make tree structure carefully.

The portion of wax joining the pattern(s) and the sprue are called "Gates", because they regulate the direction and flow of the alloy into the void made by the pattern

1.1.3. Shell Building

In next step ceramic shell is built around wax tree by continuously dipping in slurry made of Quartz powder and sodium silicate and then coating with Quartz Sand is performed until the desired thickness of the shell is achieved. After each coating tree assembly is placed inside NH_4Cl for shell hardening. After the desired thickness is achieved tree assemblies are placed inside NH_4Cl for some time for more hardening of shell.

1.1.4. Dewax & Burnout

This step is very important for investment casting process. The ceramic mold having desired thickness and hardness is placed inside a dewaxing oven in upside down direction and heated at 90°C-175°C temperature. Which cause wax to melt and flow out of the mould, leaving behind the cavity for the metal casting. The ceramic mold is then heated to around 550°C-1100°C temperature. This will enhance strength of the mould, eliminate any remaining wax or contaminants and dry any remaining water from the mould material.

1.1.5. Metal Pouring

Before metal pouring into the ceramic mould, the mould is pre-heated to a specific temperature to avoid pre-mature solidification of molten metal before it fills entire mould. Then molten metal is poured in the hot mould. Pouring the molten metal in the mold while it is hot allows the liquid metal to flow easily through the mold cavity without solidifying, filling all details and thin sections. Pouring the metal casting in a hot mold also improves dimensional accuracy, since the mould and casting will shrink together as they cool. After pouring of the molten metal into the mould, the casting is allowed to set as the solidification process takes place.

1.1.6. Shell Knock Off

After solidification the shell material is removed. This can be done by using Hammer, High Pressure Water Blast or Vibratory Table etc. Shell removal can also be done using a heated potassium hydroxide or sodium hydroxide caustic solution, but due to environmental and health issues this approach is not used by industries now.

1.1.7. Cut Off

After the removal of shell material the part is cut off from in-gates and sprue. This can be done manually by using Torch, Chop saw or Laser. Automated process can also be used to cut off part.

1.1.8. Finishing

After removing part from the sprue and in-gates, the surface finishing process can be done using different techniques like: Belting or hand grinding, Vibratory/Media finishing, polishing. Finishing can be done by hand, but in many cases it is automated. Heat treatment is also done where desired mechanical properties aren’t achieved.

The work by (Sarojrani Pattnaik, 2012) [2] helped a lot to understand about the developments in investment casting.

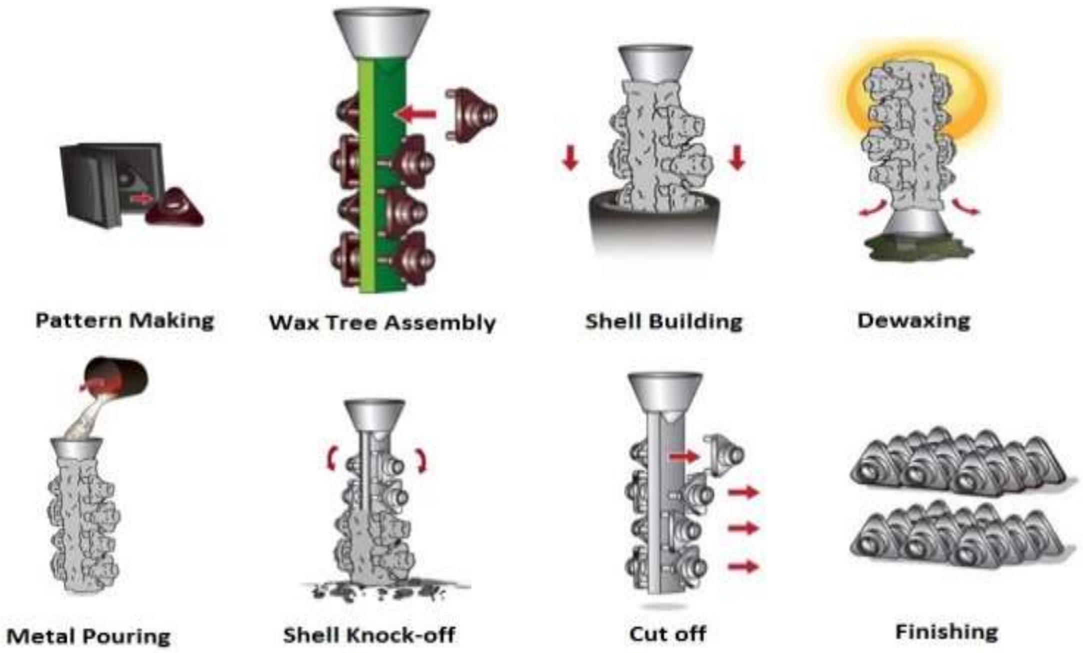


Figure 2.1: The Investment Casting Process

1.2.Defects in parts produced by investment casting:

There are many defects that might occur during manufacturing processes which might occur due to defects in materials chosen, errors during process or product design. Same issue occurs during investment casting where casters have to face even more difficulties due to the increase in processes criticalities and complexity of products to make them defects free. Cold shut, porosity caused by turbulence, hot spot, hot cracks and hot tearing, distortion and unexpected deformation, trapped gasses, inclusions, stress cracks, shrinkage, misrun, shrinkage porosity and micro-porosity caused due to improper cooling are some common defects faced during investment casting. The defects in investment casting is an important issue which should be solved without wasting time.

1.3.Background & Motivation:

Highly precise machining and drilling is required in order to produce intricate engineering products having fine details and light weight. It would not only increase cost of the product but high skill is required as lead time is also increased for production. The more the precision and quality is required the more the waste material would be there in shape of scrape increasing the cost of production. To make components cost effective one should make them as net-shape as possible. Hence investment casting is an important manufacturing process for producing net-shape components but there should be some control on process parameters to maintain the process quality to produce quality parts. It is important to understand effects of different type of process parameters, casting conditions and material properties to control process parameters to cast complex components. Investment casting at MRC-NUST was producing parts with some defects as due to thin walls of the testing part the molten metal start solidifying before reaching all the cavities. So aim of this work is to remove those defects by improving quality of products produced by investment casting at MRC by using best possible combination of parameters. So that in future with some attention MRC could commercialise their investment casting facility and make some quality products for industries.

1.4.Literature Review:

Both melting temperature and thickness of the mold cavity have a large impact on fluidity for the top-gated system as compared to the bottom-gated one. The bottom-gated system is more stable and is not significantly affected by casting parameters (i.e., casting temperature and mold-preheat temperature). A high level of porosity was observed in the castings made in the top-gated configuration on as compared to the castings in the bottom-gated one. [1]

To understand the Investment Casting and details of steps followed to make a part using this technique study concluded by (Sarojrani Pattnaik, 2012) [2] helped a lot. As step wise details is explained in his work.

The Complete Handbook of Sand Casting by (AMMEN, 1979) [3] helped to identify the pouring temperatures of different metals used in casting.

The study by (Bohez, 2013) [4] helped to identify optimal gating system for Investment Casting which later helped to decide the trees to be used in this study and some useful practices to perform investment casting is also explained in his work like: The starting times of feeding into in-gates at all levels must be as close as possible to prevent heat loss, filling as quickly as possible to prevent heat loss, the flow velocity at all levels should be the same and the fluctuation of flow velocity in the steady state should be as small as possible for eliminating turbulent flow.

Studies by (Vinish Garg, 2017) and (Nikhil Yadav, 2011) [5] , [6] helped to decide the process parameters and their levels. These two studies also helped in design of experiments as in both of these studies Taguchi's technique is used which helped me a lot to design experimentation using Taguchi.

It is necessary to meet following principles at assembling the gating systems: To provide a sufficient velocity and direction of metal flow to all parts of the mould before it solidifies, to ensure as steady as possible metal flow without turbulences (in order to limit the oxidation) and small and middle-sized castings should be arranged so that they solidify evenly [7]. This work also helped in understanding that how simulation could be used in Investment Casting.

By computer simulation of the casting process, the flow of the molten metal in the cavity, the heat transformation, the solidification, grain formation, shrinkage and stress evolution can be visualized. The details are seen on the computer in graphical form, which helps the designers to visualize the defects in the process design, to analyze the causes for the defects (such as hot tears, shrinkage porosities, cold shuts etc.). Further, the modified gating designs can be tried without resorting to the actual production of tooling. In investment casting process, the shell making, shell drying, shell heating and casting processes can be simulated in simulation software. [8]

1.5.Problem Statement:

Components made at MRC-NUST using investment casting equipment and techniques had a lot of defects in them. In most of the parts metal did not reach to all the details of the ceramic mould and solidification started resulted in producing defective components due to which time and resources were wasted. Now the purpose of this work is to identify the reasons behind those defects and suggest possible solutions and finding best combination of parameters among tree design, pouring temperature and metal poured using simulation & experimentation. The combination of these parameters has not been used in past that's why I chose this combination. Hence simulation helped me a lot to decide how to conduct experimentation. Aim of this research is to make investment casting facility at MRC-NUST able to make parts without defects and having good quality. So in future with some enhancements they could commercialise their investment casting facility and make some quality products for industries.

Following are the defects which occurred in parts produced by MRC using investment casting.

Misrun: Misrun can occur when the metal is unable to fill the mould cavity completely, leaving a very smooth, rounded edge. Likely causes are the metal is too cold; shell too cold or fill rate too slow.

Gas Porosity: This occurs because most liquid materials can hold a large amount of dissolved gas, when the metal solidifies the gas expels. Gas porosity may present itself on the surface of the casting as porosity or the pore maybe trapped inside the metal.

Chapter2: Methodology

In this chapter methodology followed during this work would be discussed. Methodology includes parameters & their levels and the design of experiment for those experiments. This chapter is also covering the simulation using defined parameters on Inspire Cast software. Then it will cover the experimentation which was done after the simulation.

2.1.Methodology:

After defining objective and problem statement of the work detailed literature review was done to find out the best possible solution done in past related to the problem. After that Simulation was done on Inspire Cast software. And then experiments were performed and after getting simulation and experimentation results comparison of results would be done to conclude results. Following flow diagram is describing the methodology followed during this work.

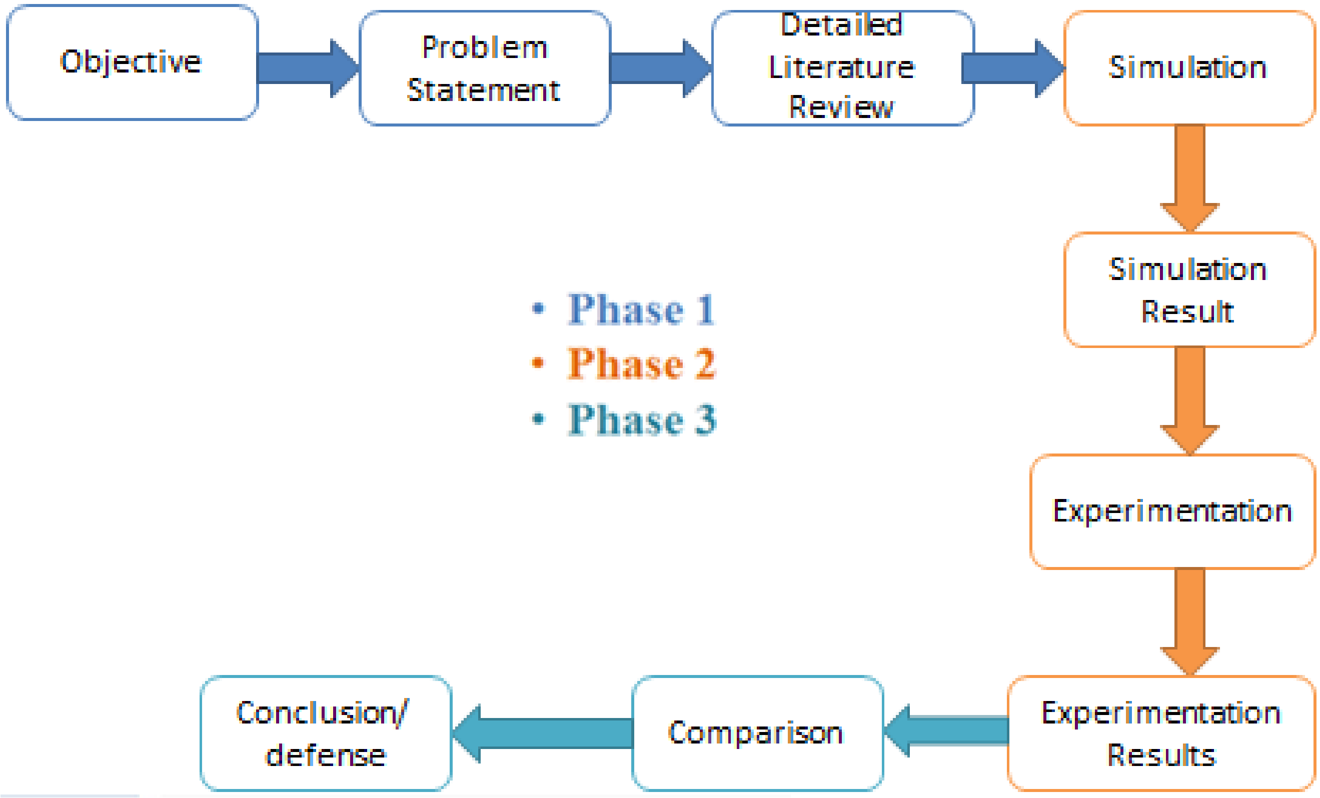


Figure 3.1: Methodology Flow chart

After detailed literature review about the problem process parameters were decided and design of experiments was done using taguchi technique.

2.1.1. Parameters and Their levels:

After detailed literature review following parameters were decided for the work as they were not used in any past work together.

- Tree structures.
- Different metals to be poured.
- Pouring temperature of molten metal.

Further details of these parameters are discussed below:

2.1.1.1. Tree Structure:

Three types of tree structures were used for this work decided after reviewing the past study done by [4] and reviewing the types of trees used in different industries**.** Following are the pictures of tree structures modeled using **SOLIDWORKS** used during this work.

Tree1:

Figure 2.2: Tree1 SolidWorks Model

Tree2:

Figure 2.3: Tree2 SolidWorks Model

Tree3:

Figure 2.4: Tree3 SolidWorks Model

2.1.1.2. Different Metals to be poured:

Following metals were used during the experimentation:

- Al1:Aluminium (A7075)
- Al2:Aluminium (Al5050)
- Brass (Delta metal D402)

Element	App Conc.	Intensity Corrn.	Weight%	Weight%	Atomic%
C K	0.98	0.1650	5.31	1.35	11.37
O K	1.96	0.6660	2.61	0.42	4.21
Mg K	3.66	1.1140	2.92	0.14	3.09
Al K	99.36	1.0714	82.48	1.28	78.68
Cu K	1.38	0.8429	1.46	0.21	0.59
Zn K	4.94	0.8422	5.22	0.35	2.05
Totals			100.00		

Table 2.1: E.D.S A7075

Element	App Conc.	Intensity Corrn.	Weight%	Weight%	Atomic%
C K	12.53	0.2807	30.09	1.74	44.51
O K	19.59	0.5803	22.75	0.76	25.26
Na K	0.67	1.0751	0.42	0.11	0.32
Mg K	1.14	0.9340	0.82	0.08	0.60
Al K	62.04	0.9818	42.59	1.11	28.04
Si K	0.45	0.5949	0.51	0.08	0.32
Cl K	0.35	0.7097	0.34	0.06	0.17
K K	0.38	0.9860	0.26	0.06	0.12
Ca K	0.37	0.9514	0.27	0.06	0.12
Cu K	1.20	0.7888	1.03	0.16	0.29
Zn K	1.09	0.7862	0.93	0.19	0.25

Table 2.2: E.D.S Aluminium mix grade scrap

Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
C K	1.40	0.2913	4.86	0.89	21.21
Al K	0.40	0.3824	1.05	0.18	2.04
Cu K	54.29	0.9801	56.17	0.81	46.34
Zn K	36.75	0.9826	37.92	0.72	30.41
Totals			100.00		

Table 2.3: E.D.S Brass

2.1.1.3. Pouring Temperature of Molten Metals:

Following pouring temperatures were used during simulation and experimentation after consulting “Hand book of Investment Casting” by (AMMEN, 1979) [3]**.**

- 690°C-750°C for A7075, further divided into 3 levels i.e.: T1= 690°C, T2= 720°C and T3= 750°C.
- 690°C-750°C for Aluminium Al5050, further divided into 3 levels i.e.: T1= 690°C, T2= 720°C and T3= 750°C.
- 910°C-930°C for Brass, further divided into 3 levels i.e.: T1= 910°C, T2= 920°C and T3= 930°C.

2.1.2. Design of Experiments:

Taguchi’s method for Design of Experiments is one of the best engineering achievements of the 20th century. This method focuses on the effective application of engineering strategies rather than advanced statistical techniques. Taguchi's method is based on the following three simple and basic concepts.

- Quality should be considered during designing phase of the product and not during the inspection.
- Quality can be achieved by reducing the deviation from the targeted results. The process or product should be designed in such a way that resistance to uncontrollable environmental variables increases.
- The cost to make quality products should be measured as a function of deviation from the standard and the losses should be measured all across the system.

Taguchi recommended Orthogonal Arrays for design of experiments. Orthogonal Arrays are generalized Graeco-Latin squares. The design of experiments is done by choosing appropriate orthogonal array and the parameters and their levels are assigned to the appropriate columns [6]. The main aim of using Taguchi method is to obtain one or more of the following objectives after analyzing the results of the experiments:

- To establish optimum conditions for a process or product.
- To estimate the contribution of individual parameters and their levels.
- To estimate the response under the optimum conditions.

The selection of Orthogonal Array is based on the number of parameters/factors and their respective levels. Here we have 3 factors and each has 3 levels. Now Degree of Freedom can be calculated by using following formula:

$$DOF = P^*(L - 1)$$

DOF = degree of freedom

P = number of factors = 3

L = number of levels = 3

$$(DOF)R = 3(3 - 1) = 6$$

The total DOF of the orthogonal array should be equal or greater than the total DOF required for the experiment [5]. Thus L9 orthogonal array is selected to perform the experiments. The L9 OA with 3 factors, 3 levels and its responses are shown in the Table

Experiment. No.	**Metal**	**Pouring Temperature**	**Tree type**
1	Aluminium type1	690°c	1
2	Aluminium type1	720°c	2
3	Aluminium type1	750°c	3
4	Aluminium type2	690°c	2
5	Aluminium type2	720°c	3
6	Aluminium type2	750°c	1
7	Brass	910°c	3
8	Brass	920°c	1
9	Brass	930°c	2

Table 2.4: Orthogonal Array of parameters

To conduct experimentation following steps were followed:

1. Selection of process parameters to be considered.
2. Selection of number of levels for those parameters.
3. Selection of appropriate orthogonal array.
4. Construct Orthogonal Array of selected parameters and their levels.
5. Conduct the experiments.
6. Analyze the results obtained from experiments.

2.2.Simulation using Inspire Cast:

Altair Inspire Cast (formerly known as Click2Cast) software is easy, accurate, fast and affordable casting simulation software focused on creating high quality components with increased profitability through a highly intuitive user experience. It is an easily tool which can be used by both experts and beginners, from foundry engineers to design engineers. Right from the early design phase, users can visualize typical casting defects such as air entrapment, shrinkage porosity, cold shuts, mold degradation and rectify those defects to avoid the loss prior to the manufacturing. Guided process templates offer 5 easy steps to simulate Gravity Die, Gravity Sand, Investment Casting, High Pressure, Low Pressure Die Casting and Tilt Pouring. Altair Inspire Cast's innovative experience enables users to increase product quality and design better products with a few hours of training. [9]

After the completion of tree structure models following steps were followed during the simulation phase to get desired results:

2.3.1. Importing Tree structure models from SolidWorks and select process parameters:

In the first step of simulation, the tree structure models made using SolidWorks are imported in the Inspire Cast software to perform simulation. And then process parameters on which we want simulation to run are applied after defining the cast part and in-gates. The software library has a lot of materials used for casting the desired material and pouring temperature first selected after defining in-gates and cast part. Following figures illustrate how process parameters are defined after importing the model:

