



# Computer Modeling Verification of Microcellular Injection Molding process using Physical Blowing Agents

Master thesis

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2. Overview of computer modeling of microcellular injection process. Software limits, advantages, disadvantages.
3. Computer modeling of microcellular injection molding process.
4. Realization of microcellular injection molding process.
5. Verification of computer modeling and microcellular injection molding process.
6. Conclusions.

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- [1] Heim, H. P. *Specialized Injection Molding Techniques*. 1st Edition, Published by: William Andrew Oxford, UK, 2013. p. 265. ISBN 978-0-323-34100-4.  
[2] JINGYI XU. *Microcellular Injection Molding*. Published by: Wiley, Jon Wiley & sons, New Jersey, Canada, 2010. p. 618. ISBN 978-0-470-46612-4.  
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**Annotation:**

The work deals with comparison of the result of CAD mould 3D F Simulation software with Actual process of foaming by using Mucell Technology.

The challenge is to set the optimize process parameter from actual process and keep the same in to simulation software by making same CAD model. The aim is to verify the quality of the results from simulation software, thereby realizing the benefits of software Cad mould 3D F for industrial practice.

**Keywords:**

Injection, Cad mould 3D F, MuCell technology,

## **Preface**

I don't know which force has helped me throughout my whole academic journey to accomplish my work in the best way.

Though had so many obstacles and challenges yet I have done until this just because of the support of each person who was concerned about it. I must thank to all those who have helped me in a different ways. During this journey I have enjoyed with them and have learned great things about various aspects of polymers and its foams, for which I am grateful.

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## Short cuts

CAE	Computer Aided Engineering, Broad usage of computer software to aid in engineering analysis task
Cad mould@3D F	CAE software Synthesis to simulate and analyze the process of plastic
MOLDEX 3D	CAE software for analysing plastic injection process
CATIA	Computer Aided Three Dimensional Interactive application
STL	Steoerolithography, CAD software created by 3D system
MuCell	Micro cellular Injection Moulding technology
STP	Abbreviation in standard temperature and pressure
PBA	Physical blowing agent
CBA	Chemical blowing agent
SCF	A supercritical fluid is any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. It can effuse through solids like a gas, and dissolve materials like a liquid.
CNT	Classical nucleation theory, theoretical model used to understand why nucleation may take hours or years, or in effect never happen.
Injection speed (cm <sup>3</sup> /s)	After the required amount of molten plastic is accumulated, injection process is started. While molten plastic is flowing in a mould, the machine controls the moving speed of the screw, or injection speed
Holding pressure(Bars)	After filling the cavity, a holding pressure is maintained to compensate for material shrinkage.

## **1. Introduction:**

No one can imagine the world without plastics. Plastic plays a very significant role in almost every field. Plastic holds special kind of properties which makes it more demanding in today's world. Due to revolution in technology so many different ideas have been introduced for making light weight product out of plastic though they are comparatively lighter in weight than other materials like metal, ceramics, glass etc.

The idea about to make foam structure of plastic it is not new. The researcher has been doing the research since 1990s. So many researches have been done until now to make light weight product. There are different techniques and methods through which one can make foam part of plastic. Among them, Micro cellular injection moulding process so called MuCell technology which is by far the most used technology for foaming of plastic parts. This technology is typical for physical blowing agents by which foaming is created. It was first developed by Dr. Nam Shu and his Co-worker at MIT, USA during the year 1980s. The main unique feature of this technology is to make foam for complex geometry with better dimensional stability and mass reduction.

Today, engineer wants to know the future model of the product's behaviour before actual process gets done. This thought of engineer developed the idea of making the software which can predict the future product so called Simulation. Nowadays, it is used almost everywhere especially in the field of research. In plastic field, simulation also helps to predict the distribution of cell, cell size, density throughout the part, weight and so on. Cad mould 3D F is one of the most widely used simulation software. It is well known in Europe due to its own 3d frame patented method, flexibility and reliability.

In my experiment, I made the foam product by using MuCell technology and got the result from Cad mould 3D F simulation software by keeping the same process parameter. My task was to compare both the result and made evaluation if the simulation can predict nearly the same result like actual process or not. Especially for foaming parts, size of the cell and density are dominant factor to makes it more durable and flexible. So, I measured the value of both of them and made the conclusion about how simulation can helps us and which areas of the simulation part should be improved.

## 2. Theoretical part

Theoretical part is divided into several parts. The first is about Micro cellular injection molding process. The second is about the materials and in the last; the problem of simulation software was discussed.

### 2.1 Microcellular Injection Moulding Process:

Micro cellular injection moulding process has been widely analysed in the last decades. Micro cellular plastics are generally made by cell nucleation and growth of bubbles in the polymer matrix. Physical blowing agents (PBA) or Chemical blowing agents (CBA) are dominantly used to introduce gas that creates the cellular structure.