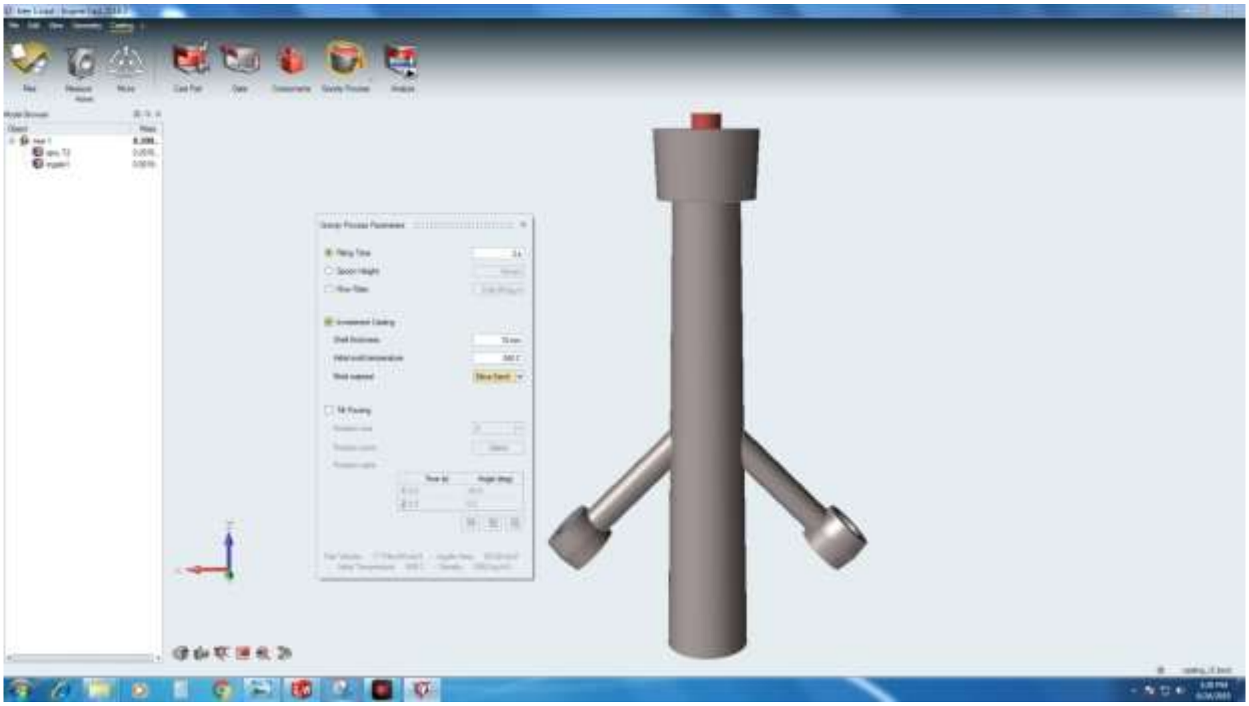


Figure 2.5: Importing tree 1 in SolidCast

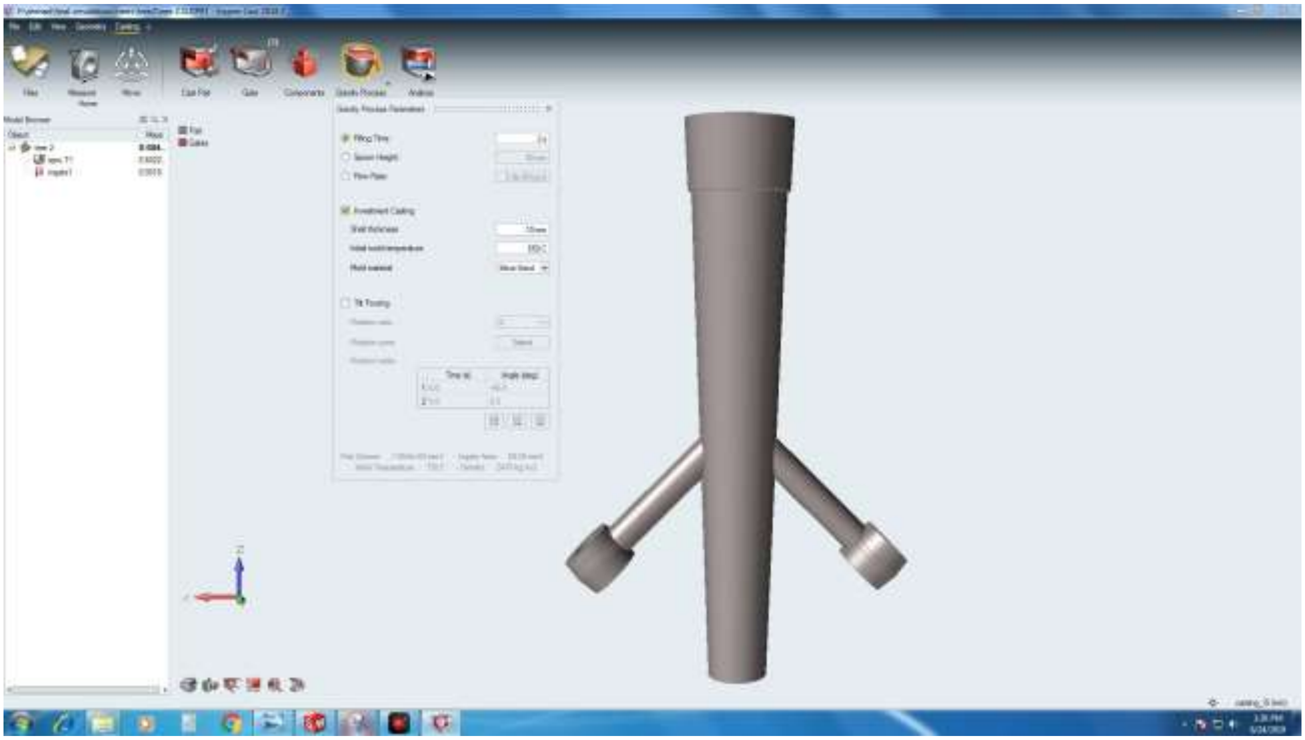


Figure 2.6: Importing tree 2 in SolidCast

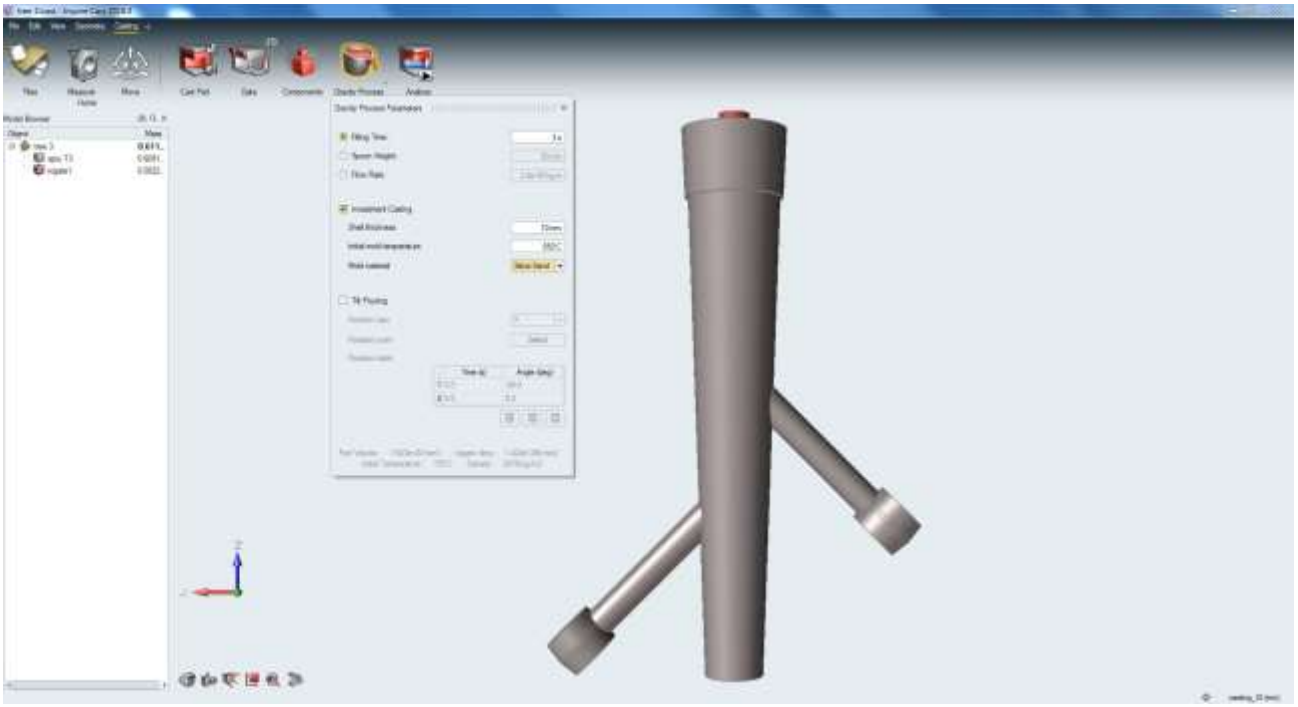
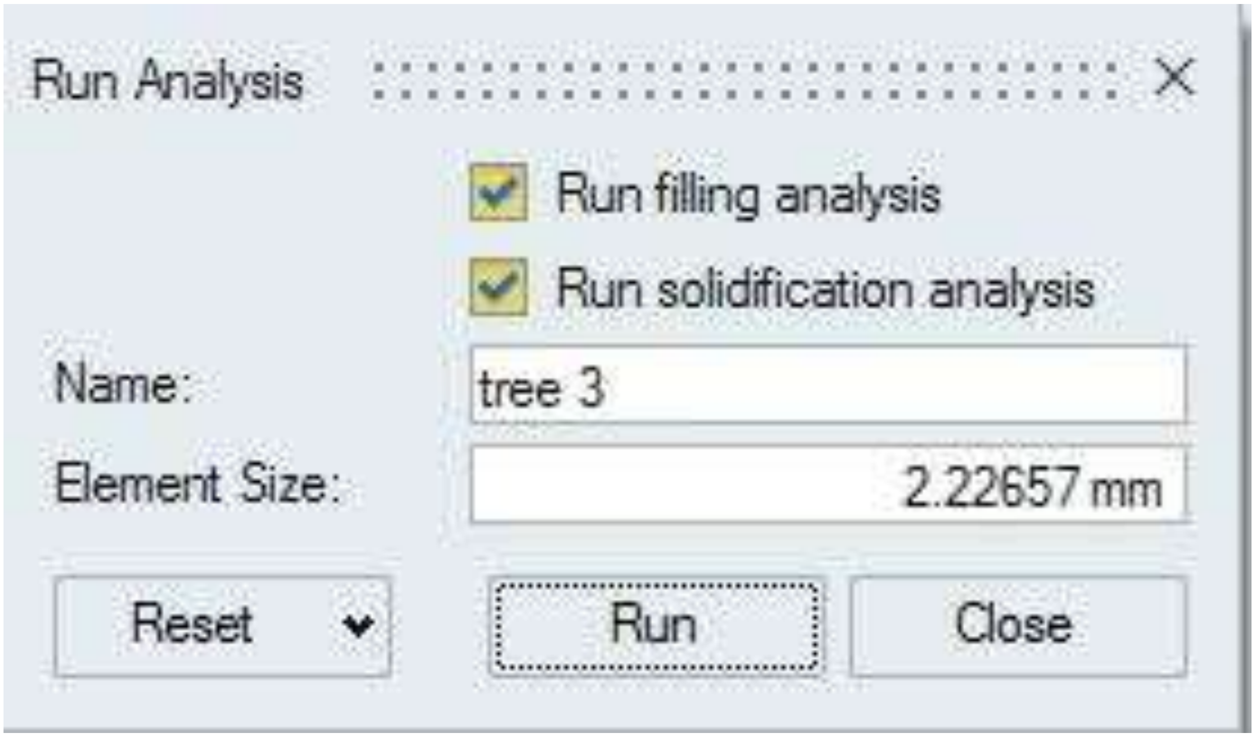


Figure 2.7: Importing tree 3 in SolidCast

All of the three trees are imported one by one and process parameters are also defined according to design of experiments data from orthogonal array. Hence nine simulations were performed.

2.3.2. Run simulation on software defined Mesh size:

After defining process parameters run simulation on the software defined mesh size to get results faster, but we can change the mesh size to as small as possible but that require a lot of time and specially a powerful computer to do so. Following figure shows how we can run simulation of software defined Mesh size:



☑ Run filling analysis

☑ Run solidification analysis

Name: tree 3

Element Size: 2.22657 mm

Figure 2.8: Simulation on software defined mesh size

After the simulation process is completed results can be seen to observe the outcome which would be discussed later in the results section.

2.3.Experimentation:

Step by step experimentation is described in this topic

1st Step: (Pattern making):

In first step of investment casting wax patterns are made and for internal cavities urea cores were used and to obtain desired hardness of wax stearic acid was added in wax. Molten wax was poured into the pattern die to get the wax pattern as shown in figures:

Figure 2.9: Wax Pattern

2nd Step: (Sprue making):

After making the desired number of wax patterns wax sprues were made according to the tree design selected for this research. Following figure is showing a wax sprue made for this purpose:

Figure 2.10: Wax Sprue

3rd Step: (Wax tree assembly):

After making both the patterns and the sprues, desired number of patterns are attached on the sprue to make a wax tree assembly as shown in figures below:

Figure 2.11: Wax Tree1

Figure 2.12: Wax Tree2

Figure 2.13: Wax Tree3

4th Step: (Slurry coating):

After the wax tree is made the assembly is dipped in slurry made of **Quartz powder and Sodium Silicate** and after dipping in slurry it is then coated with Quartz sand and slurry acts like binder. After coating of sand, tree is dipped inside NH_4Cl for hardening of sand shell coated. This whole process is repeated till we get the desired thickness of shell. Following is the figure showing trees left for drying after this whole process:

Figure 2.14: Trees after coating

5th Step: (Dewaxing):

In this step the shells are placed inside dewaxing oven to melt out all the wax available in the shell to leave behind the cavity for casting.

Figure 2.15: Dewaxing Oven

6th Step: (Burnout):

In this step shells are placed in baking oven with higher temperature ranges and heated so that any was which wasn't being removed in previous step could be removed in this along with the remaining water in shell, this process also enhance the strength of the shell.

Figure 2.16: Burnout oven/ Heating furnace

7th Step: (Pre-heating):

Before pouring of molten metal in the shells they are placed inside baking oven again to pre-heat them at a higher temperature to avoid pre-mature solidification of metal during pouring.

Figure 2.17: Pre heating

8th Step: (Metal Pouring):

When shells reach a high temperature of more than 550°C molten metal is poured in them and then they are left for solidification.

Figure 2.18: Metal Pouring

Product:

After performing the experiments according to the design of experiments done using taguchi technique following product is obtained:

Figure 2.19: Trees obtained after pouring

So after removing parts from the tree assembly parts as shown in following figures are obtained

Figure 2.20: Finished Products

2.4. Summary:

Simulation and experimentation was performed to remove the defects which were occurring in the parts produced by MRC-NUST. Simulations and experimentation was done using the parameters and their levels and their D.O.E which was done using Taguchi technique. However weather is a hurdle as in rainy weather shell takes a lot of time for drying and layout of investment casting isn’t appropriate in MRC as a lot of heat is wasted due to the distance between the baking oven and heating furnace.

Chapter3: Results and Analysis

In this chapter results obtained from simulation and experimentation would be discussed. To obtain results from the products produced from experimentation following tests were done to identify defects:

- Visual Inspection
- Simulation Results
- Microscopy

And also results obtained from simulation would be discussed in this chapter and comparison of results obtained from simulation and experimentation is also present in this chapter.

3.1.Visual Inspection:

Parts obtained after experimentation inspected visually for any defects which could be seen by naked eye and the main aim of this work was to make the flow of molten metal reachable to every cavity of the mould i.e to remove the “misrun” defect which is achieved. Following figures are showing the difference between part produced previously by MRC and parts produced now by MRC using the parameters and their levels discussed in this study:

Figure 3.1: Parts Produced before this work

Figure3.2: Parts produced by performing experimentation according to parameters discussed in this work

3.2.Simulation Results:

After running simulations on the defined parameters and their levels following results were obtained:

- Filling time
- Cold shuts
- Last air
- Porosity
- Solidification time
- Total shrinkage volume

Following figures are showing all of the above mentioned results obtained by simulation for all of the experiments

3.1.1. Aluminium A7075, temp1 and tree 1:

Filling time:

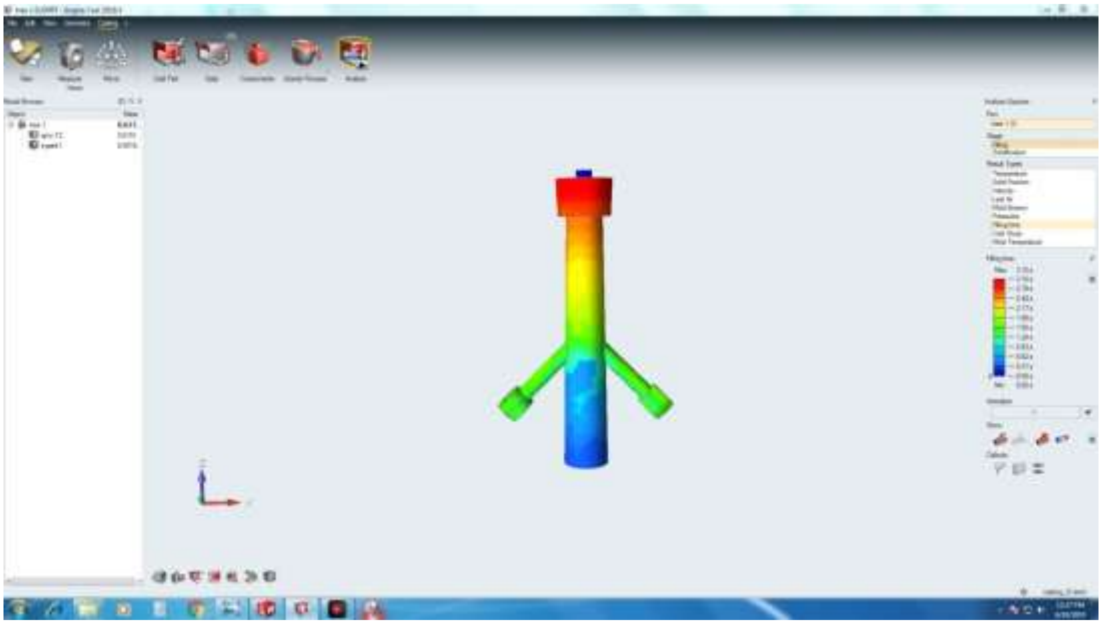


Figure 3.3: Filling Time Aluminium A7075, temp1 and tree 1

Cold shuts:

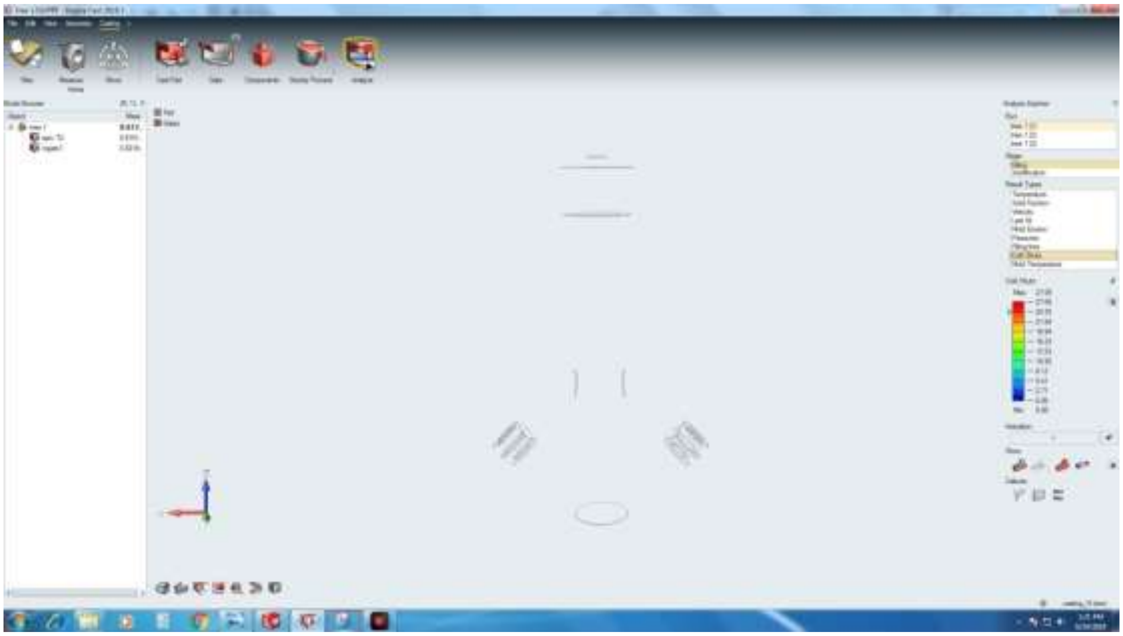


Figure 3.4: Cold shuts Aluminium A7075, temp1 and tree 1

Last air:

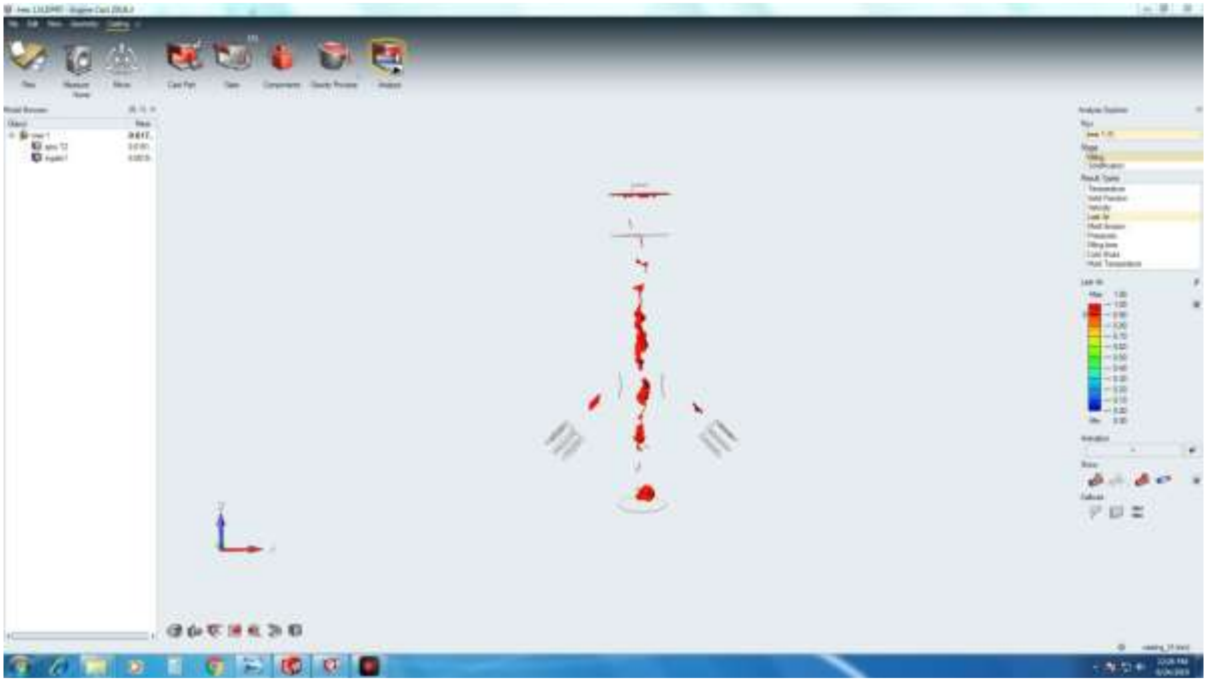


Figure 3.5: Last Air Aluminium A7075, temp1 and tree 1

Porosity:

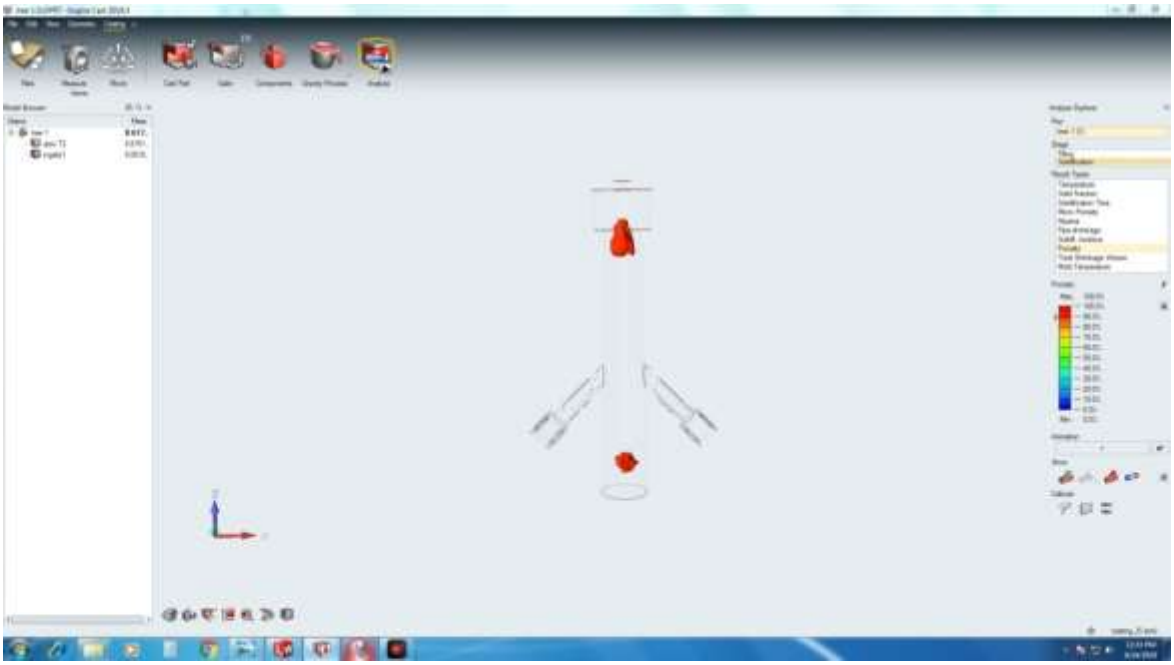


Figure 3.6: Porosity Aluminium A7075, temp1 and tree 1

Solidification time:

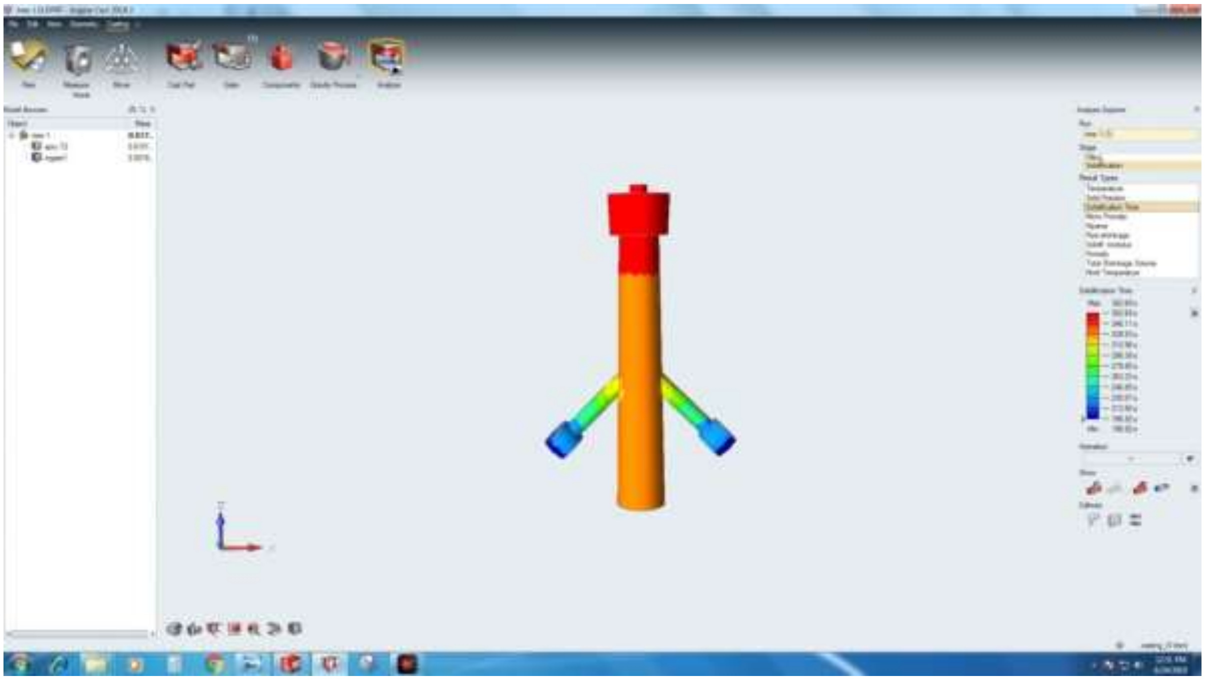


Figure 3.7: Solidification Time Aluminium A7075, temp1 and tree 1

Total shrinkage volume:

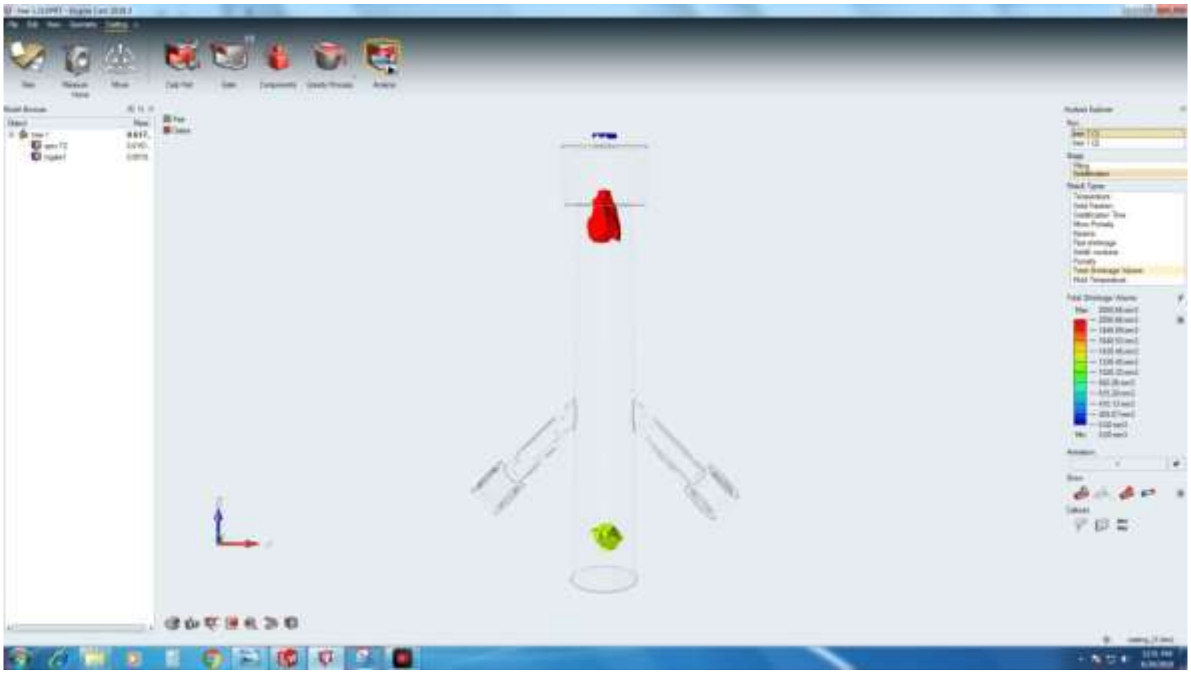


Figure 3.8: Total Shrinkage Volume Aluminium A7075, temp1 and tree 1

3.1.2. Aluminium A7075, Temperature 2, Tree2:

Filling time:

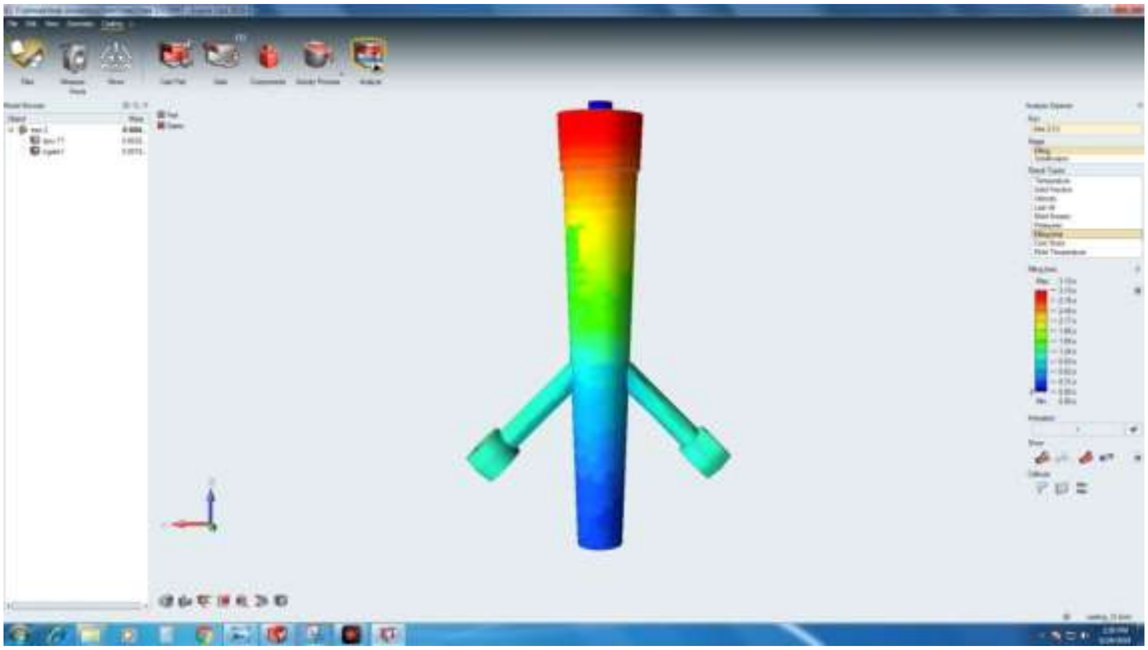


Figure 3.9: Filling Time Aluminium A7075, Temperature 2, Tree2

Cold shuts:

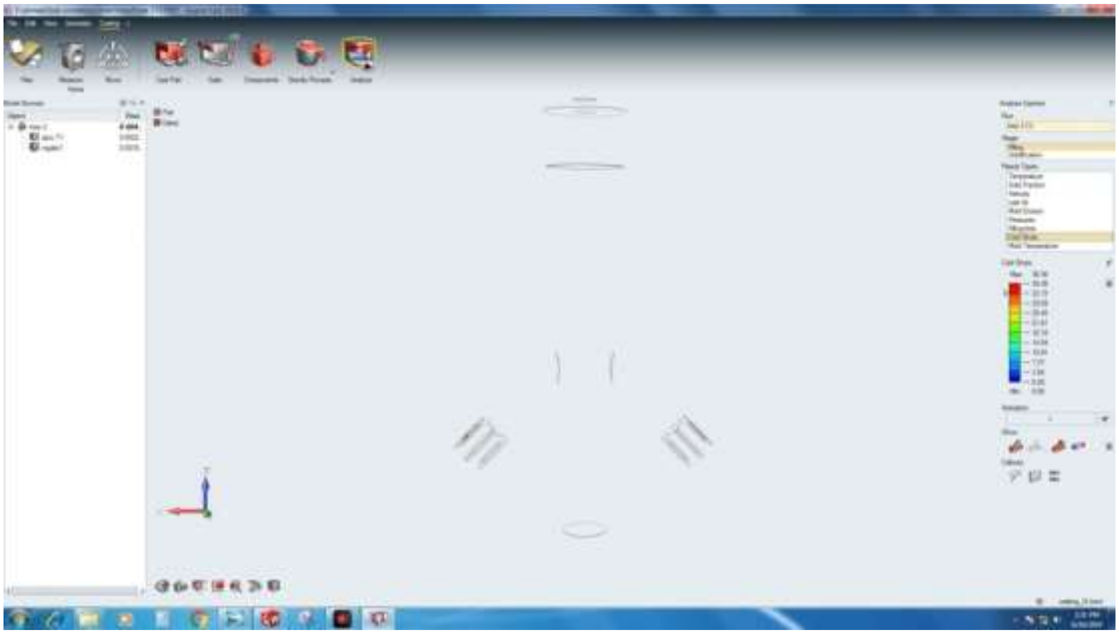


Figure 3.10: Cold shuts Aluminium A7075, Temperature 2, Tree2

Last air:

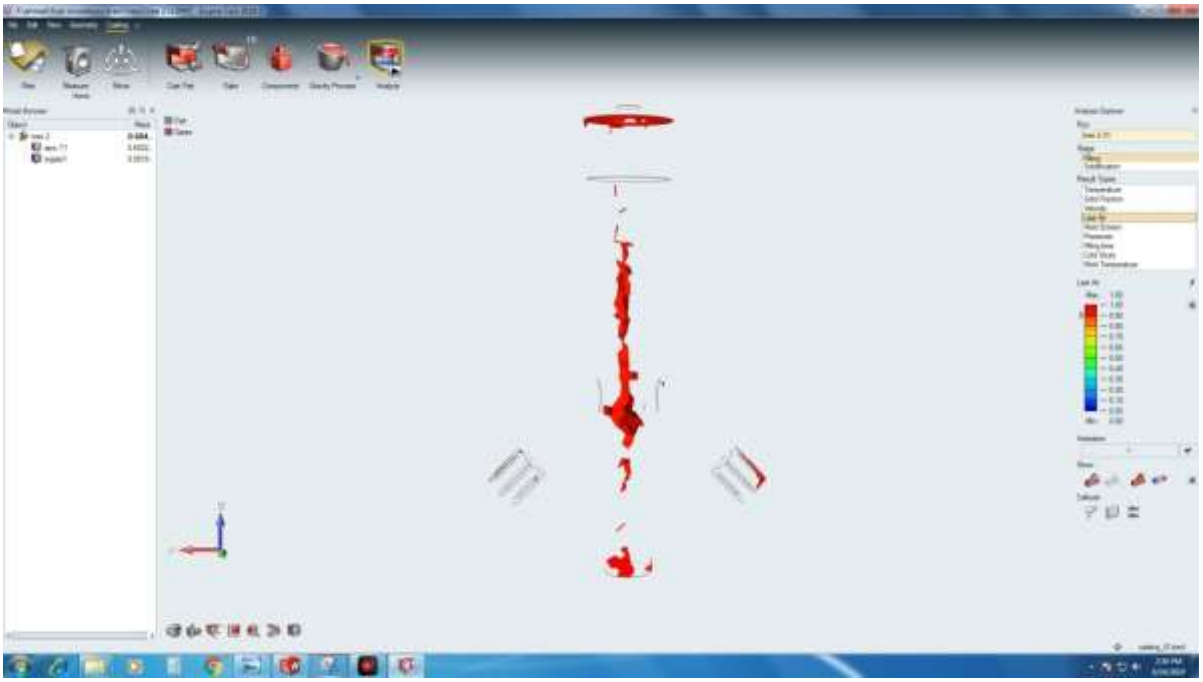


Figure 3.11: Last Air Aluminium A7075, Temperature 2, Tree2

Porosity:

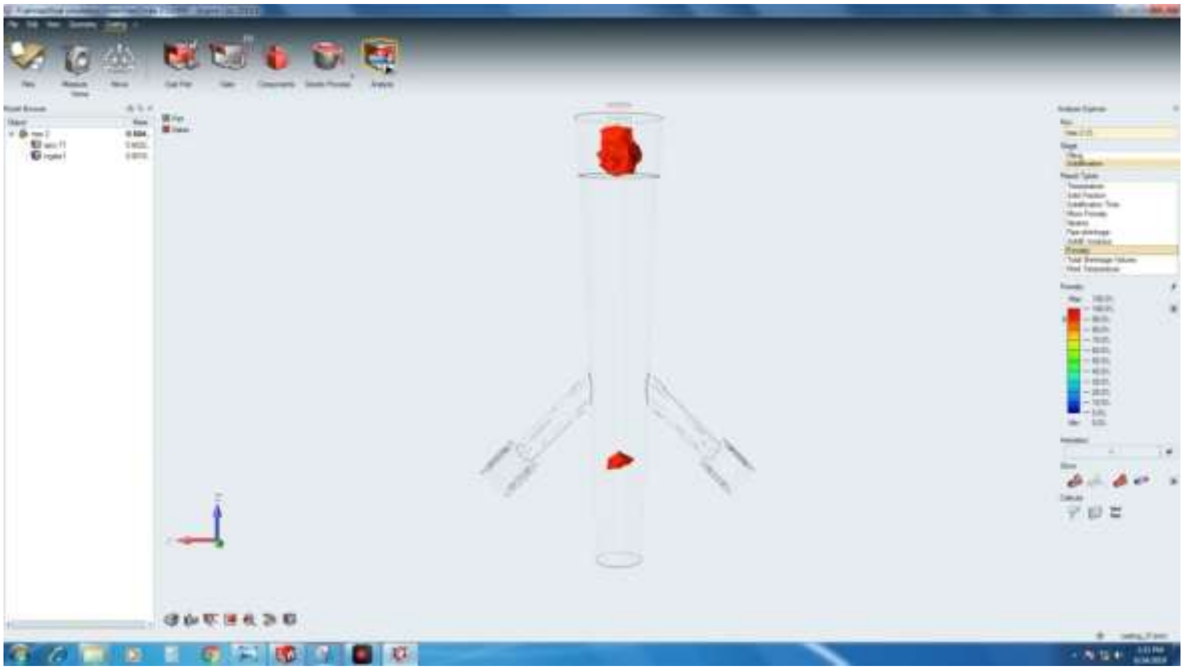


Figure 3.12: Porosity Aluminium A7075, Temperature 2, Tree2

Solidification time:

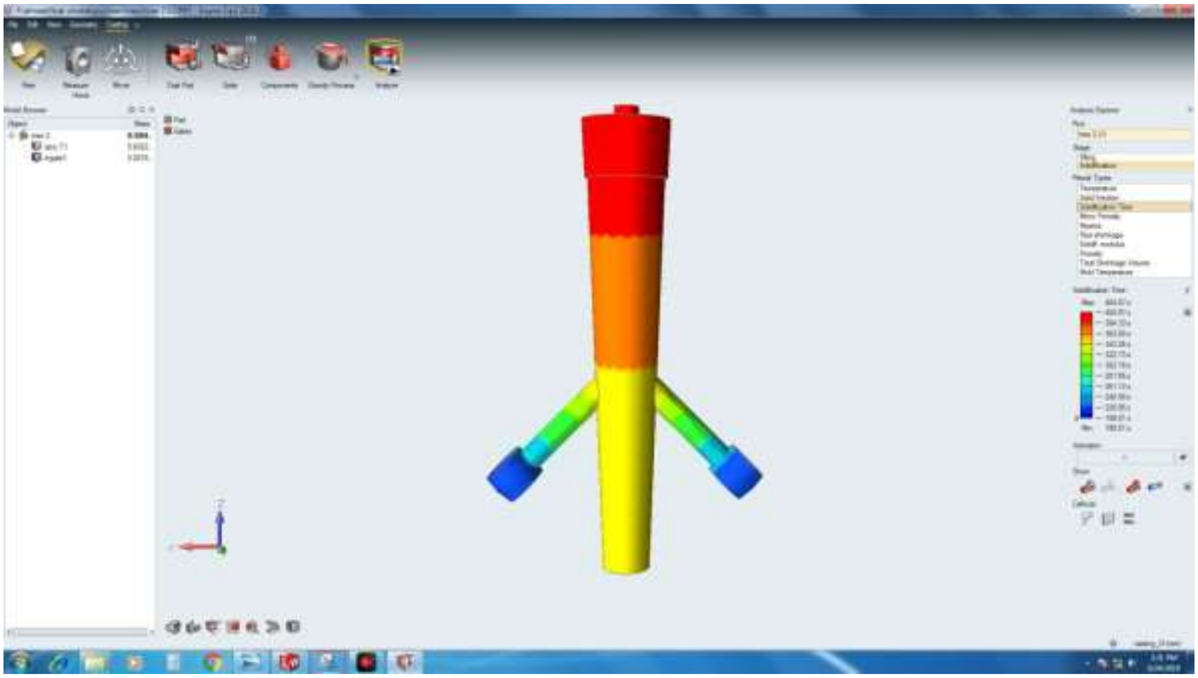


Figure 3.13: Solidification Time Aluminium A7075, Temperature 2, Tree2

Total shrinkage volume:

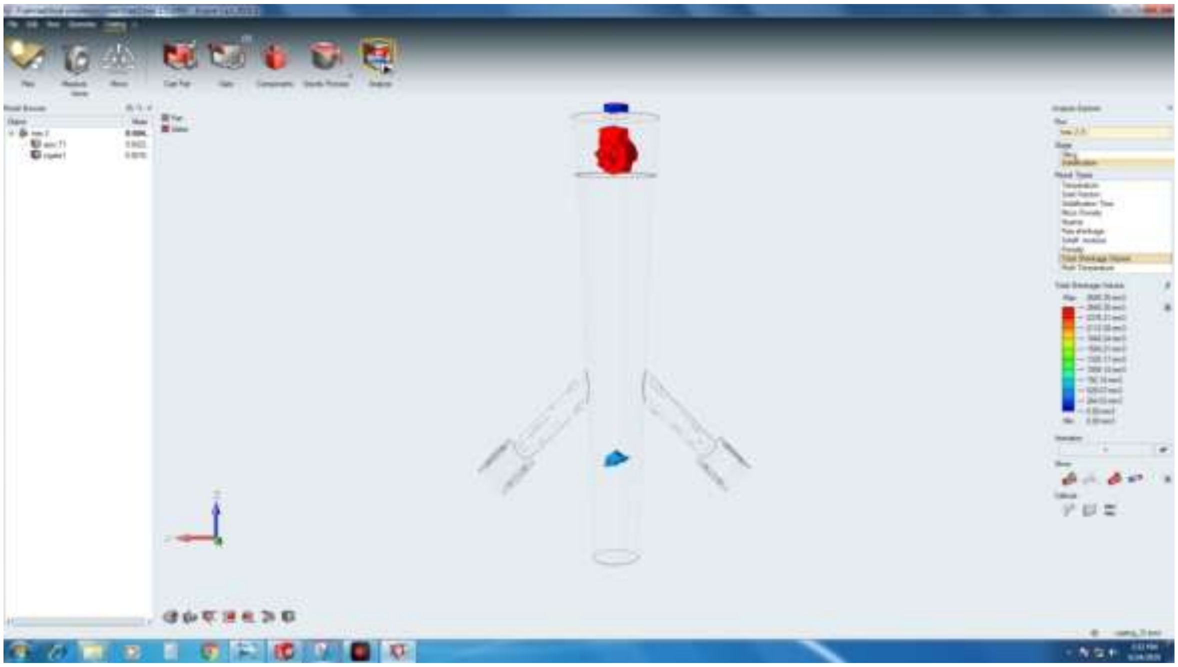


Figure 3.14: Total Shrinkage Volume Aluminium A7075, Temperature 2, Tree2

3.1.3. Aluminium A7075, Temperature 3, Tree 3:

Filling time:

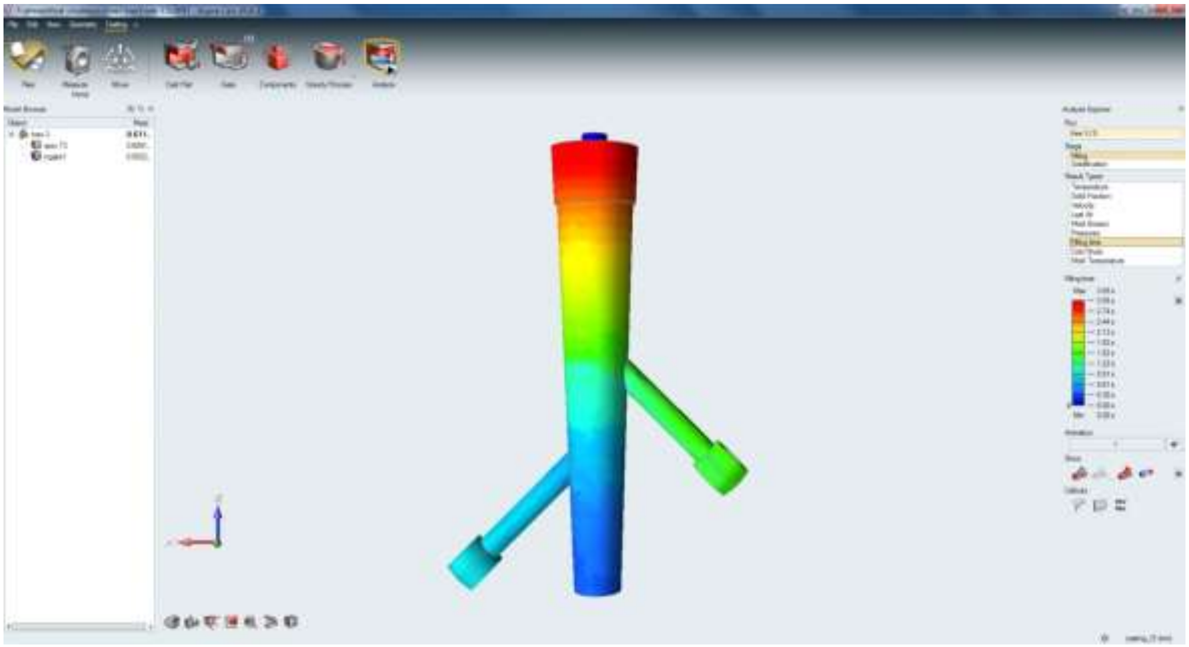


Figure 3.15: Filling time Aluminium A7075, Temperature 3, Tree 3

Cold shuts:

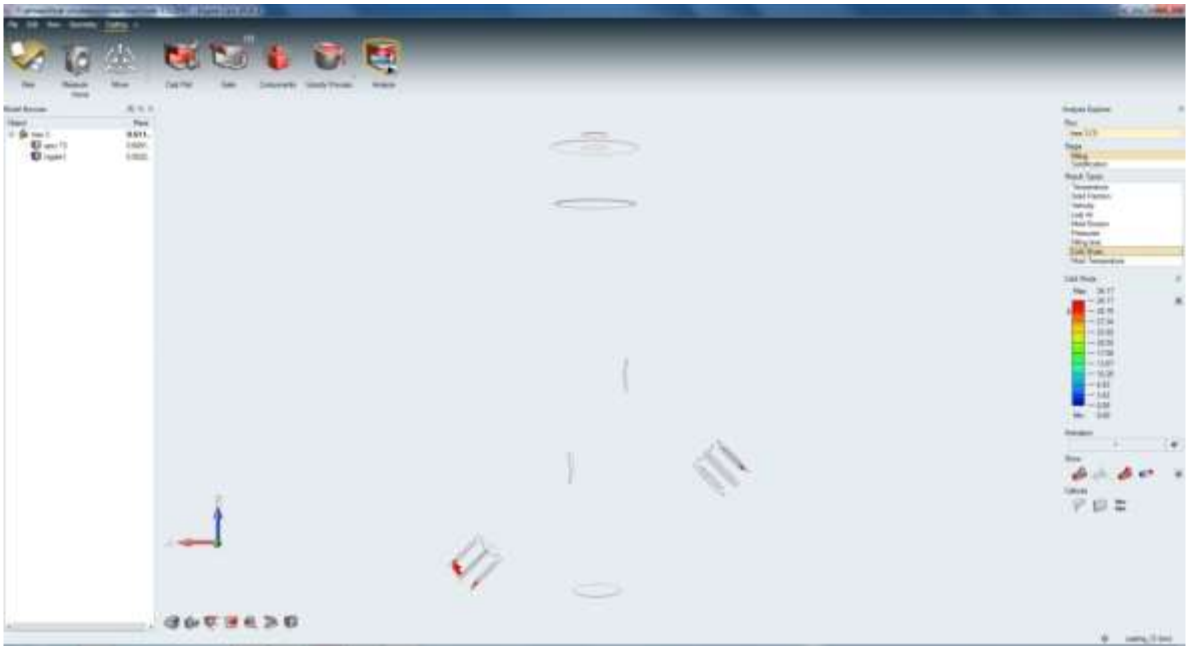


Figure 3.16: Cold shuts Aluminium A7075, Temperature 3, Tree 3

Last air:

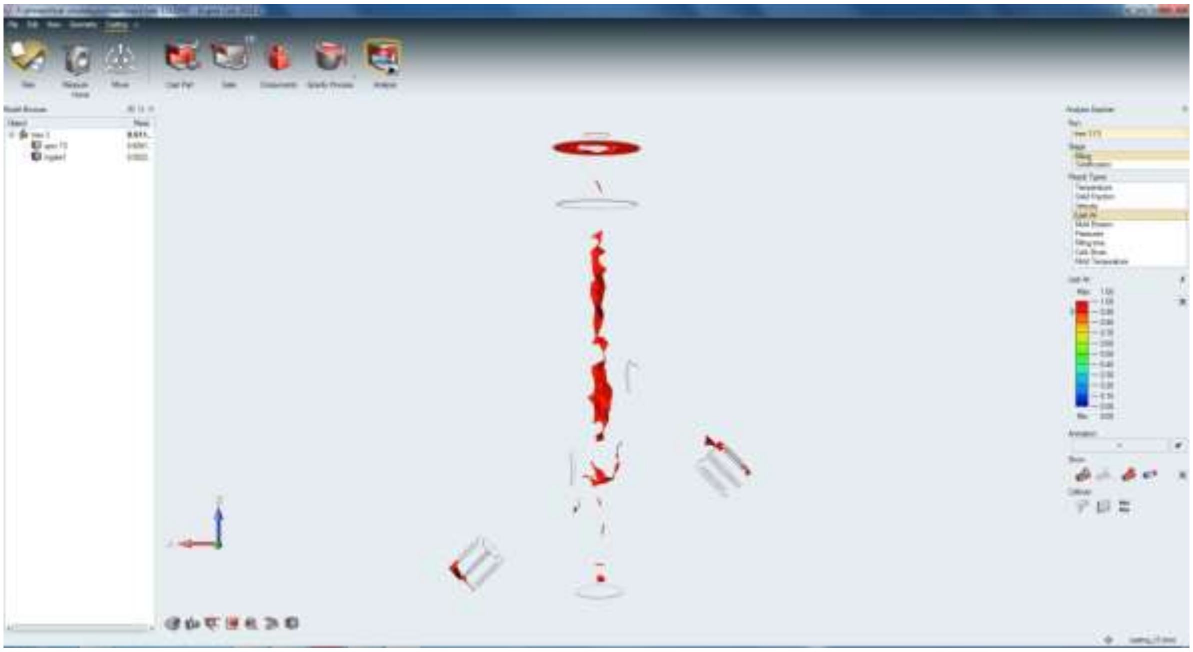


Figure 3.17: Last Air Aluminium A7075, Temperature 3, Tree 3

Porosity:

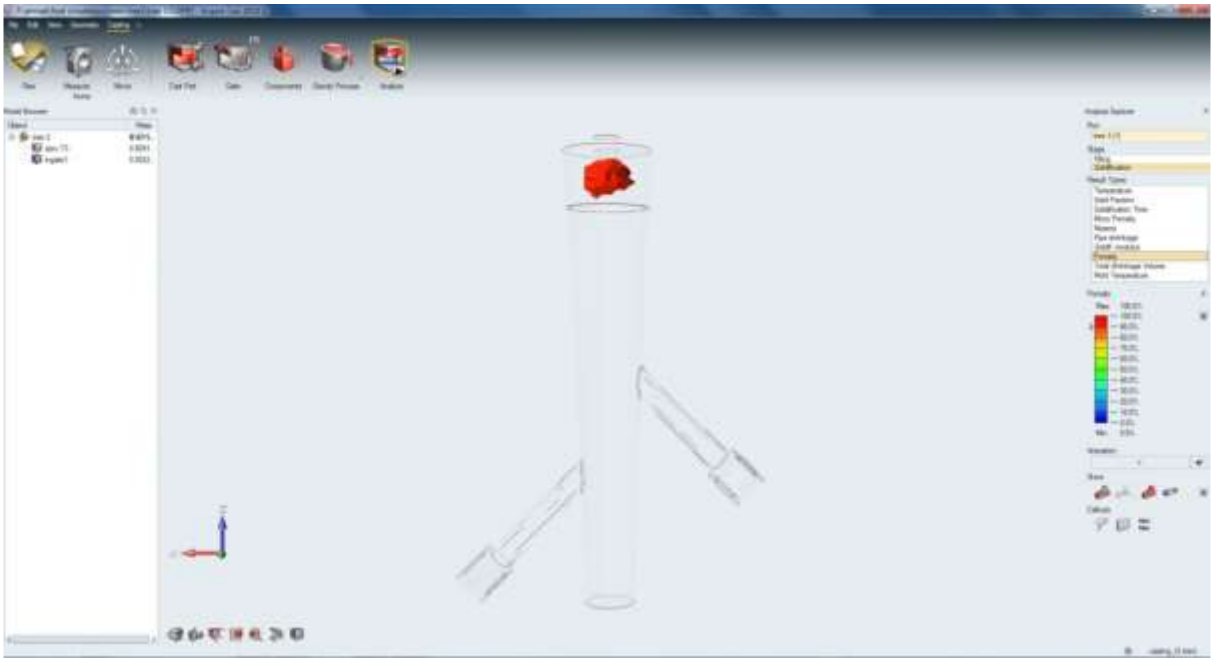


Figure 3.18: Porosity Aluminium A7075, Temperature 3, Tree 3

Solidification time:

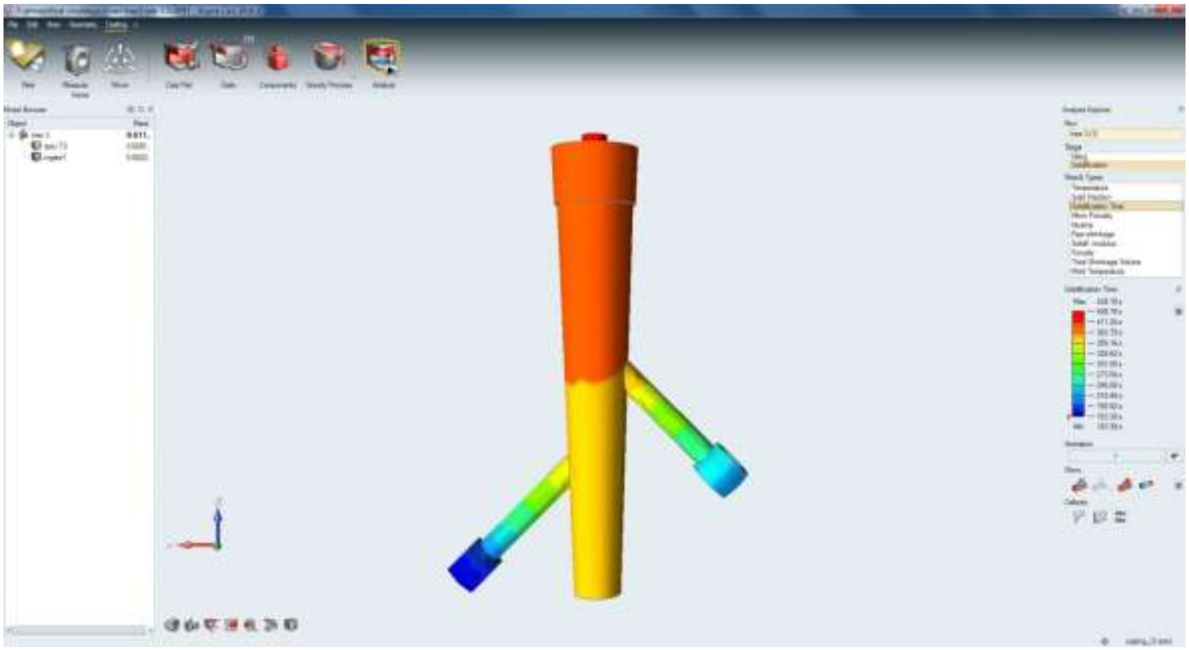


Figure 3.19: Solidification time Aluminium A7075, Temperature 3, Tree 3

Total shrinkage volume:

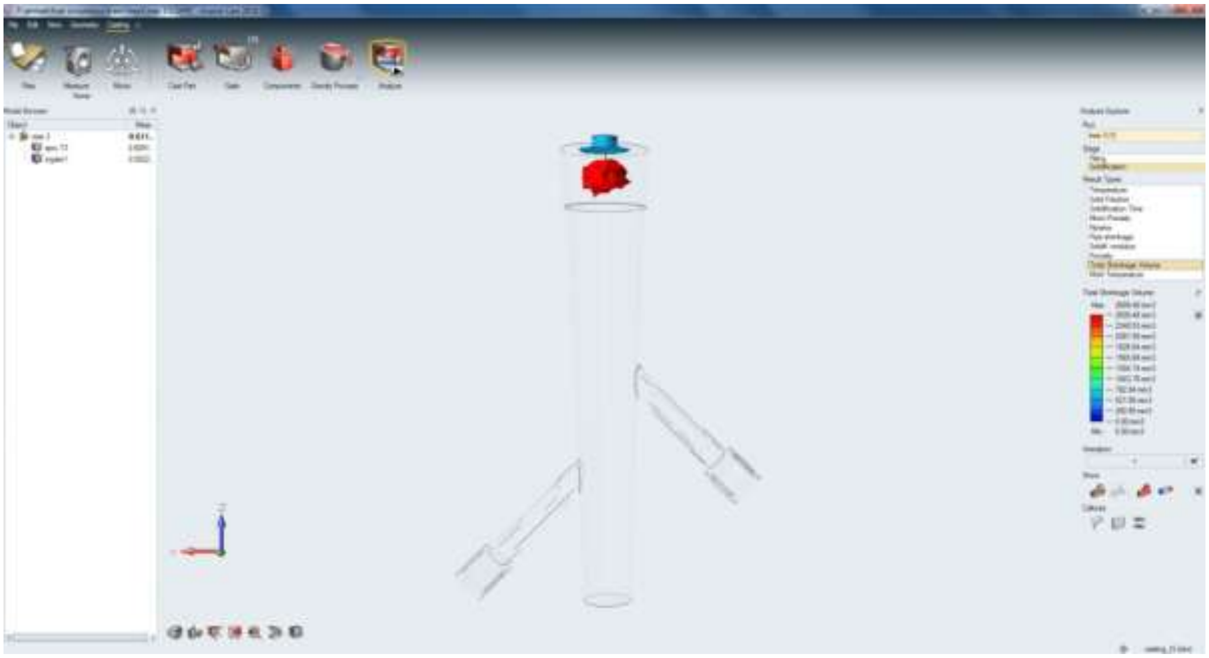


Figure 3.20: Total Shrinkage Volume Aluminium A7075, Temperature 3, Tree 3

3.1.4. Aluminium available at MRC, Temperature 1, Tree 2:

Filling time:

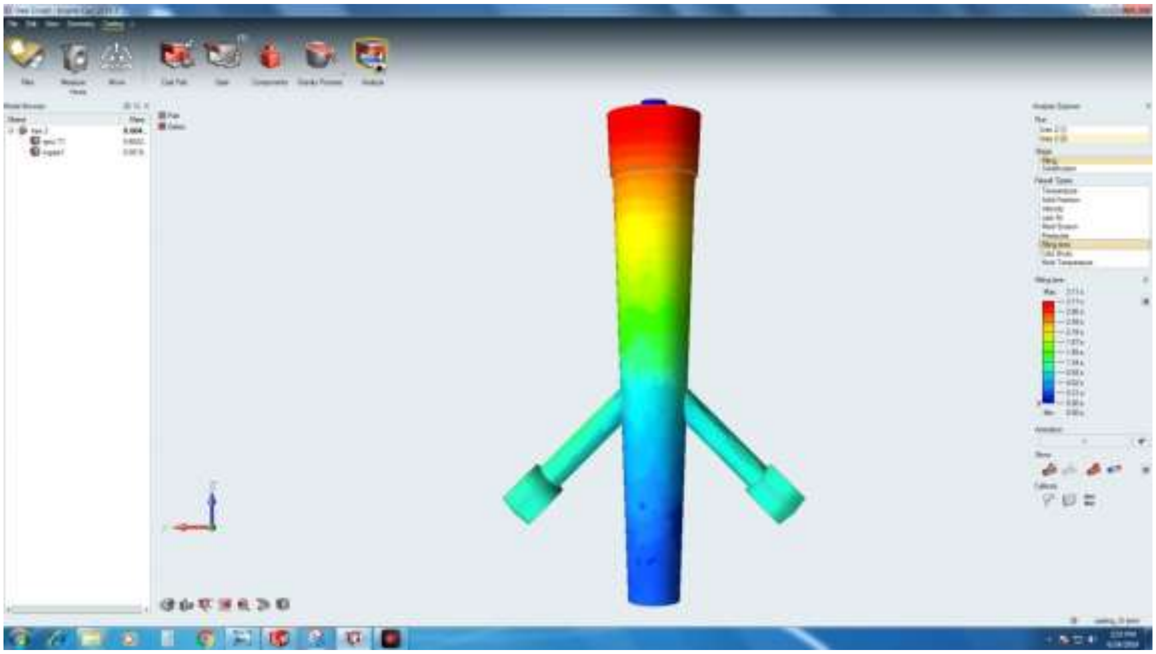


Figure 3.21: Filling Time Aluminium available at MRC, Temperature 1, Tree 2

Cold shuts:

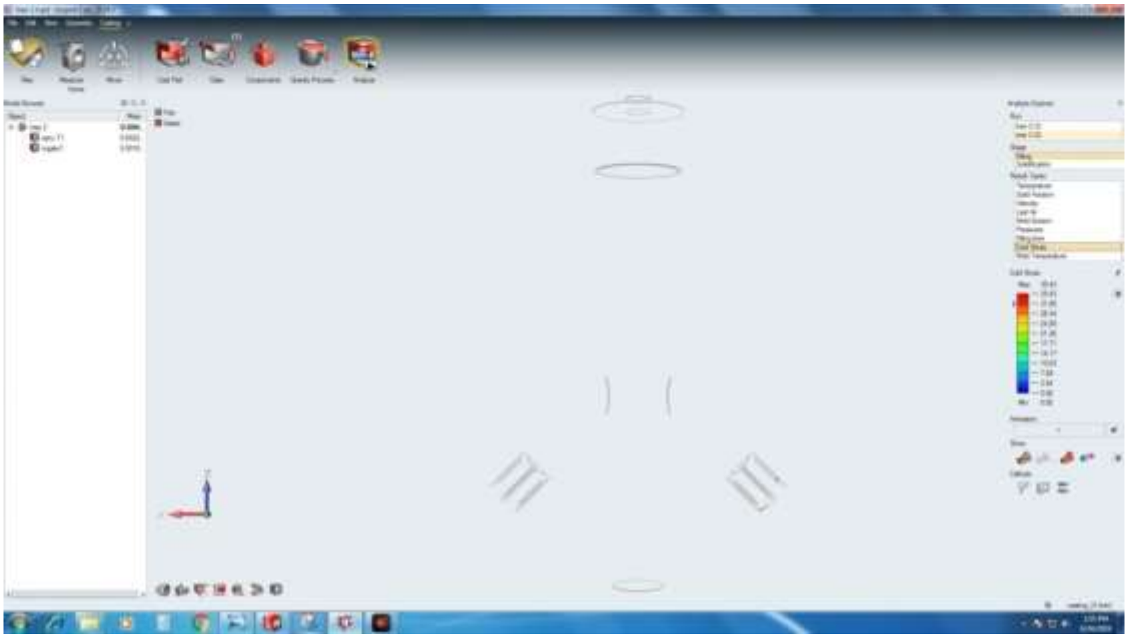


Figure 3.22: Cold shuts Aluminium available at MRC, Temperature 1, Tree 2

Last air:

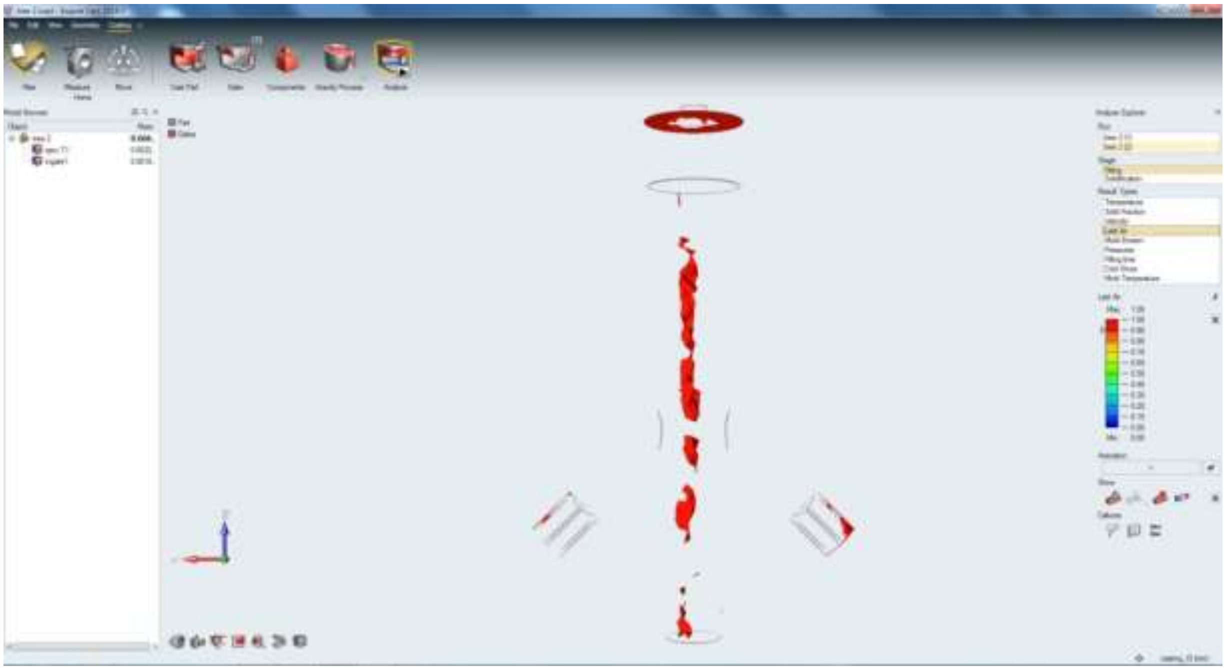


Figure 3.23: Last Air Aluminium available at MRC, Temperature 1, Tree 2

Porosity:

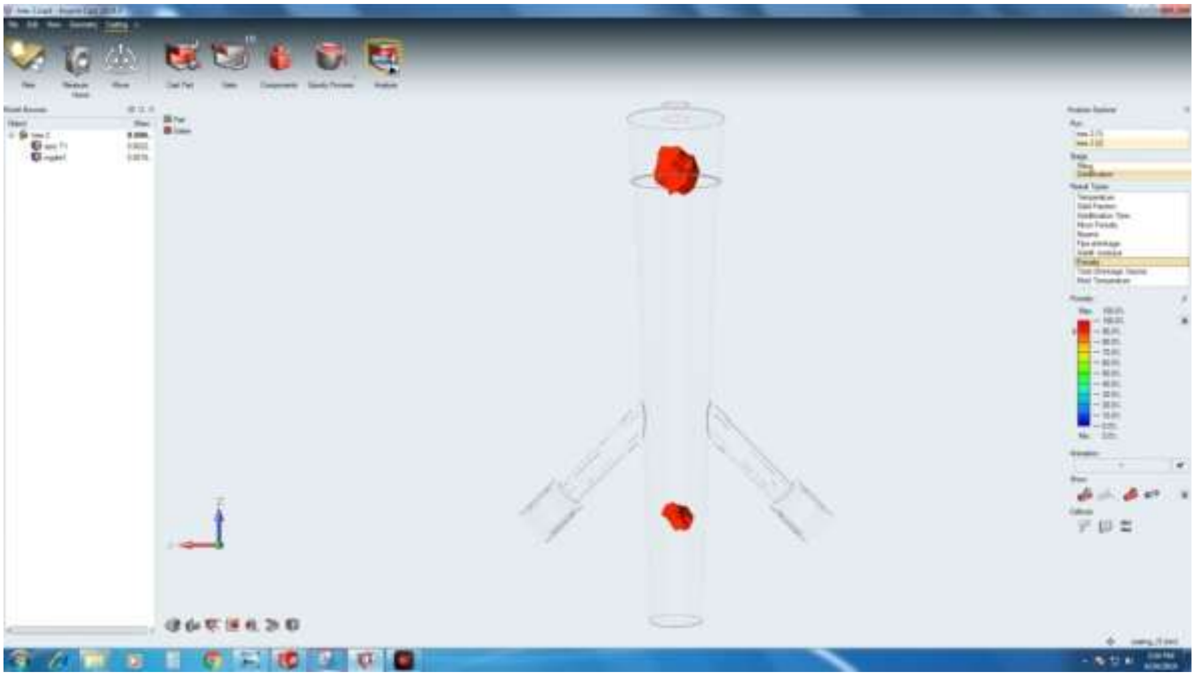


Figure 3.24: Porosity Aluminium available at MRC, Temperature 1, Tree 2

Solidification time:

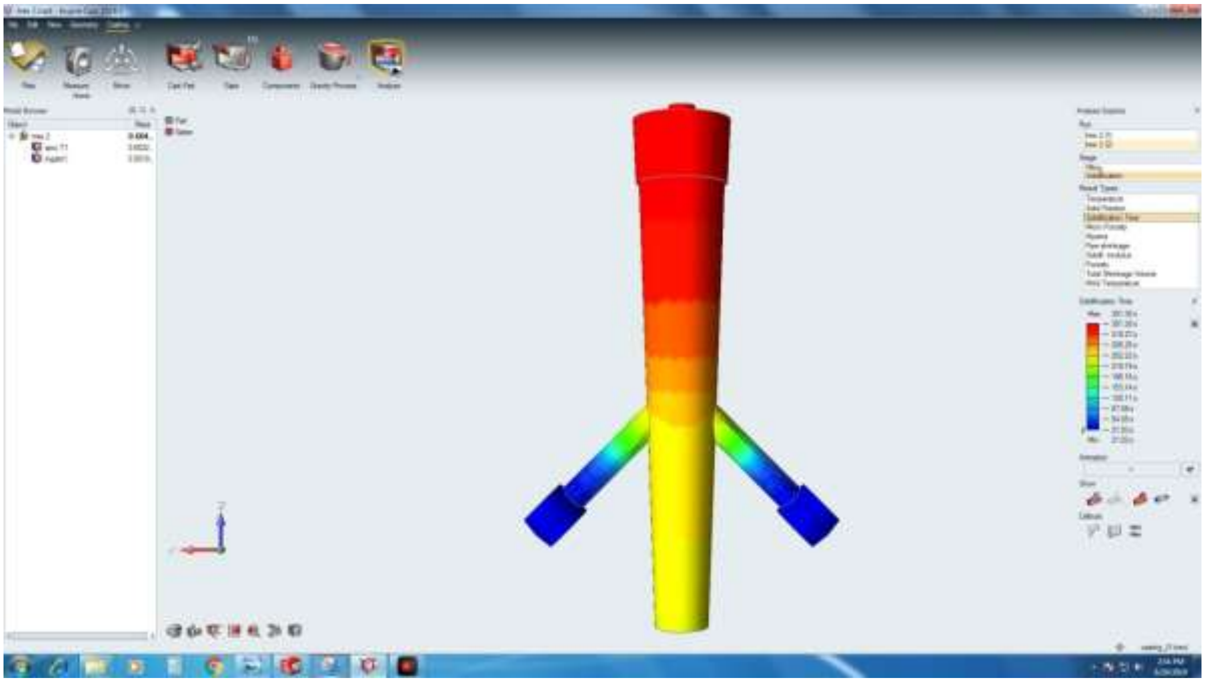


Figure 3.25: Solidification Time Aluminium available at MRC, Temperature 1, Tree 2

Total shrinkage volume:

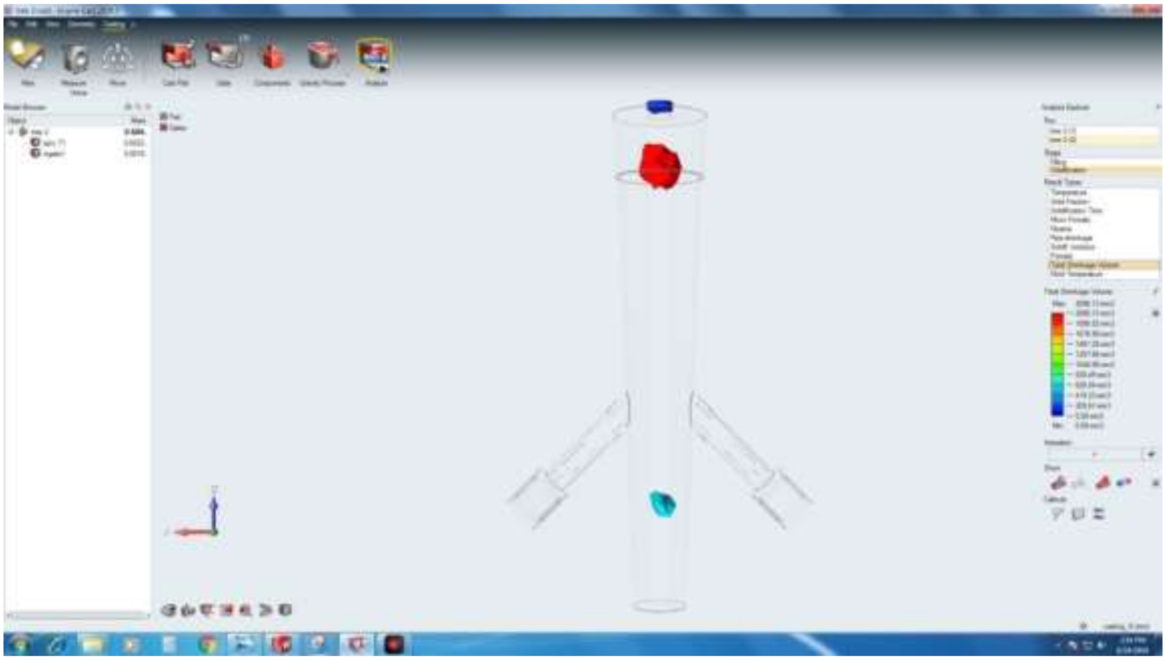


Figure 3.26: Total Shrinkage Volume Aluminium available at MRC, Temperature 1, Tree 2

3.1.5. Aluminium available at MRC, Temperature 2, Tree 3

Filling time:

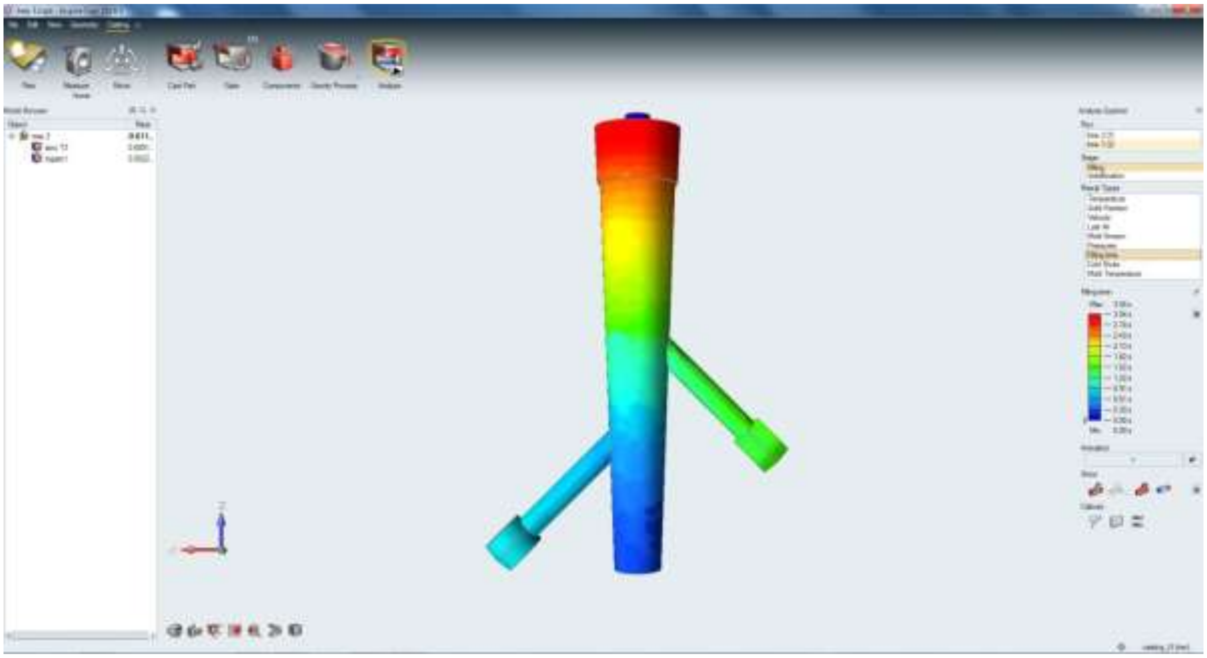


Figure 3.27: Filling Time Aluminium available at MRC, Temperature 2, Tree 3

Cold shuts:

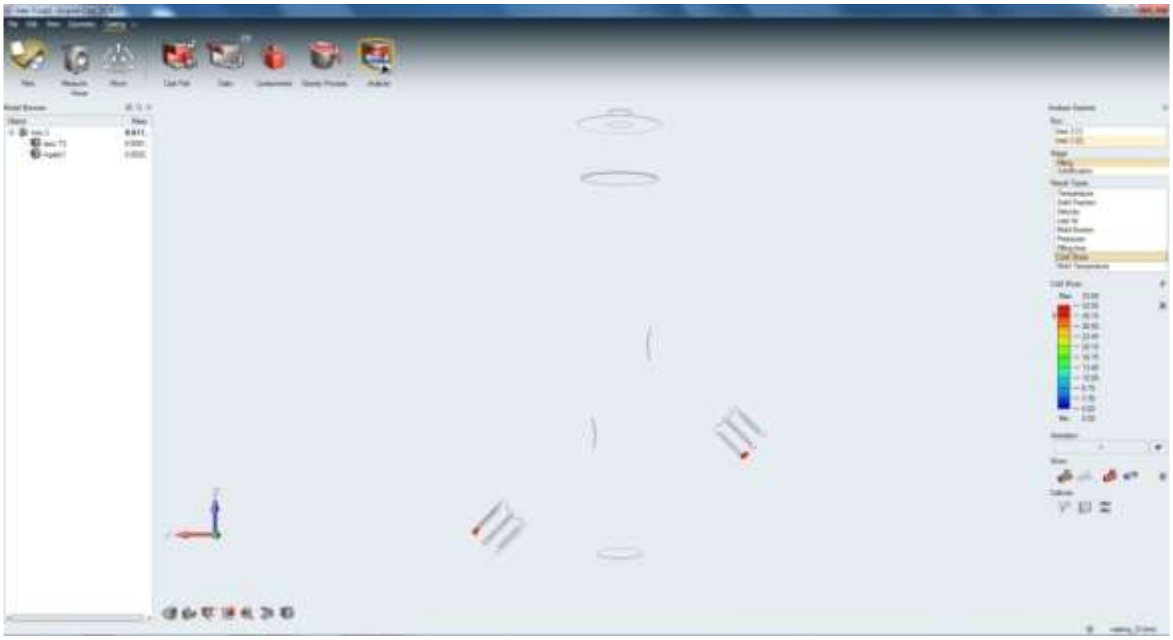


Figure 3.28: Porosity Aluminium available at MRC, Temperature 2, Tree 3

Last air:

Figure 3.29: Last Air Aluminium available at MRC, Temperature 2, Tree 3

Porosity:

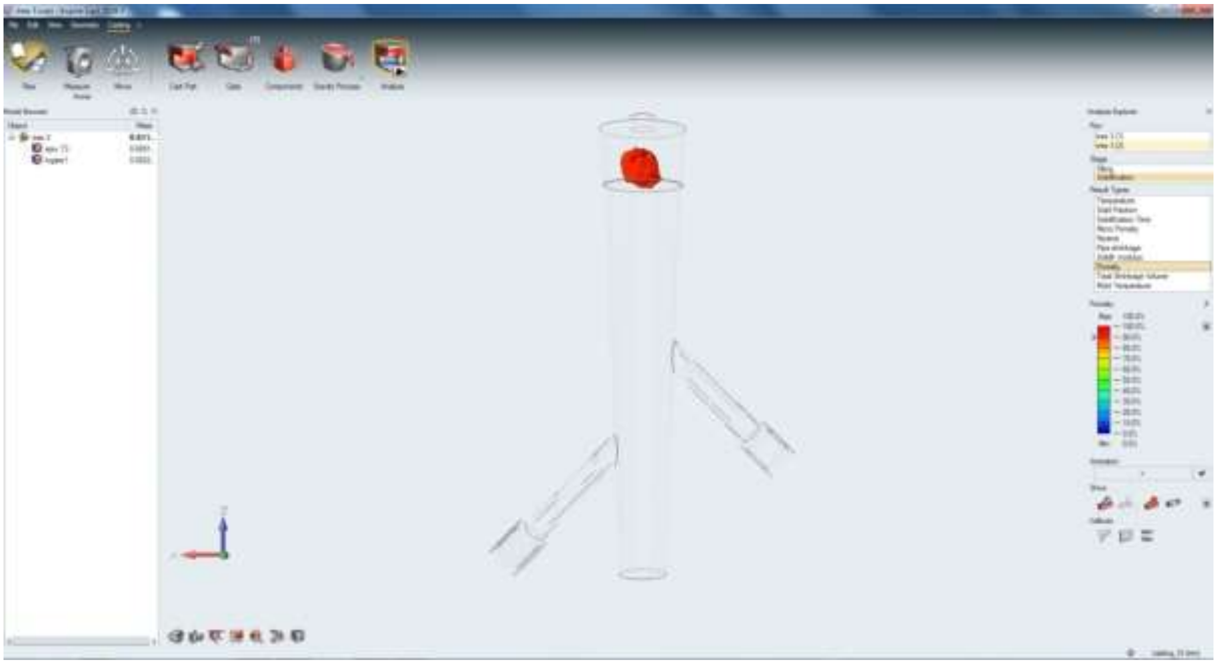


Figure 3.30: Porosity Aluminium available at MRC, Temperature 2, Tree 3

Solidification time:

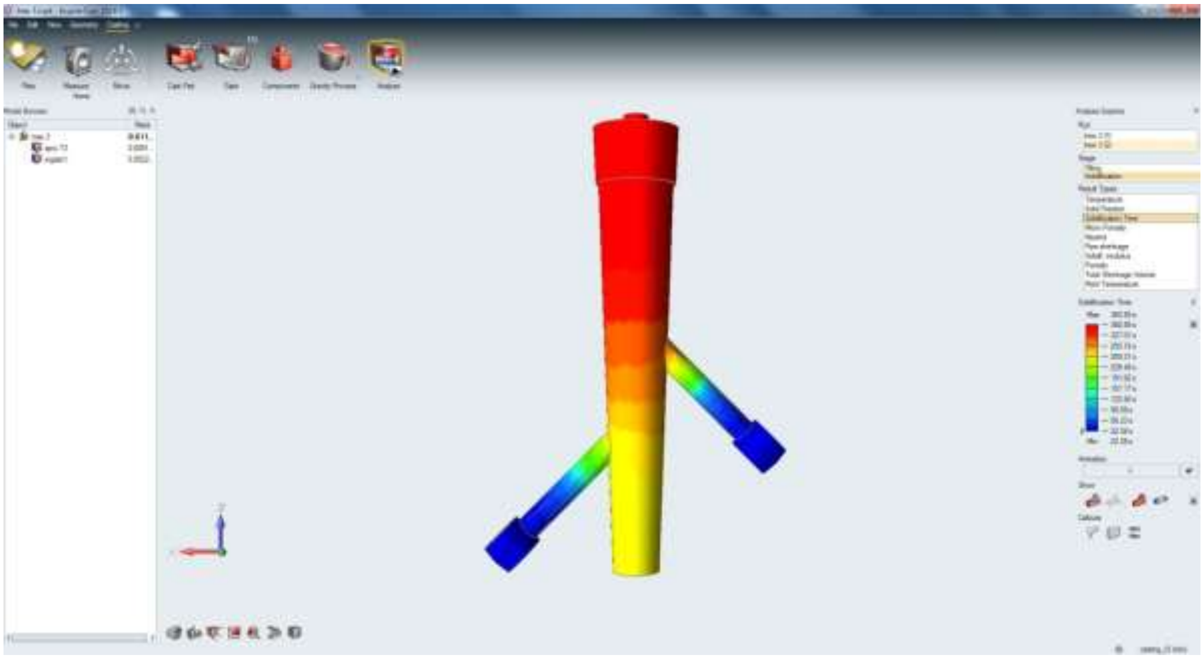


Figure 3.31: Solidification Time Aluminium available at MRC, Temperature 2, Tree 3

Total shrinkage volume:

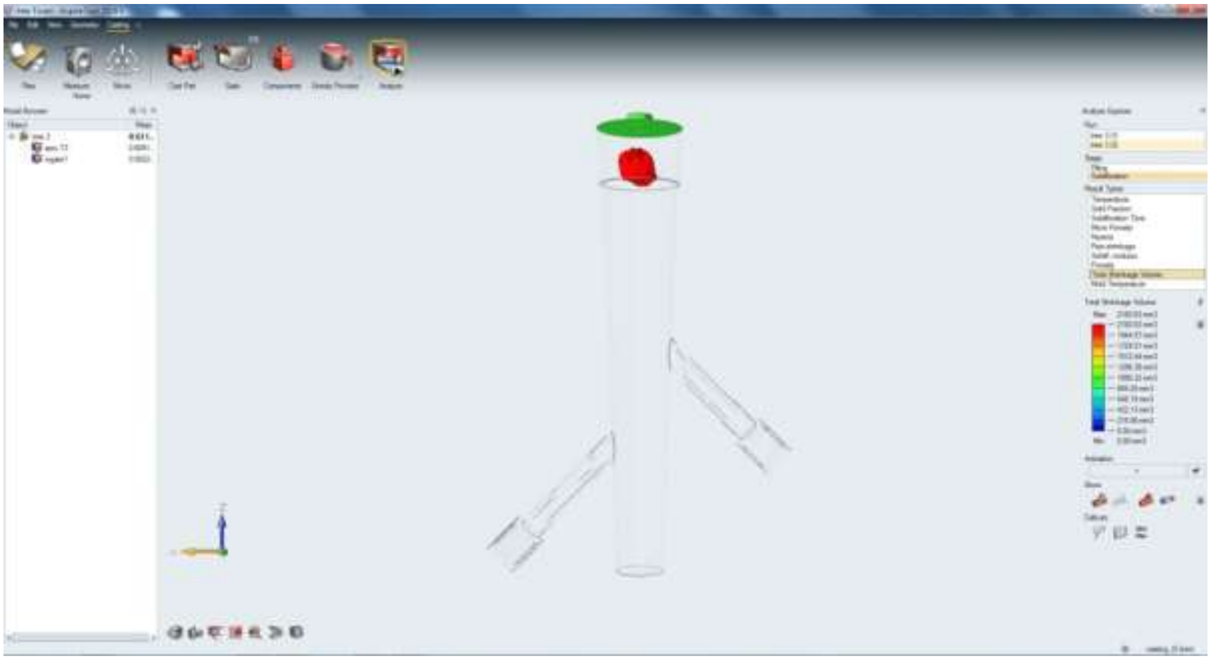


Figure 3.32: Total Shrinkage Volume Aluminium available at MRC, Temperature 2, Tree 3

3.1.6. Aluminium available at MRC, Temperature 3, Tree 1:

Filling time:

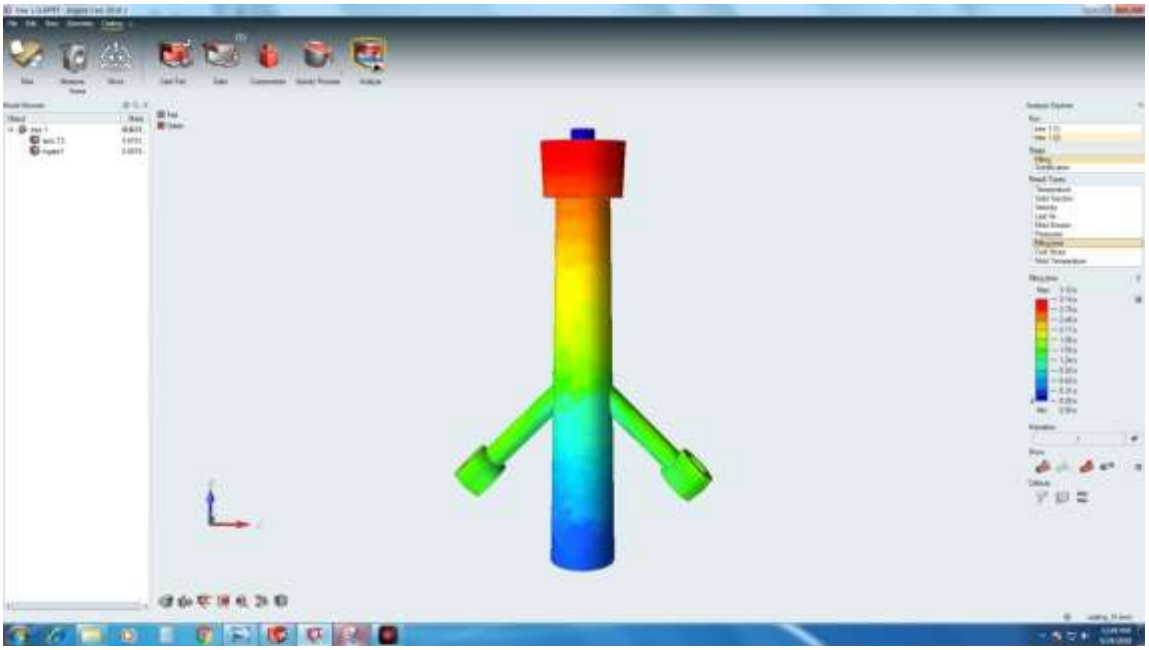


Figure 3.33: Filling Time Aluminium available at MRC, Temperature 3, Tree 1

Cold shuts:

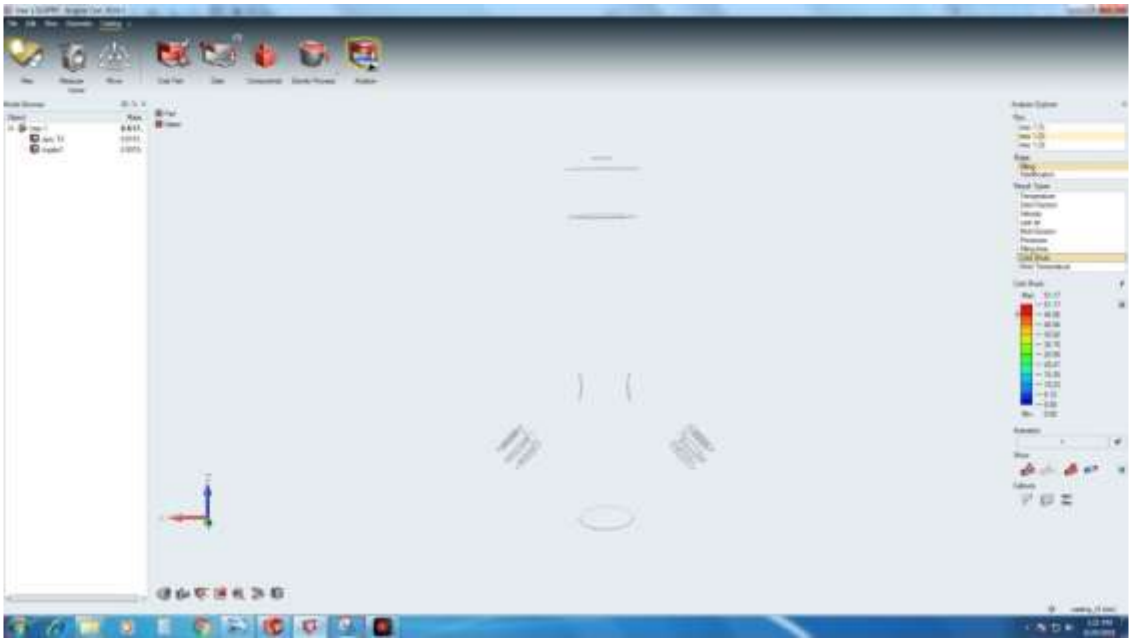


Figure 3.34: Cold shuts Aluminium available at MRC, Temperature 3, Tree 1

Last air:

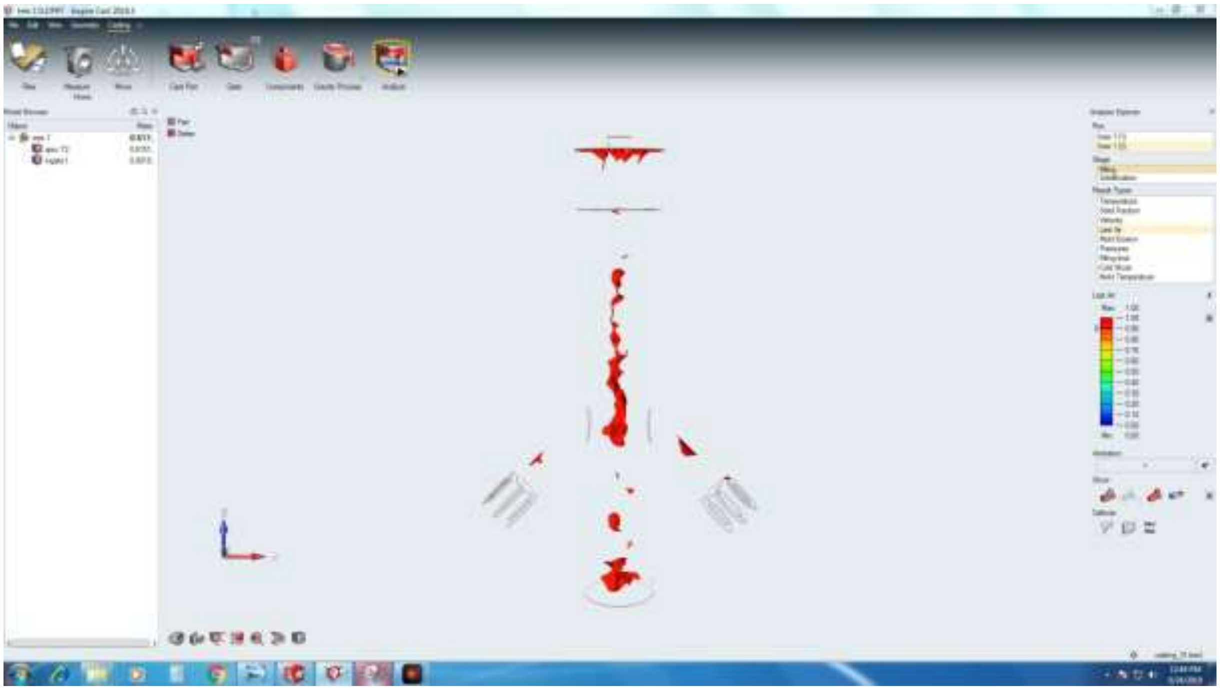


Figure 3.35: Last Air Aluminium available at MRC, Temperature 3, Tree 1

Porosity:

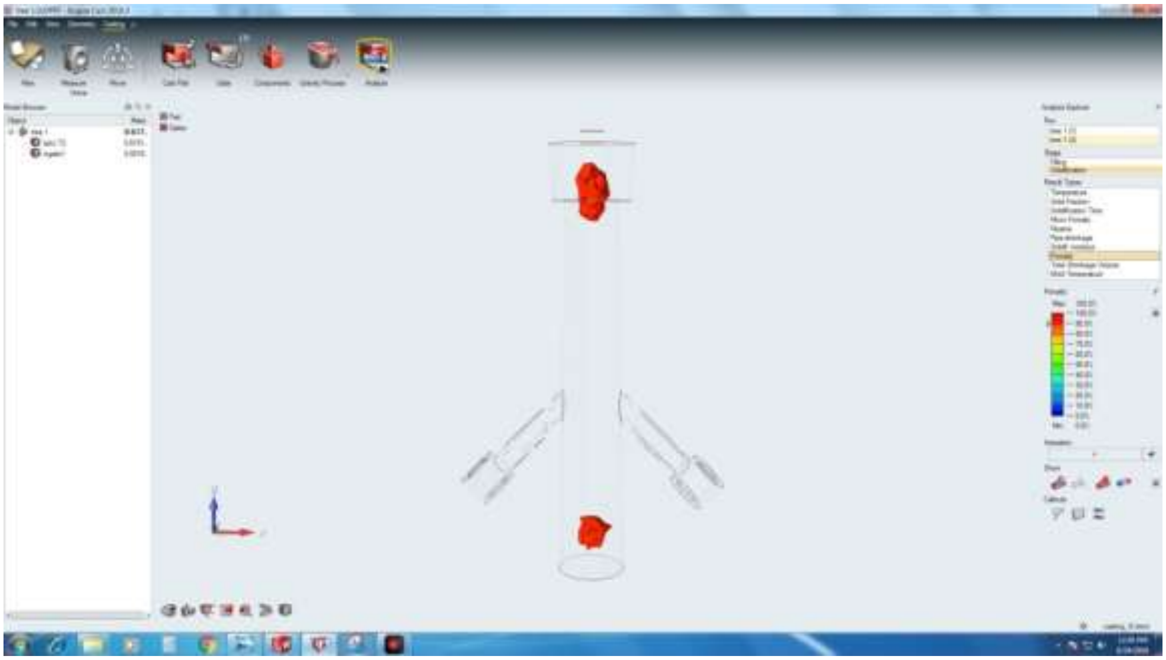


Figure 3.36: Porosity Aluminium available at MRC, Temperature 3, Tree 1

Solidification time:

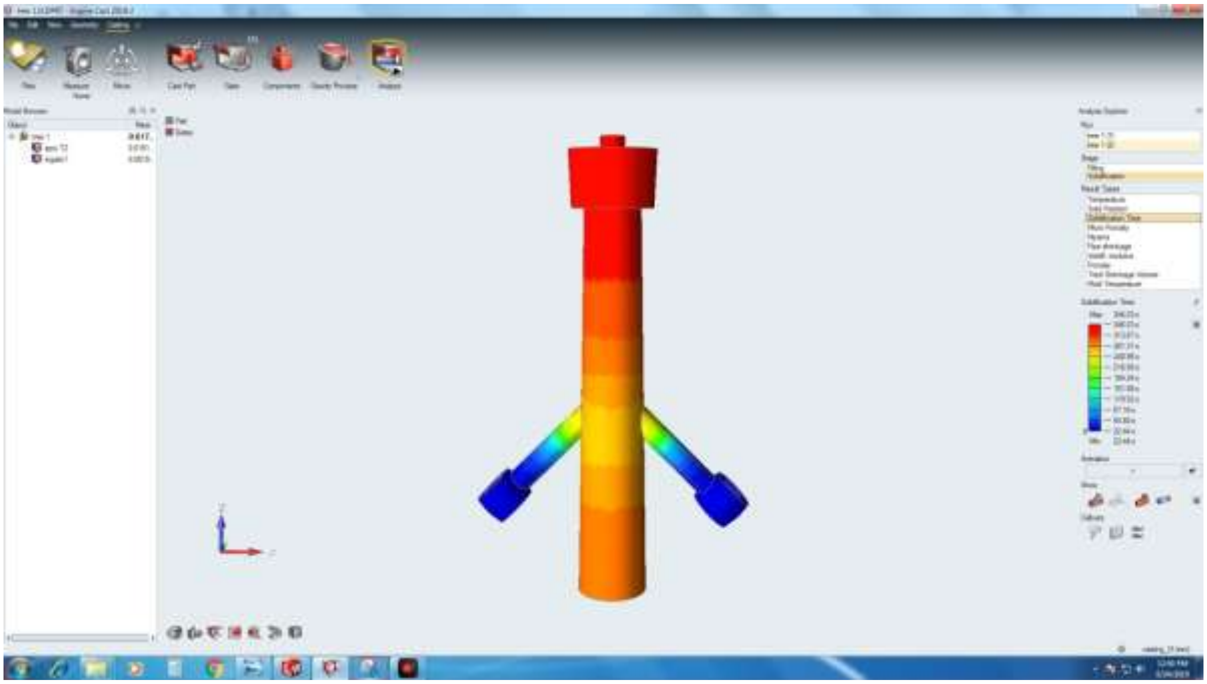


Figure 3.37: Solidification Time Aluminium available at MRC, Temperature 3, Tree 1

Total shrinkage volume:

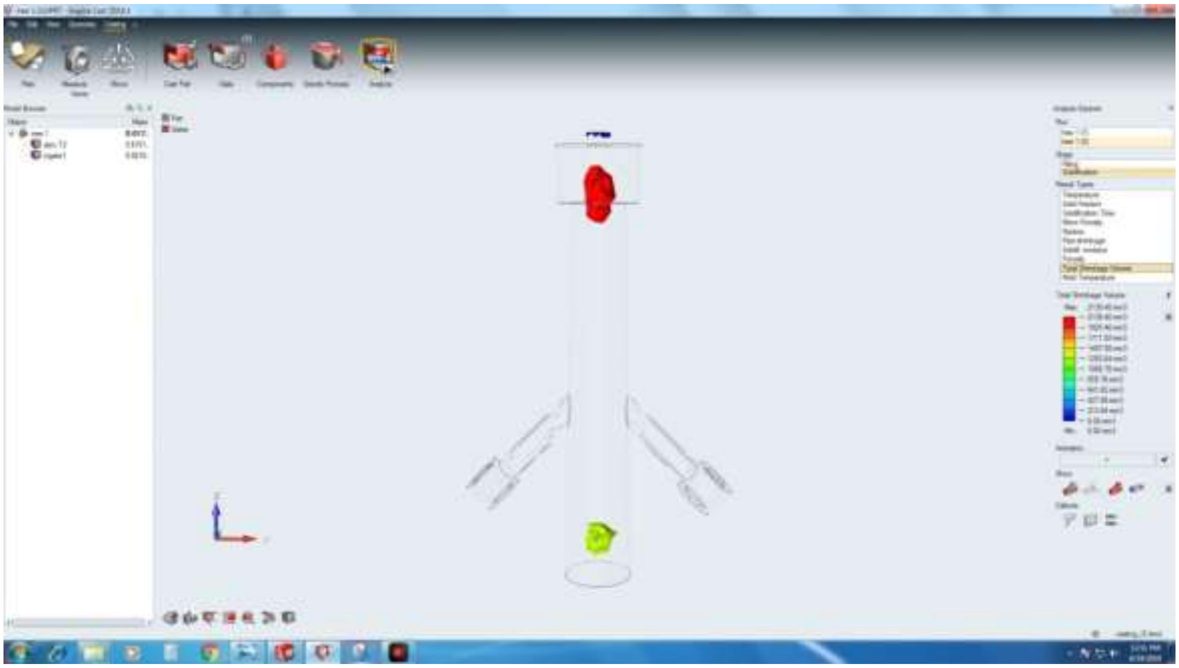


Figure 3.38: Total Shrinkage Volume Aluminium available at MRC, Temperature 3, Tree 1

3.1.7. Brass, Temperature 1, Tree 3:

Filling time:

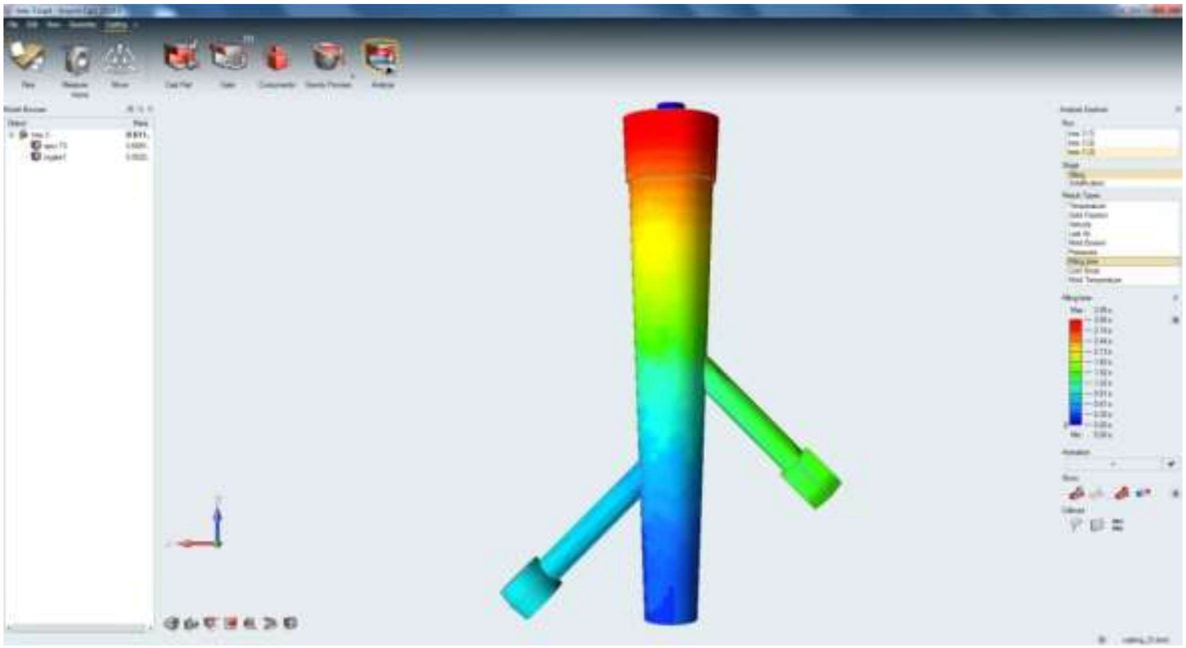


Figure 3.39: Filling Time Brass, Temperature 1, Tree 3

Cold shuts:

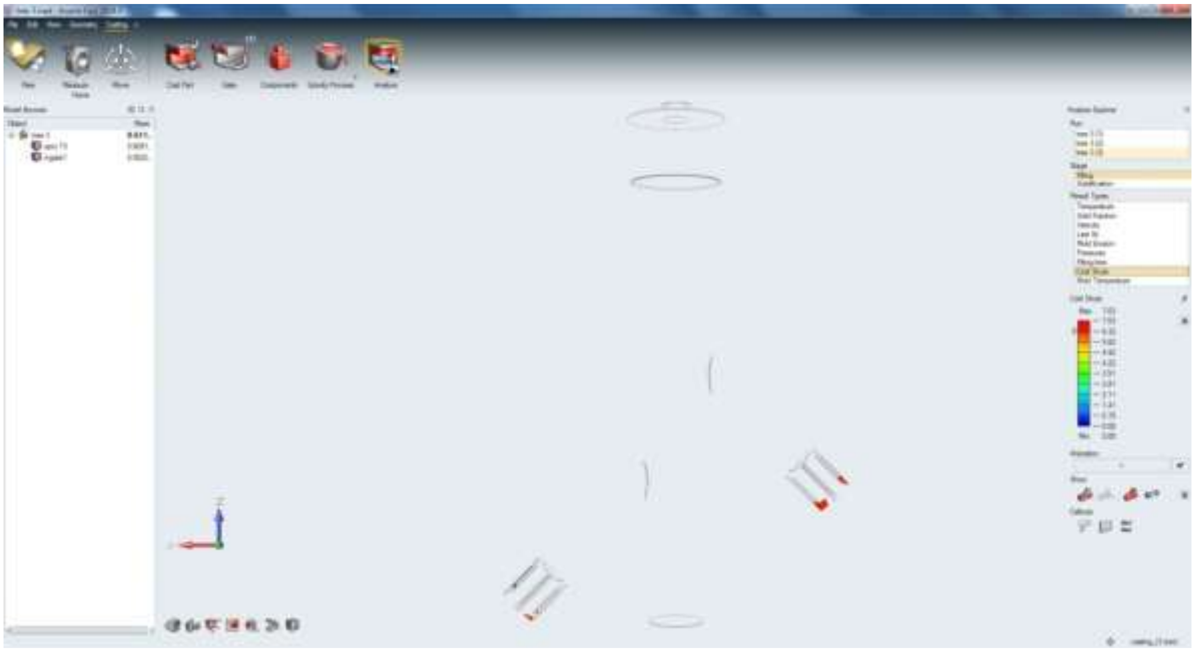


Figure 3.40: Cold shuts Brass, Temperature 1, Tree 3

Last air:

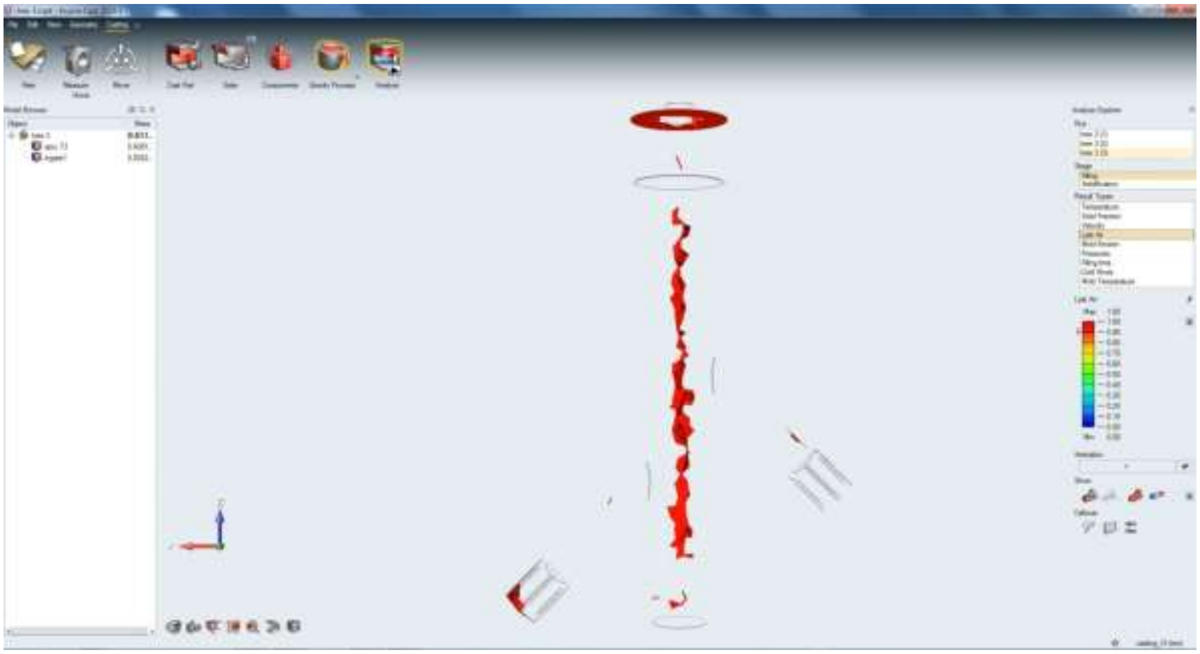


Figure 3.41: Last Air Brass, Temperature 1, Tree 3

Porosity:

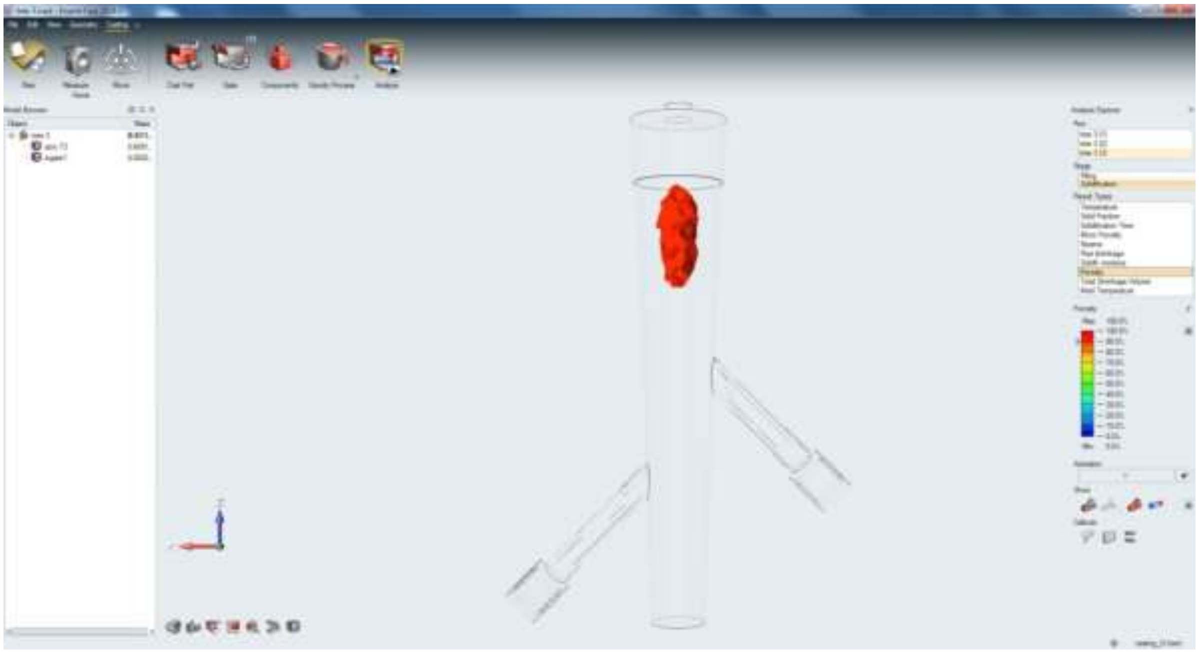


Figure 3.42: Porosity Brass, Temperature 1, Tree 3

Solidification time:

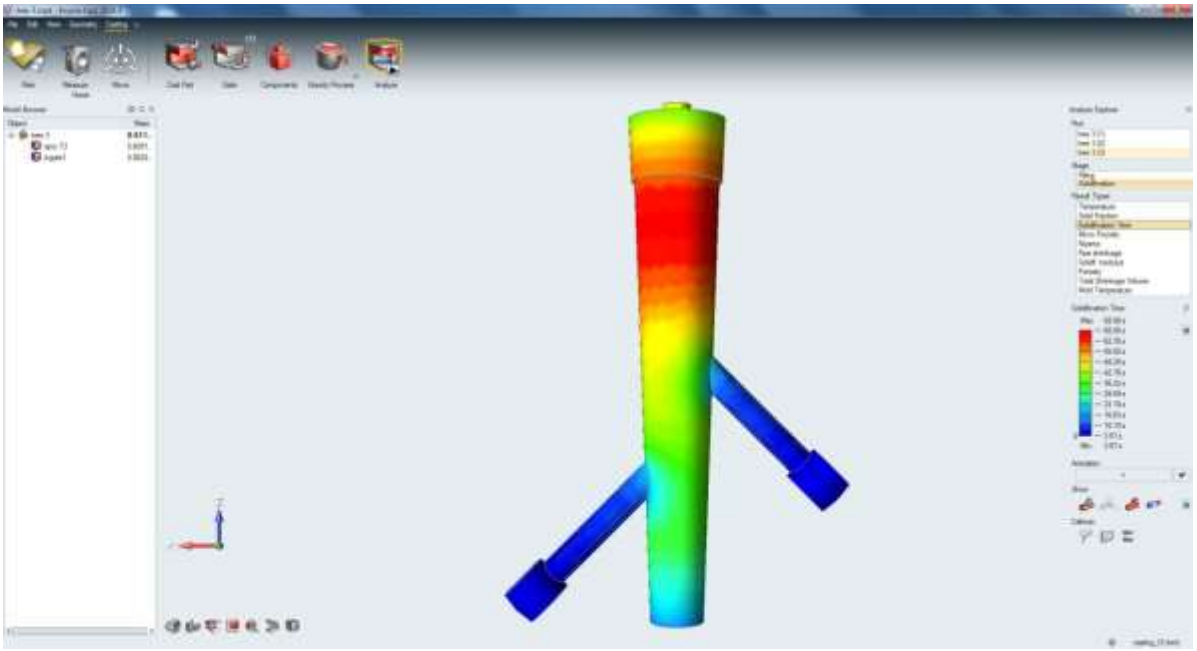


Figure 3.43: Solidification Time Brass, Temperature 1, Tree 3

Total shrinkage volume:

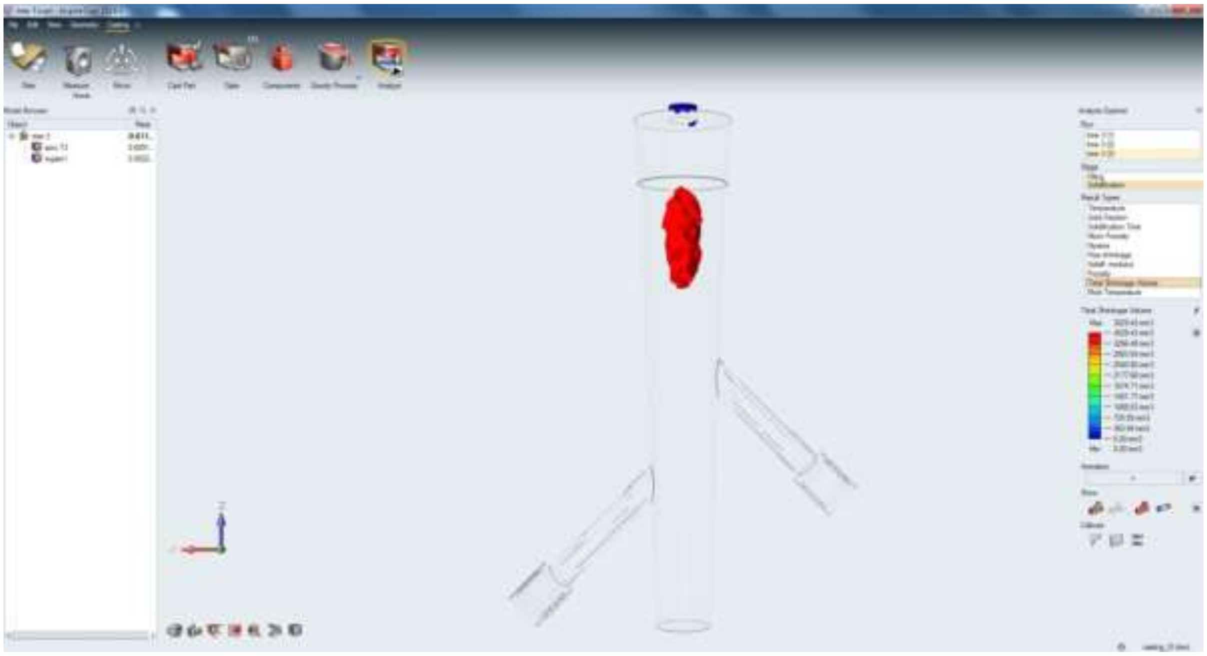


Figure 3.44: Total Shrinkage Volume Brass, Temperature 1, Tree 3

3.1.8. Brass, Temperature 2, Tree 1:

Filling time:

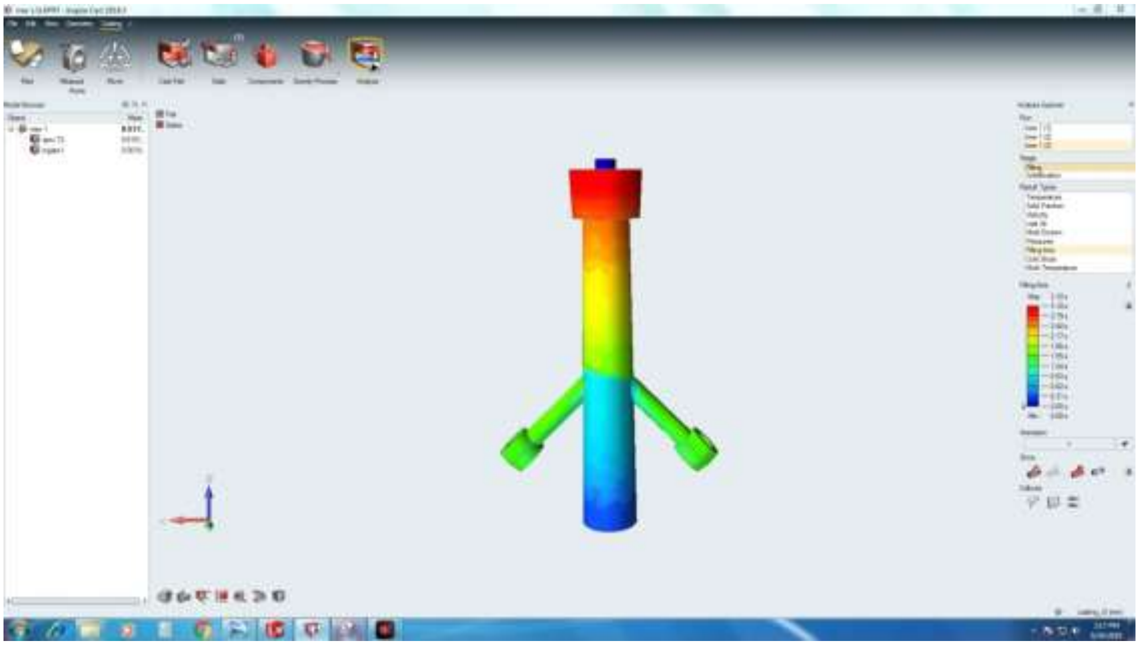


Figure 3.45: Filling Time Brass, Temperature 2, Tree 1

Cold shuts:

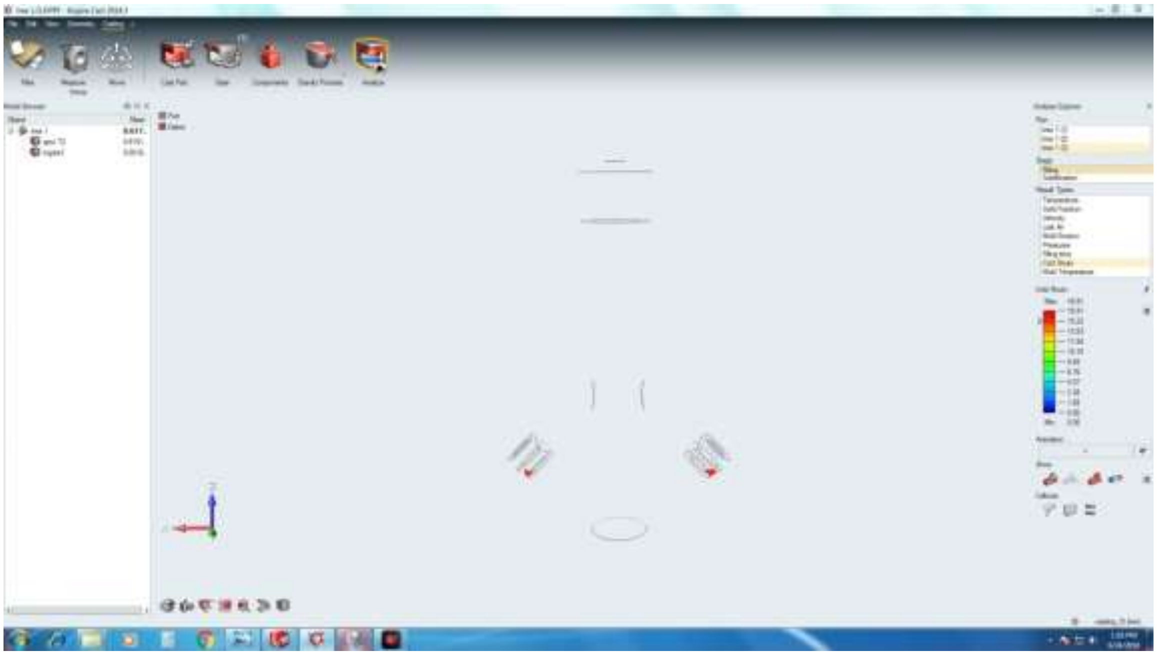


Figure 3.46: Cold shuts Brass, Temperature 2, Tree 1

Last air:

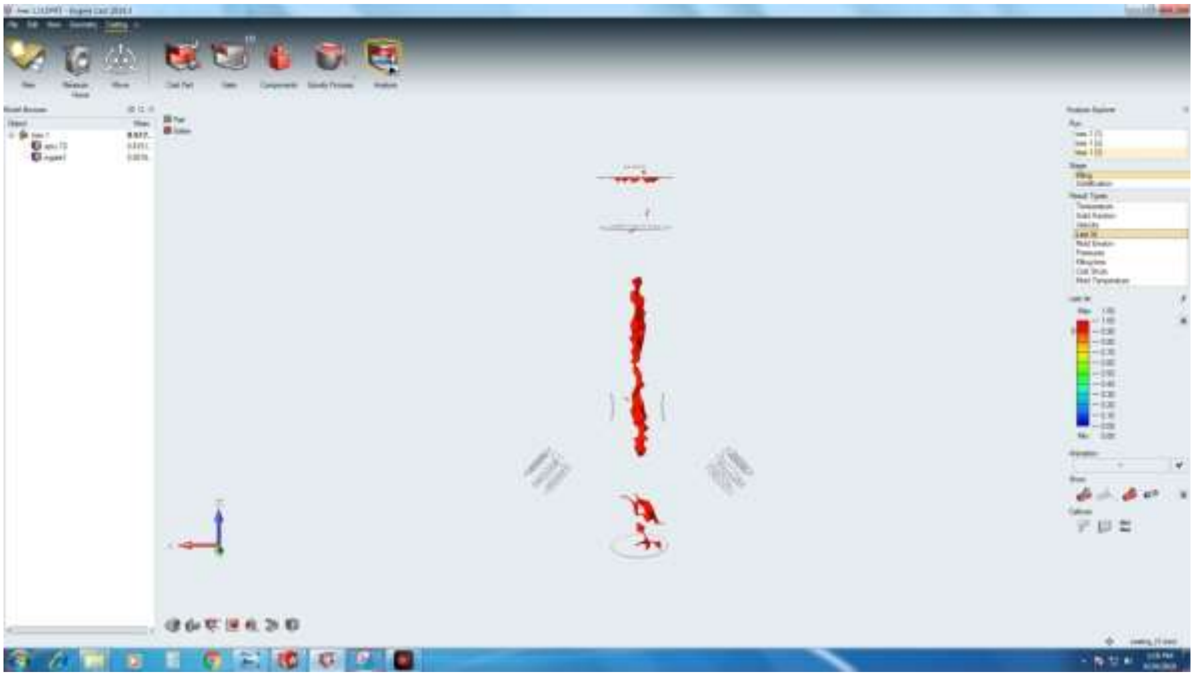


Figure 3.47: Last Air Brass, Temperature 2, Tree 1

Porosity:

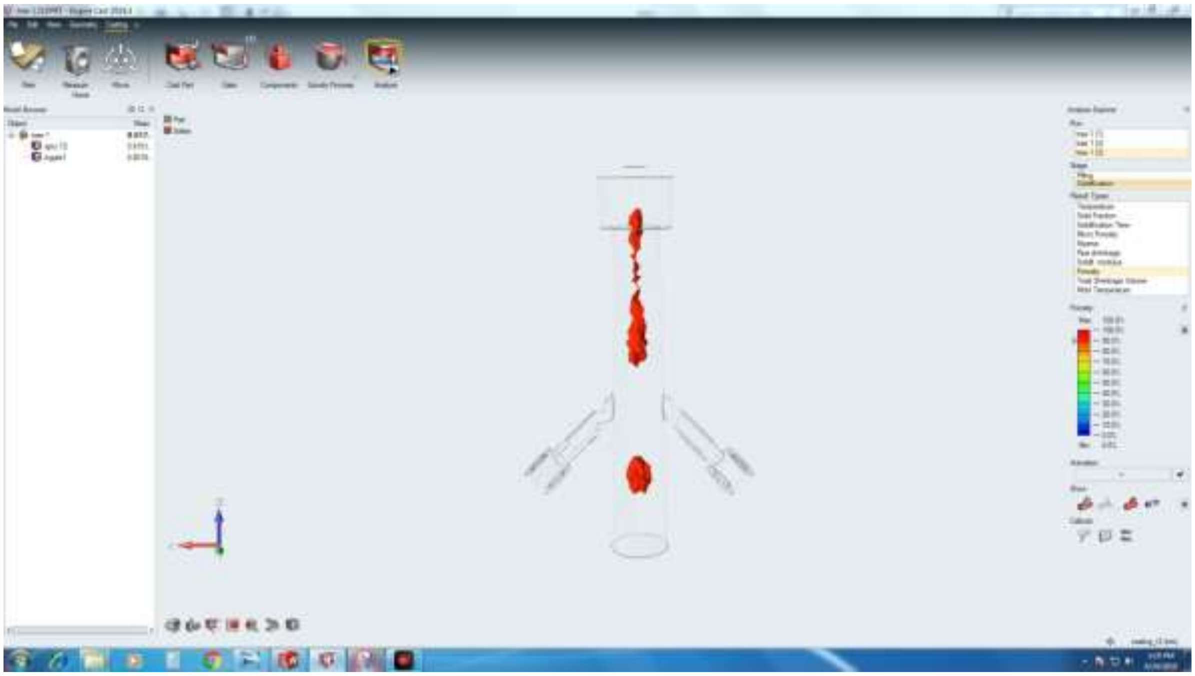


Figure 3.48: Porosity Brass, Temperature 2, Tree 1

Solidification time:

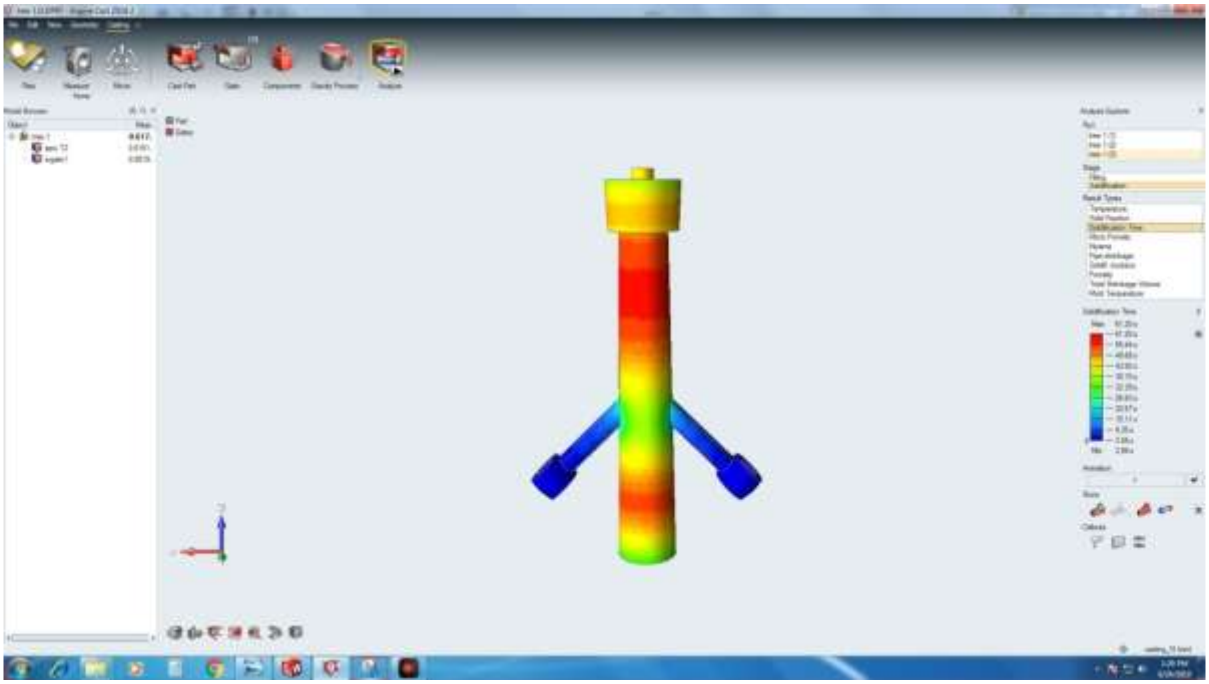


Figure 3.49: Solidification Time Brass, Temperature 2, Tree 1

Total shrinkage volume:

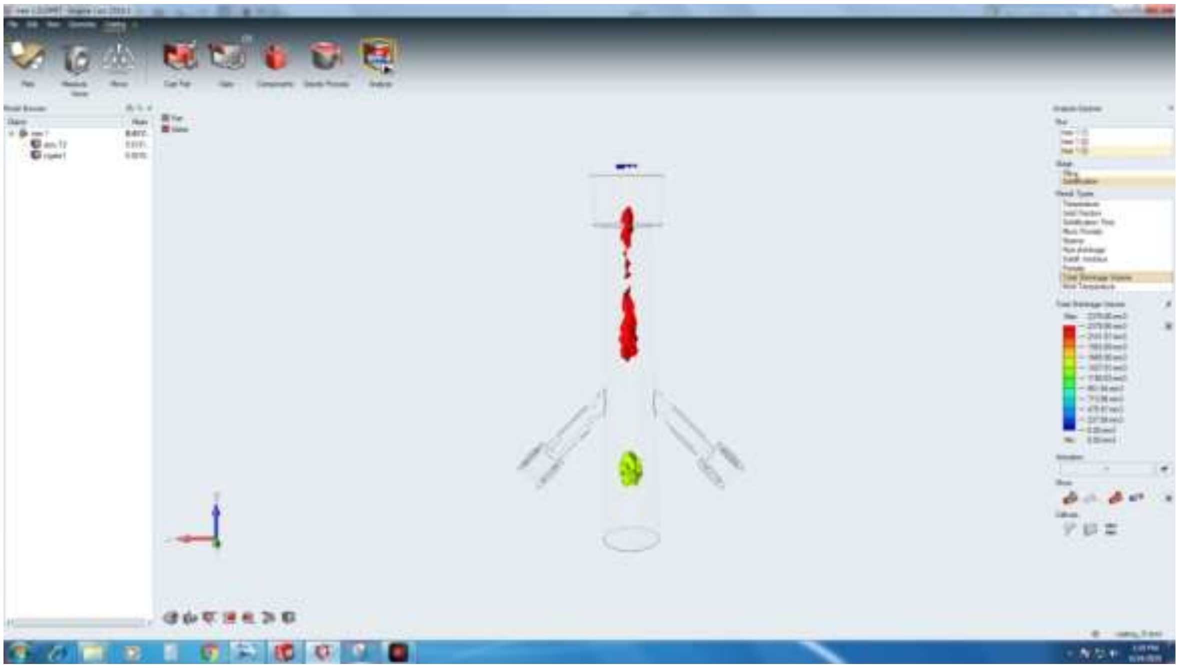


Figure 3.50: Total Shrinkage Volume Brass, Temperature 2, Tree 1

3.1.9. Brass, Temperature 3, Tree 2:

Filling time:

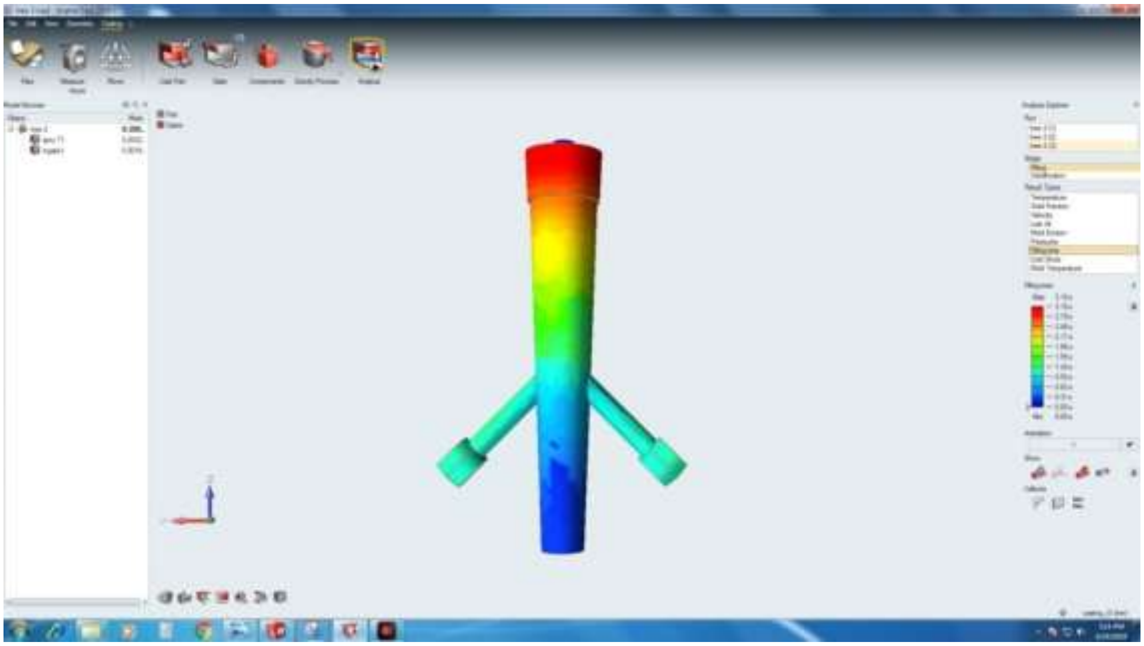


Figure 3.51: Filling Time Brass, Temperature 3, Tree 2

Cold shuts:

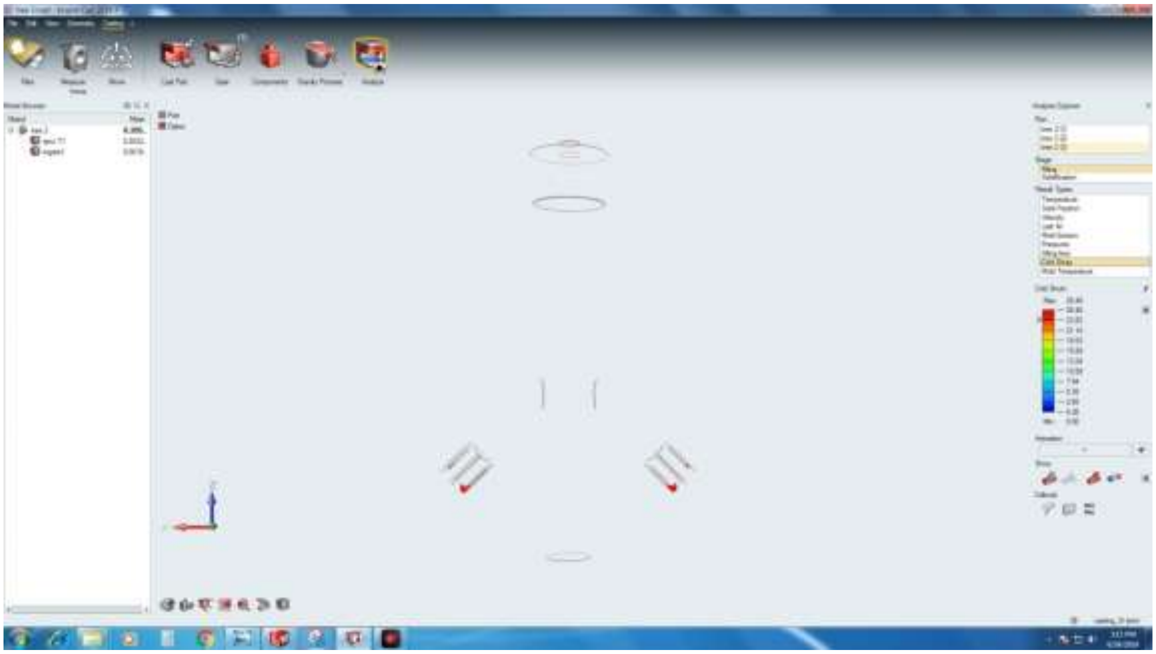


Figure 3.52: Cold shuts Brass, Temperature 3, Tree 2

Last air:

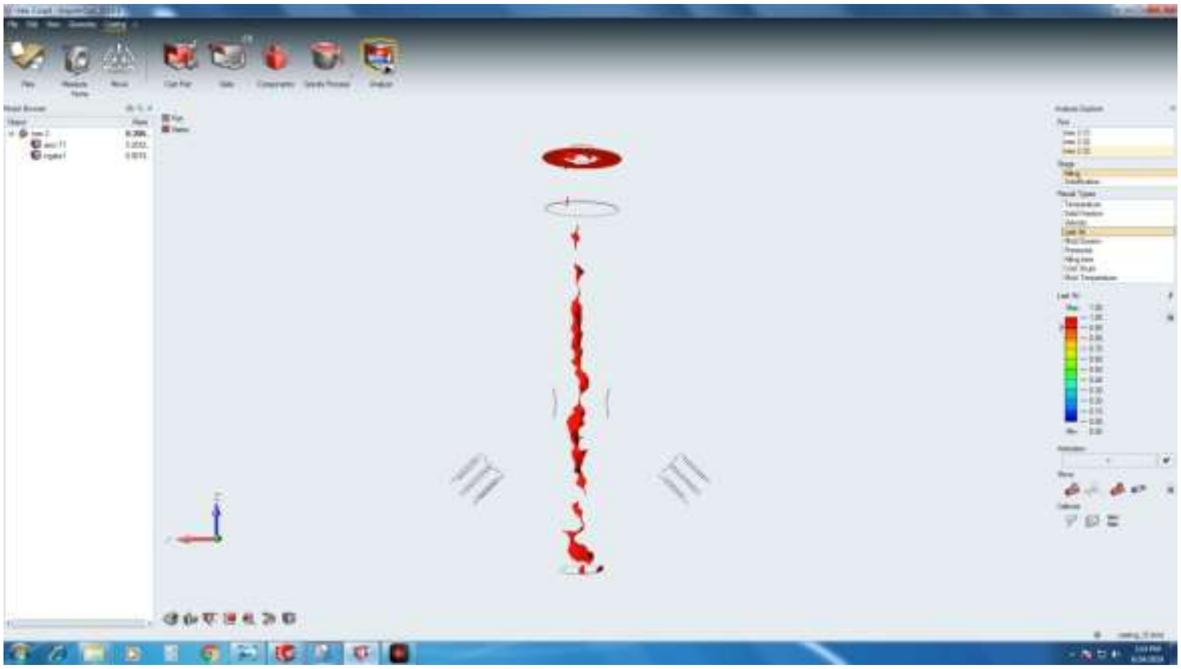


Figure 3.53: Last Air Brass, Temperature 3, Tree 2

Porosity:

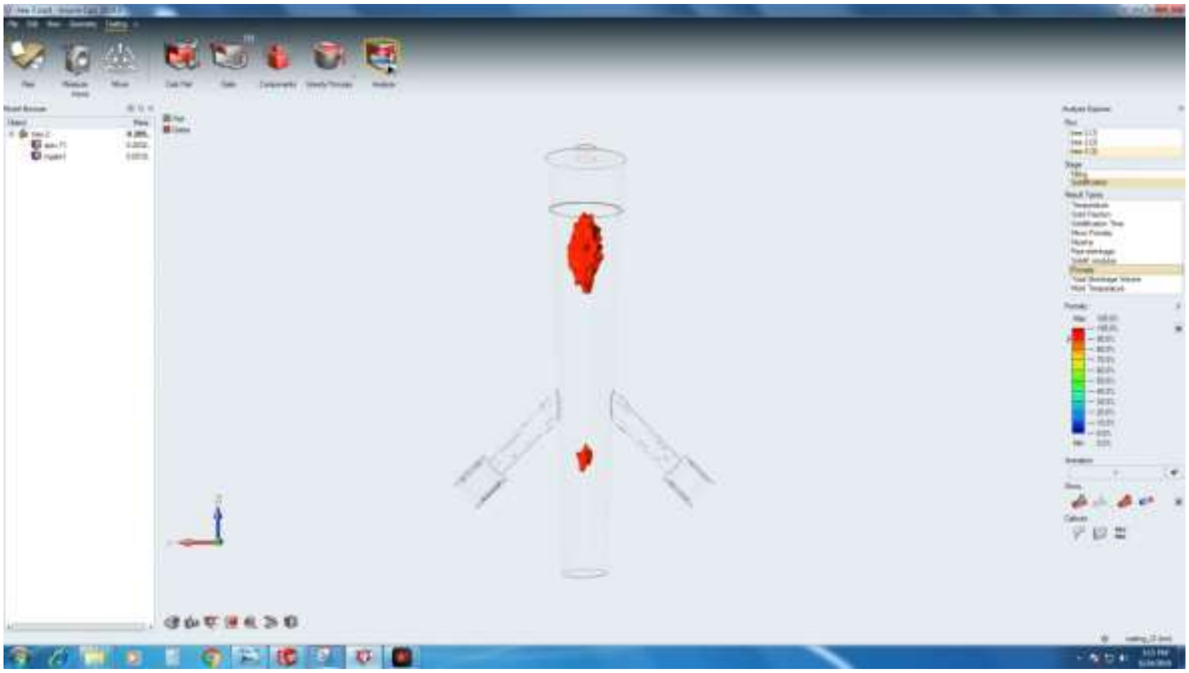


Figure 3.54: Porosity Brass, Temperature 3, Tree 2

Solidification time:

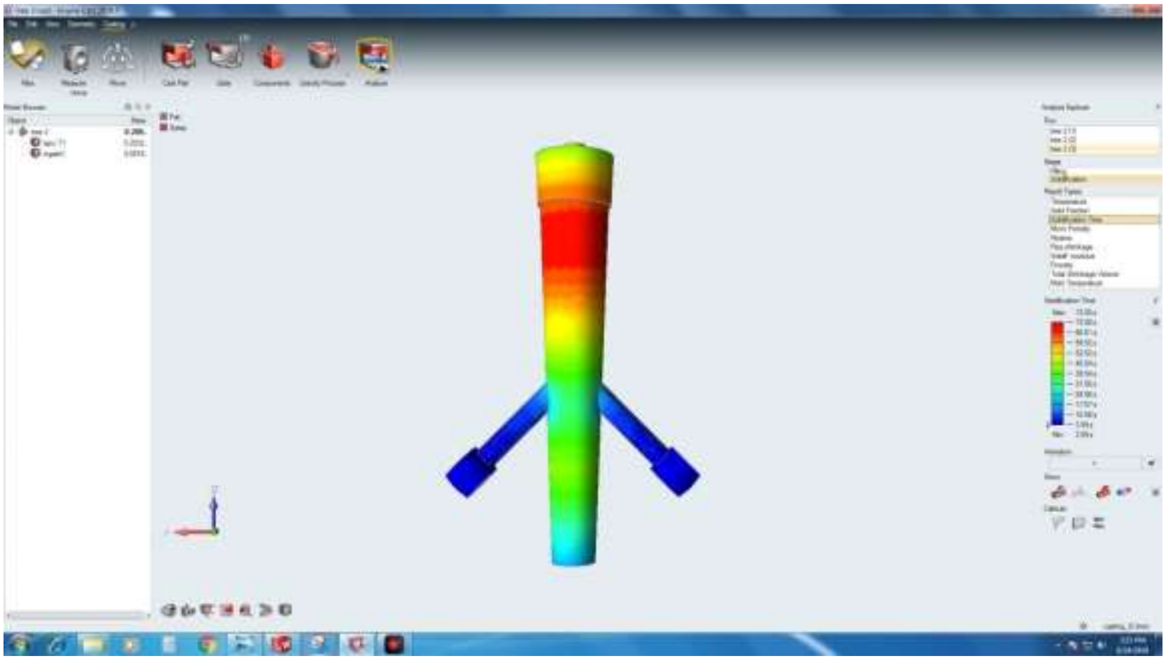


Figure 3.55: Solidification Time Brass, Temperature 3, Tree 2

Total shrinkage volume:

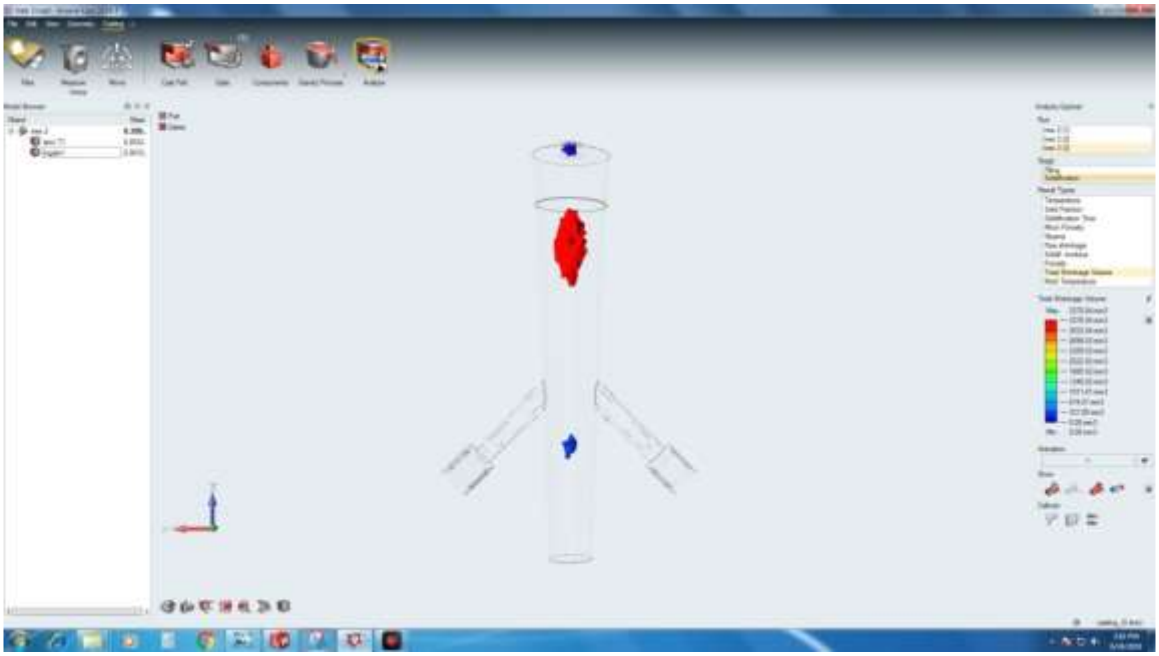


Figure 3.56: Total Shrinkage Volume Brass, Temperature 3, Tree 2

Simulation result of all the simulations is summarized in the table below:

Experiment	Filling Time	Number of Cold Shuts	Porosity in Parts	Solidification Time	Total Shrinkage Volume
A7075, T1(690°c), Tree1	1.5 sec	32.72	0%	196s-362s	0 mm³
A7075, T2(720°c), Tree2	0.95sec	0	0%	199s-404s	0 mm³
A7075, T3(750°c), Tree3	1.2 sec	30	0%	163s-438s	0 mm³
Al5050, T1(690°c), Tree2	0.95 sec	31.88	0%	21s-351s	0 mm³
Al5050, T2(720°c), Tree3	1.25 sec	30.15	0%	22.38s-360s	0 mm³
Al5050, T3(750°c), Tree1	1.25 sec	0	0%	22.44s-346s	0 mm³
Brass, T1(910°c), Tree3	1 sec	6.32	0%	3.57s-68.88s	0 mm³
Brass, T2(920°c), Tree1	1.5 sec	15.22	0%	3.58s-61.20s	0 mm³
Brass, T3(930°c), Tree2	0.95 sec	0	0%	3.59s-73.50s	0 mm³

Table 3.1: Simulation Results

Hence from simulation results it can be easily seen that solidification is tree 2 is slower that rest of trees hence, it is the best tree among the three used during this work as metal gets enough time to reach to cavities without starting cooling. Following are the best combinations according to simulation results:

1st: Brass, Temp 3 (930°c), Tree 2

2nd: Al1 (A7075), Temp 2 (720°c), Tree 2

3rd: Al2 (Al5050), Temp 3 (750°c), Tree 1

3.3. Microscopy:

Microscopy was done after cutting parts from different sections and then doing Bakelite Mounting samples were observed under microscope to get picture at 20x zoom. Following are the pictures of experiment Brass, Temperature 3, Tree 2, the part with best quality.

Edge:

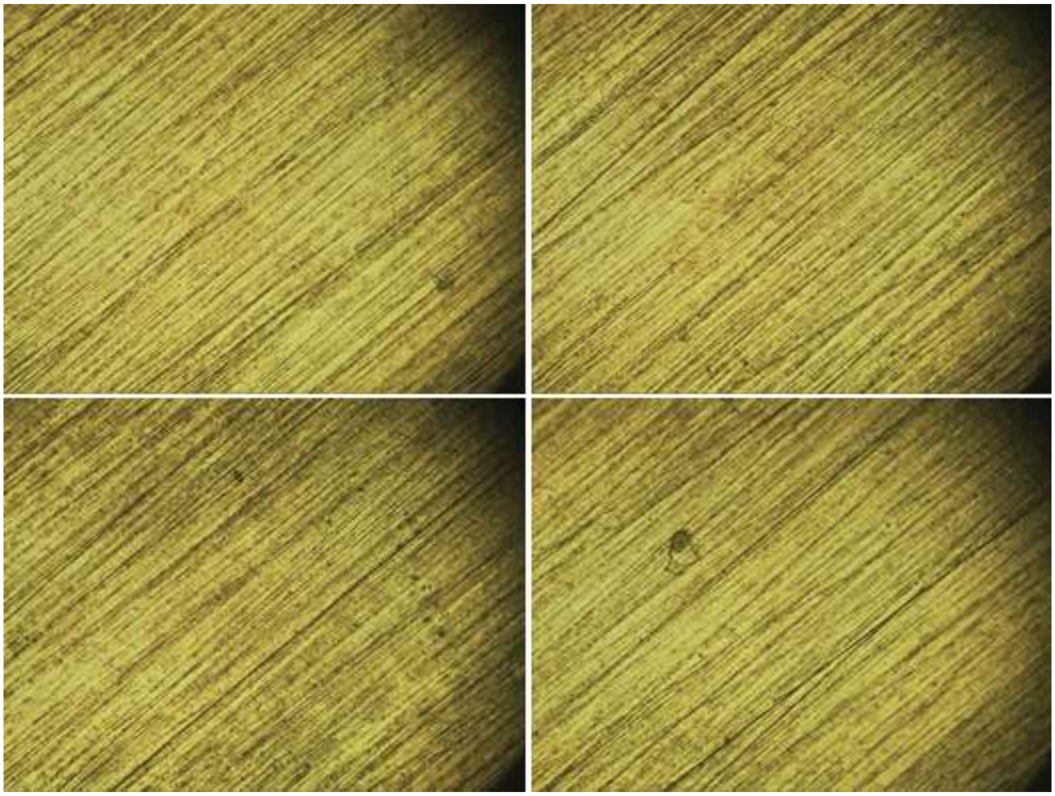


Figure 3.57: Microscopy of edge of part obtained from Brass, Temperature 3, Tree 2

Shaft:

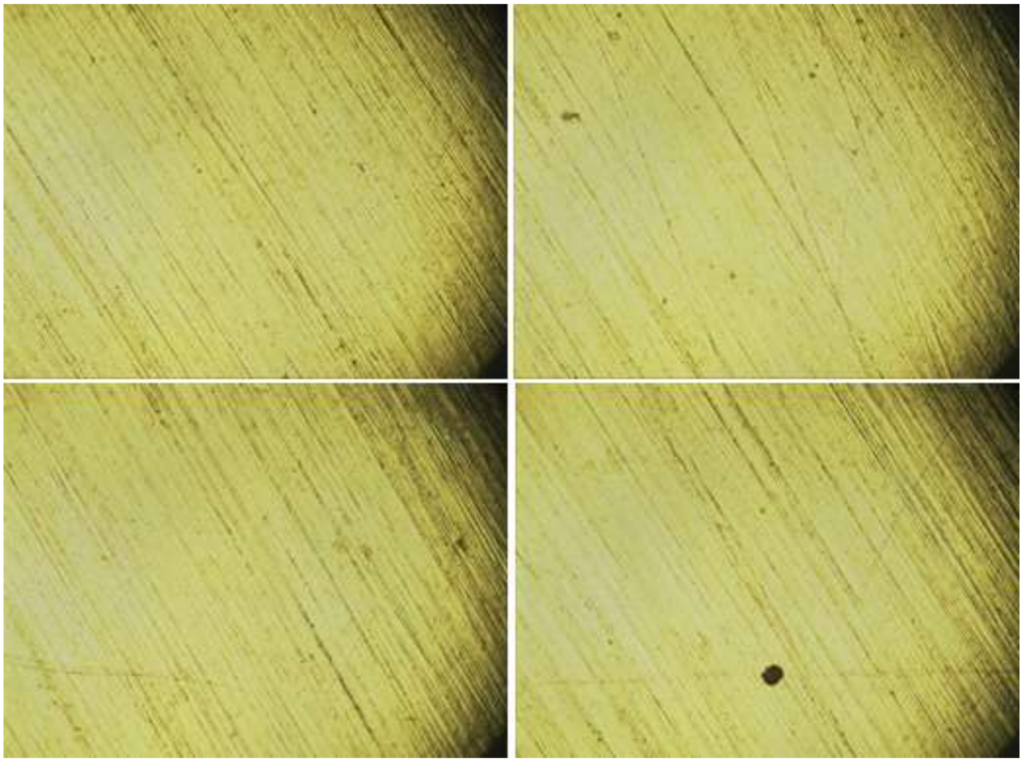
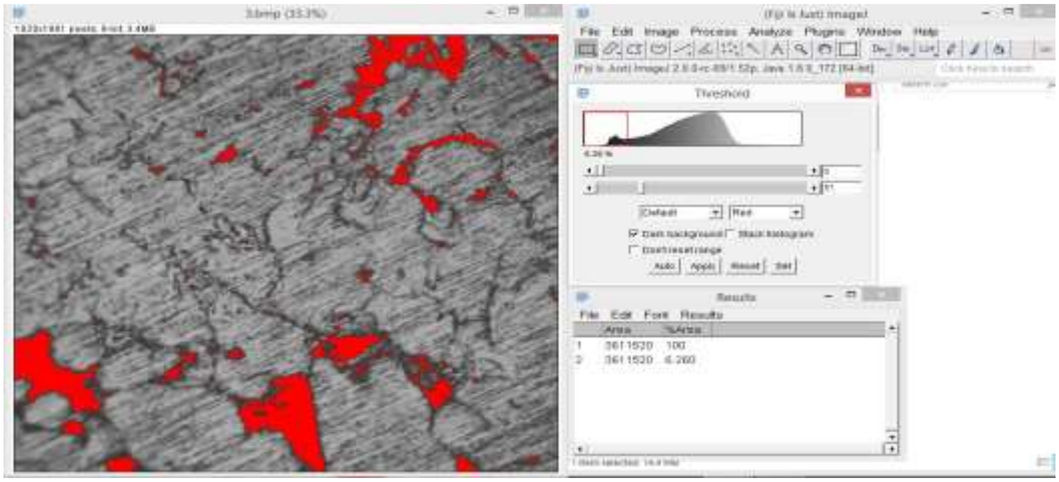


Figure 3.58: Microscopy of Shaft of Part obtained from Brass, Temperature 3, Tree 2

After getting pictures of all the samples obtained from parts after experimentation images are observed in software named as **ImageJ** to find out approximate porosity percentage. An example is showed in figure.



Default | Red

☑ Dark background ☐ Stack histogram

☐ Don't reset range

Auto | Apply | Reset | Set

	Area	%Area
1	3611520	100
2	3611520	6.260

Figure 3.59: Using of Imagej to calculate approximate porosity

Following are the microscopic images of rest of the samples:

Al1 A7075, Temp1, Tree1:

Figure 3.60: Microscopy of edge of part obtained from Al1, Temperature 1, Tree 1

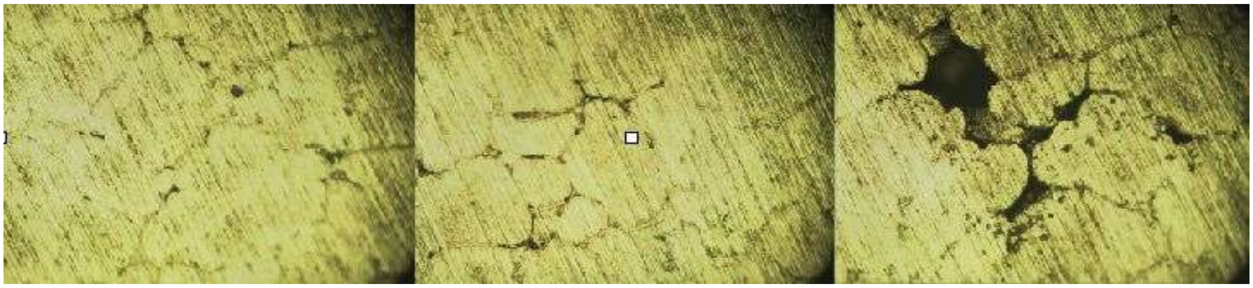


Figure 3.61: Microscopy of shaft of part obtained from Al1, Temperature 1, Tree 1

Al1 A7075, Temp2, Tree2:

Figure 3.62: Microscopy of Edge of part obtained from Al1, Temperature 2, Tree 2

Figure 3.63: Microscopy of shaft of part obtained from Al1, Temperature 2, Tree 2

Al1 A7075, Temp3, Tree3:

Figure 3.64: Microscopy of edge of part obtained from Al1, Temperature 3, Tree 3

Figure 3.65: Microscopy of shaft of part obtained from Al1, Temperature 3, Tree 3

Al2 MRC, Temp1, Tree2:

Figure 3.66: Microscopy of edge of part obtained from Al2, Temperature 1, Tree 2

Figure 3.66: Microscopy of shaft of part obtained from Al2, Temperature 1, Tree 2

Al2 MRC, Temp2, Tree3:

Figure 3.67: Microscopy of edge of part obtained from Al2, Temperature 2, Tree 3

Figure 3.68: Microscopy of shaft of part obtained from Al2, Temperature 2, Tree 3

Al2 MRC, Temp3, Tree1:

Figure 3.69: Microscopy of edge of part obtained from Al2, Temperature 3, Tree 1

Figure 3.70: Microscopy of shaft of part obtained from Al2, Temperature 3, Tree 1

Brass, Temp1, Tree3:

Figure 3.71: Microscopy of edge of part obtained from Brass, Temperature 1, Tree 3

Figure 3.72: Microscopy of shaft of part obtained from Brass, Temperature 1, Tree 3

Brass, Temp2, Tree1:

Figure 3.73: Microscopy of edge of part obtained from Brass, Temperature 2, Tree 1

Figure 3.74: Microscopy of shaft of part obtained from Brass, Temperature 2, Tree 1

Brass, Temp3, Tree2:

Figure 3.75: Microscopy of edge of part obtained from Brass, Temperature 3, Tree 2

Figure 3.76: Microscopy of shaft of part obtained from Brass, Temperature 3, Tree 2

MRC Part:

Figure 3.77: Microscopy of edge of part obtained from MRC

Figure 3.78: Microscopy of edge of part obtained from MRC

After repeating all the process on imagej for all the samples following results are obtained.

Porosity in Edge				
Parameter combination	**Porosity %1**	**Porosity %2**	**Porosity %3**	**Avg Porosity**
Al1 A7075, Temp1, Tree1	2.196	5.5	8.756	5.484
Al1 A7075, Temp2, Tree2	1.552	1.706	1.462	1.573333333
Al1 A7075, Temp3, Tree3	9.162	5.452	6.26	6.958
Al2 MRC, Temp1, Tree2	1.779	1.933	1.673	1.795
Al2 MRC, Temp2, Tree3	5.345	14.409	3.867	7.873666667
Al2 MRC, Temp3, Tree1	3.225	4.924	3.874	4.007666667
Brass, Temp1, Tree3	4.605	5.401	1.892	3.966
Brass, Temp2, Tree1	4.498	4.027	4.543	4.356
Brass, Temp3, Tree2	1.214	0.104	2.155	1.157666667
MRC	9.277	10.65	43.583	21.17

Table 3.2: Porosity in Edge of parts obtained from all experiments

Porosity in Shaft				
Parameter combination	Porosity %1	Porosity %2	Porosity %3	Avg Porosity
Al1 A7075, Temp1, Tree1	2.418	8.514	10.44	7.124
Al1 A7075, Temp2, Tree2	1.418	1.687	1.242	1.449
Al1 A7075, Temp3, Tree3	2.375	2.312	1.319	2.002
Al2 MRC, Temp1, Tree2	0.831	1.001	1.085	0.972333333
Al2 MRC, Temp2, Tree3	1.723	2.844	3.754	2.773666667
Al2 MRC, Temp3, Tree1	3.387	3.23	3.813	3.476666667
Brass, Temp1, Tree3	3.164	2.291	3.47	2.975
Brass, Temp2, Tree1	2.139	1.948	1.958	2.015
Brass, Temp3, Tree2	0.347	1.789	0.463	0.866333333
MRC	9.818	24.134	22.917	18.95633333

Table 3.3: Porosity in Shaft of parts obtained from all experiments

3.5 ANOVA:

The ANOVA technique is also used to show the degree of significance of each process (Tree type, Metal used and Pouring Temperature). parameter influencing results in the Investment Casting process. The significance level is determined by statistical p-value. If the p value is lower than 0.05 then it shows that the power level has a statistically substantial effect on the responses.

Source	DOF	Adj SS	Adj MS	F- Value	P- Value
Metal	2	0.05248	0.02624	0.02	0.977
Pouring Temperature	2	0.22926	0.11463	0.10	0.905
Tree	2	5.64864	2.82432	2.58	0.280
Error	2	2.19302	1.09651		
Total	8	8.12340			

Table 3.4: ANOVA of 1st run

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Metal	2	8.080	4.040	0.72	0.582
Pouring Temperature	2	5.459	2.729	0.49	0.673
Tree	2	14.749	7.374	1.31	0.433
Error	2	11.250	5.625		
Total	8	39.538			

Table 3.5: ANOVA of 2nd run

Source	DOF	Adj SS	Adj MS	F-Value	P-Value
Metal	2	8.565	4.283	0.48	0.676
Pouring Temperature	2	17.207	8.604	0.96	0.510
Tree	2	30.224	15.112	1.69	0.372
Error	2	17.880	8.940		
Total	8	73.877			

Table 3.6: ANOVA of 3rd run

Following table is telling about the S/N ratio of the experimentation

Experiment	S/N Ratio	Mean	StDev	Ln(StDev)
A7075, T1(690°c), Tree1	12.3447	1.44367	0.73081	-1.18453
A7075, T2(720°c), Tree2	13.1396	6.16422	3.07156	0.27223
A7075, T3(750°c), Tree3	5.9206	2.96711	1.20181	0.32517
Al5050, T1(690°c), Tree2	17.3654	3.47133	0.80837	-0.88736
Al5050, T2(720°c), Tree3	17.2366	1.81389	-0.09886	-1.14276
Al5050, T3(750°c), Tree1	12.8600	1.93744	0.73888	-1.19596
Brass, T1(910°c), Tree3	9.8702	2.96967	1.11850	-0.18027
Brass, T2(920°c), Tree1	9.2041	-0.09344	-0.31503	-1.38163
Brass, T3(930°c), Tree2	20.7997	2.98011	0.71698	-1.38137

Table 3.7: S/N ratio of the experimentation

Higher the S/N ratio better the combination of parameters is. So from the results obtained from microscopy it can be easily seen that Brass, Pouring Temperature 3 i.e.: the upper limit of pouring temperature of the metal and Tree 2 are best parameter combination for the experiment. Also porosity in all of the experiments is less than the porosity in part which was previously made in MRC by investment casting.

Following graphs are obtained after ANOVA and S/N ratio:

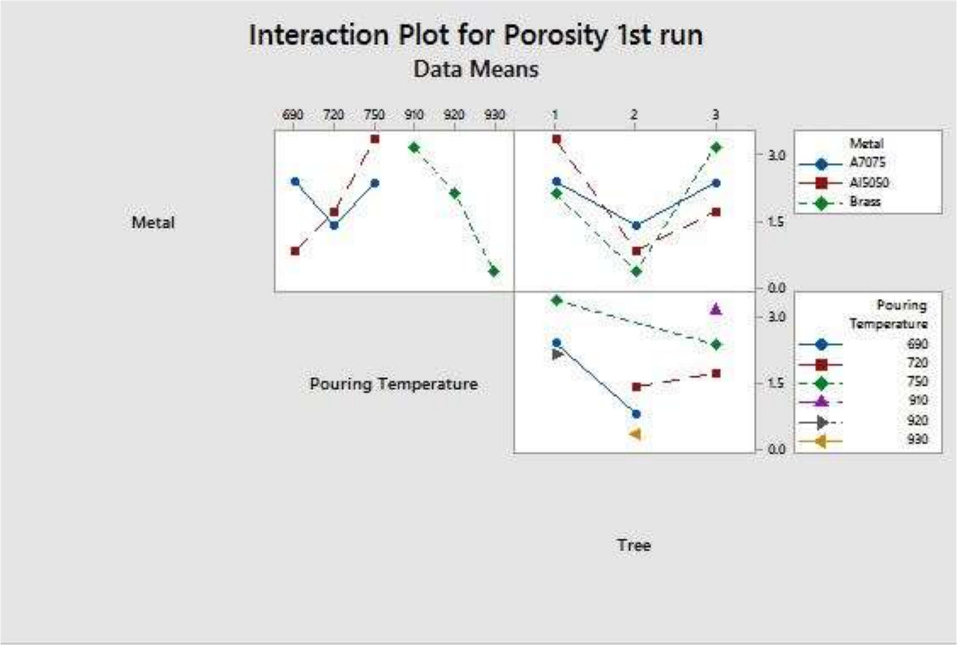


Figure 3.79: Interaction Plot for Porosity in 1st run

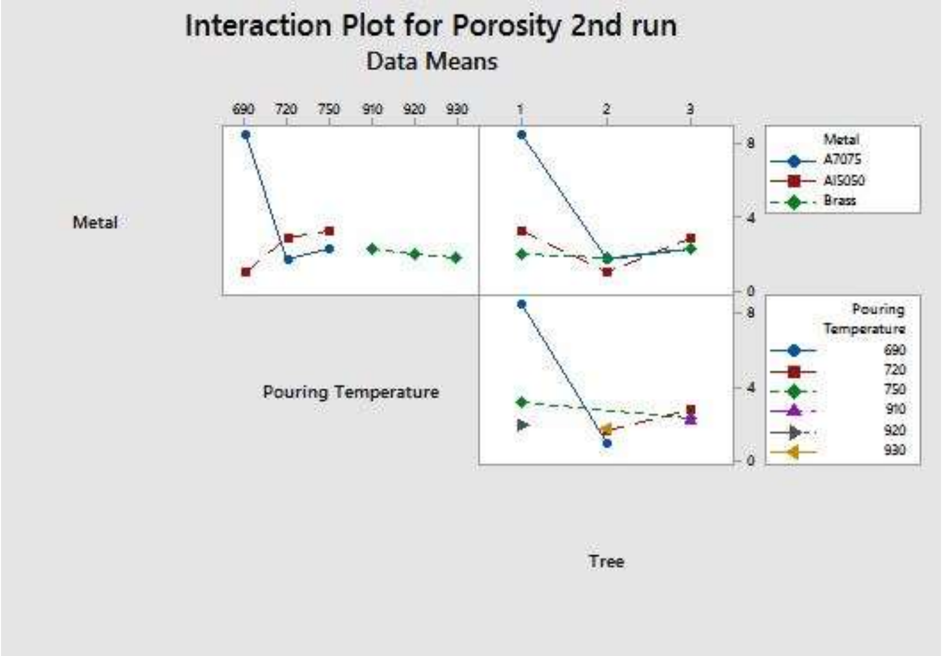


Figure 3.80: Interaction Plot for Porosity in 2nd run

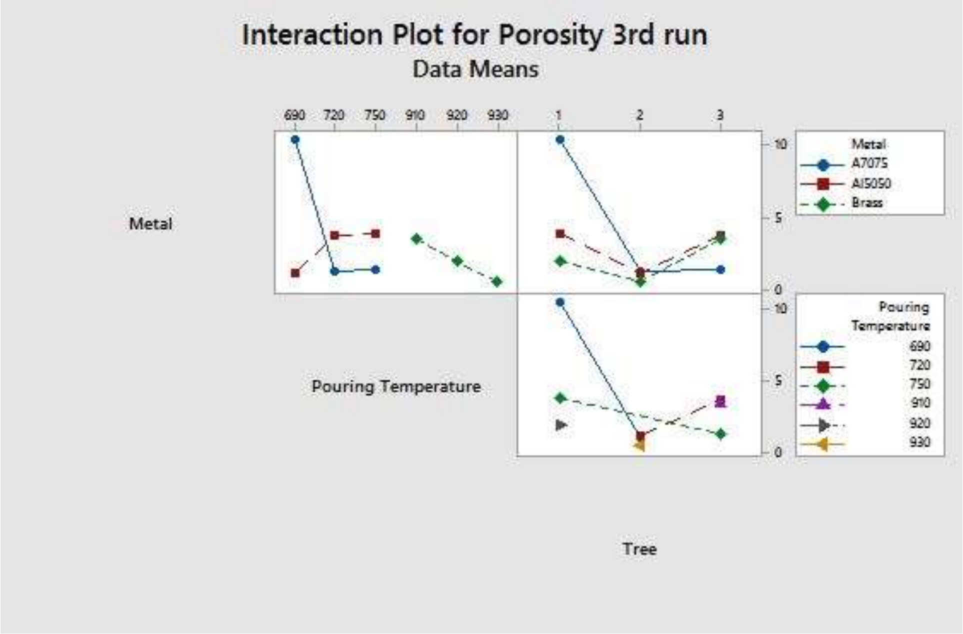


Figure 3.81: Interaction Plot for Porosity in 3rd run

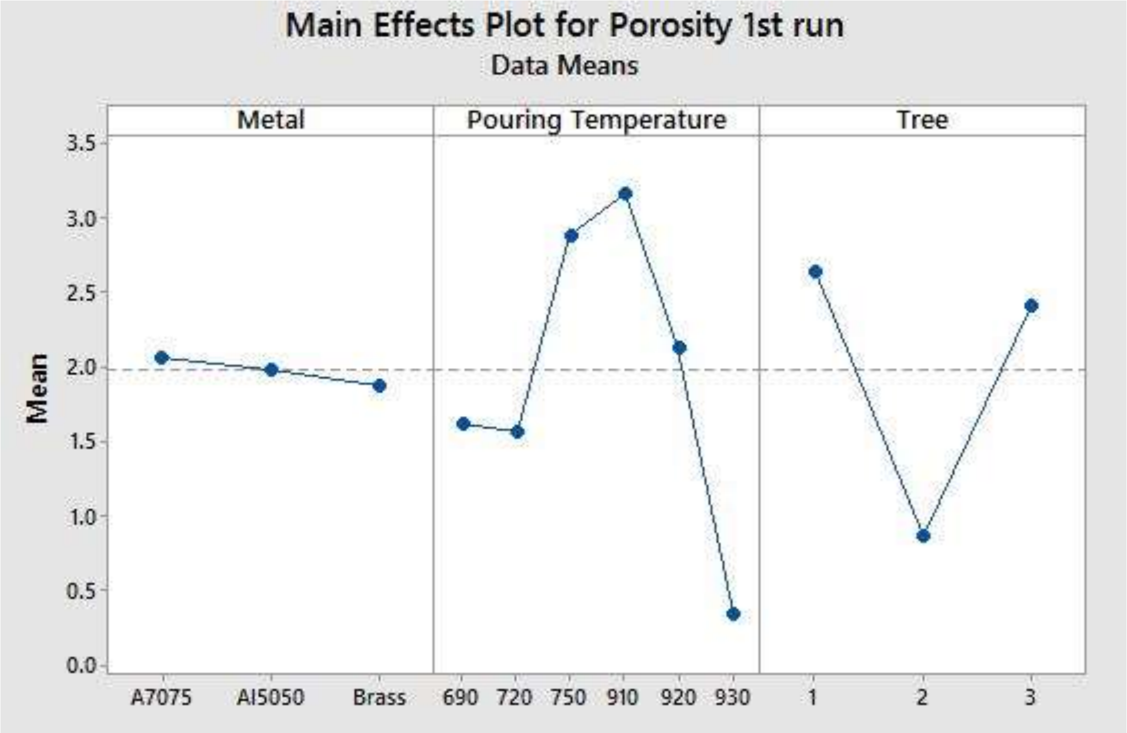


Figure 3.82: Main Effects Plot for Porosity in 1st run

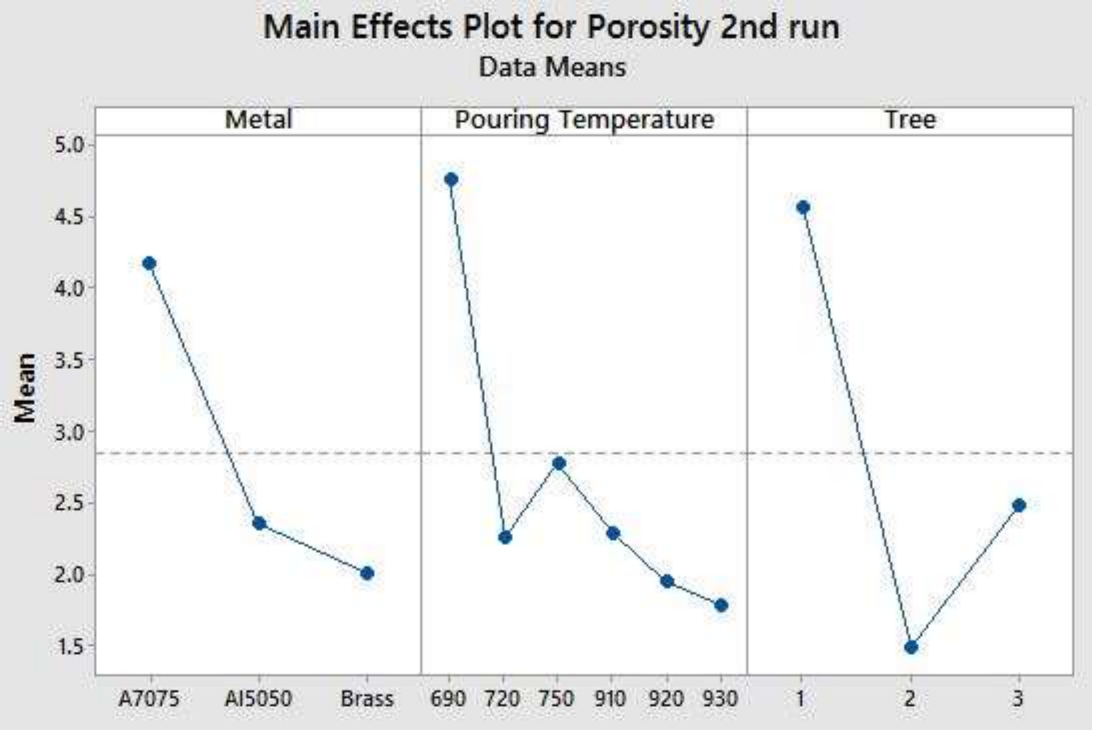


Figure 3.83: Main Effects Plot for Porosity in 2nd run

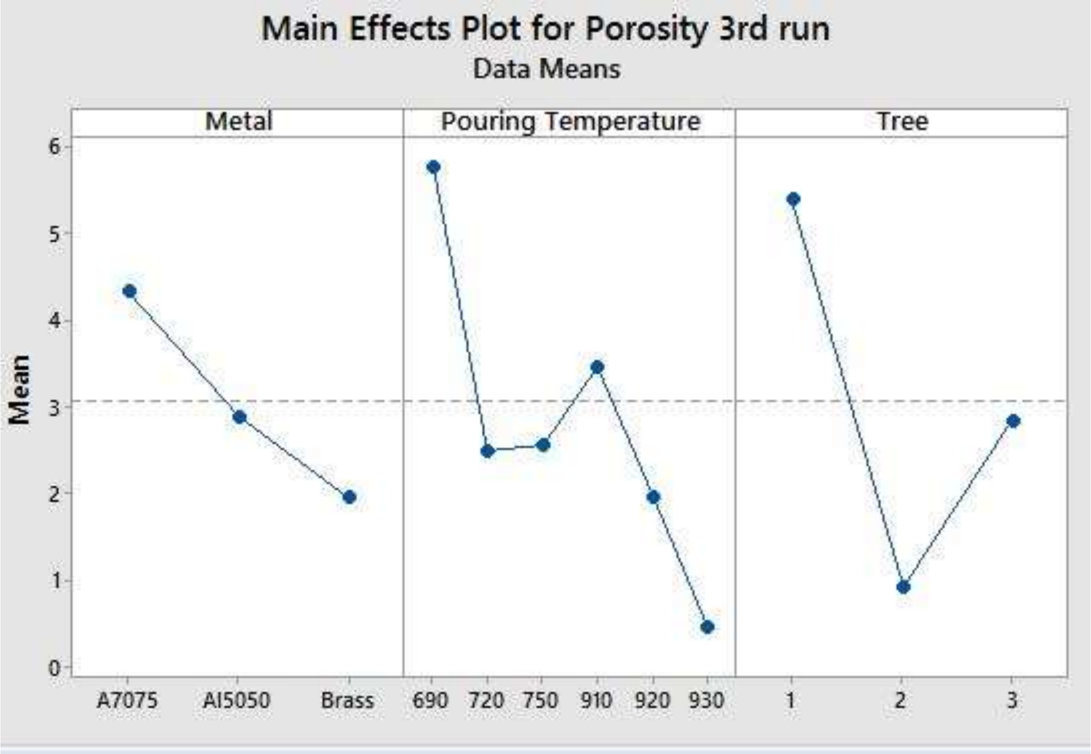


Figure 3.84: Main Effects Plot for Porosity in 3rd run

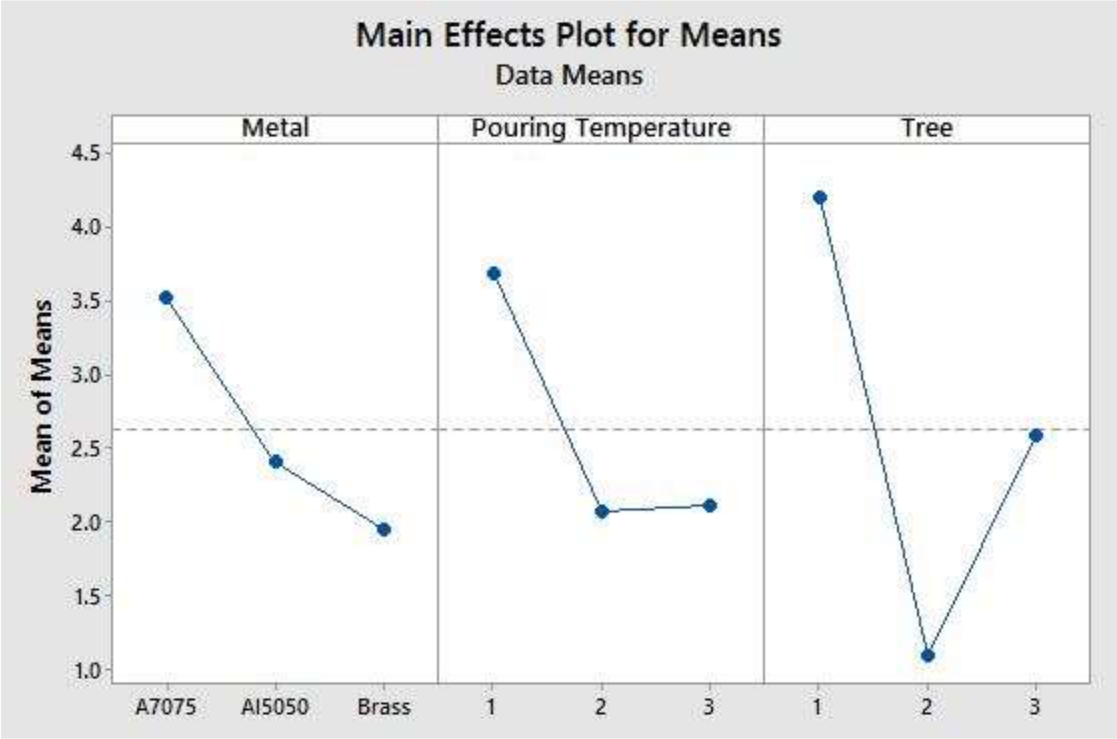


Figure 3.85: Main Effects Plot for Means

Following are the best Parameters combination according to Experimentation Results:

1st: Brass, Temp 3 (930°c), Tree 2

2nd: Al1 (A7075), Temp 2 (720°c), Tree 2

3rd: Al2 (Al5050), Temp 1 (690°c), Tree 2

3.6 Results Summary:

Following is the comparison between results obtained from simulation and Experimentation:

No.	**Combinations**	
	Simulation	Experimentation
1st	Brass, Temp 3 (930°c), Tree 2	Brass, Temp 3 (930°c), Tree 2
2nd	Al1 (A7075), Temp 2 (720°c), Tree 2	Al1 (A7075), Temp 2 (720°c), Tree 2
3rd	Al2 (Al5050), Temp 3 (750°c), Tree 1	Al2 (Al5050), Temp 1 (690°c), Tree 2

Table 3.8: Simulation and Experimentation results comparison

Chapter4: Discussion and Future Work

4.1. : Discussion:

Results obtained from simulation is showing that solidification is tree 2 is slower that rest of trees hence, it is the best tree among the three used during this work as metal gets enough time to reach to cavities without starting cooling. And simulation results are showing that A7075 is a good material for casting due to its slower solidification time which allows metal to reach every cavity before solidification starts. While due to limited resources Brass gave good results. And the upper limit of pouring temperature is good as it also prevent pre-mature solidification of metal. And Tree 2 is also showing good results as compared to rest due to less porosity and slower solidification time.

4.2.: Future Work:

In future more work could be done on tree design as there is very less work done in the area of tree design for complex parts. And also to increase quality and productivity the layout of equipment related to investment casting should be in such a way that minimum heat losses could occur.

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