Microcellular polymeric forms are produced by two main processes depending on the way to introduce the gas into polymer matrix. Chemical blowing agents (CBA) are capable of liberating gaseous component via chemical reaction or thermal decomposition. Generally, CBAs produce nitrogen (N<sub>2</sub>) or carbon dioxide (CO<sub>2</sub>) after decomposition. CBAs reactions can be endothermic or exothermic. Most exothermic CBAs, such as azodicarbonamide, generate N<sub>2</sub> upon decomposition. In contrast, the primary gas generated from endothermic CBAs, such as sodium bicarbonate and citric acid, is CO<sub>2</sub>. Exothermic CBAs tend to decompose more readily than endothermic CBAs because the heat generated upon their decomposition can trigger the decomposition of the neighbouring CBA particles in a chain like effect. A clear advantage of chemical blowing agents is the simple volumetric dosage, the possibility to use standard injection moulding equipment and to achieve an even distribution of gas in the polymer matrix. However, it has many cons due to which it is not applicable easily. CBAs generate bubbles which are larger than that obtained with PBA results in lowering the mechanical properties and also they are more expensive than PBAs [1, 2, and 3].

In comparison with suitability of requirement sets for PBAs, more precise requirement sets are needed for CBAs. This is due to chemical reaction or heat is involved, so that the dispersion of the blowing agent throughout the melt and the heat sensitivity of the polymer impose serious concerns that aggravate the processing of polymeric foams using CBAs. In addition to, CBAs possess a decomposition temperature 100°C above the melting point of the semi crystalline polymers. Removing the extra heat usually becomes a serious problem with processing condition. Apart from this, Decomposition of CBA depends both on the processing thermal profile and the residence time under the decomposition temperature. If it requires too high temperature to trigger its decomposition, or takes too much time to complete the decomposition reaction, it will be extremely difficult to incorporate to the plasticator. Because

of these problems, CBAs are having limited use for the foaming of thermoplastic materials [1, 2, and 3].

In contrast the usage of PBAs does not have the problems which can be faced by using CBAs because the use of supercritical fluid does not require any decomposition process and thus it is easy to handle reaction during foaming. Also there are no deposits or solid residues remaining in the part which means that the range of applications of physically blown parts includes food packaging and medical products. In physical foaming agents, the gases are introduced directly into the barrel of an extruder or of the plasticising unit of an injection moulding machine, in the polymer matrix. This method, (Mucell® process), has been extensively analysed by Park and Tomasko. Several types of PBAs such as CO<sub>2</sub>, N<sub>2</sub>, Chlorofluorocarbon or argon have been used with different polymer resins such as polypropylene, polyethylene, polystyrene. Although PBAs can be employed both in extrusion and injection process, the foaming injection process using CO<sub>2</sub> or N<sub>2</sub> commonly used. Though processing with PBAs demanding machinery and process control. A special kind of set up must be installed to the injection moulding machine which adds initially high level of investment cost. Numerous investigations and reports that compare chemical and physical foaming have been prepared in the past, with partially different conclusions. Apart from the component surface quality, physical foaming tended to be slightly better [2].

## **2.2 Fundamentals of Physical foaming process:**

Polymeric foam prepared by the formation of gas bubbles in a liquid system which followed by the growth and stabilization of bubbles due to this the viscosity of the liquid polymer increase which in turn makes solid cellular resin matrix.

Fundamentally process involves the use of blowing agent which is injected to the polymer melt. At certain temperature and pressure the solution is obtained as single phase mixture. And this mixture is injected into the mould. During this process the pressure is dropped from its initial level to atmospheric pressure. Because of it gas separation into the polymer melt nucleation is taken place. Finally these nuclei grow up to the stable state. Four dominant stages are involved in foaming process,

- Generation of single phase mixture of Polymer melt with gas
- Nucleation of cells
- Growth of cells
- Cell stabilization

### **2.2.1 Generation of single phase mixture of polymer melt with gas:**

A single-phase polymer-gas mixture is required to create a homogeneous foam structure. The basic prerequisite for creation of a homogeneous foam structure is dissolving of the gas in the polymer melt. The solubility of gas in polymer melt relies on the interaction between polymer and gas, as well as between temperature and pressure in the cylinder. The amount of gas that can be dissolved in a polymer varies depending on the type of polymer and blowing agents. The maximum amount of gas that can be dissolving in the polymer melt at given condition is known as saturation concentration. The process parameter should be harmonized in order to dissolve certain gas concentration in the polymer melt. Excess or undissolved gas leads to formation of large cavities in the foam structure. Furthermore diffusion also plays a crucial role for solubility of gas in to polymer melt to make single phase of polymer melt-gas-solution. A high local concentration of gas molecules cause to an exceeding solubility of gas in the polymer and separate gas phase can be observed. For this the gas should be distributed as evenly as possible in the polymer melt [4, 5].

### **2.2.2 Nucleation of cells:**

Once the first stage, single phase solution is achieved, the second stage requires attention on nucleation and cell growth. Nucleation is the process of formation of small bubbles in different phases. Formation of foam pore structure is started during the nucleation process.

A variety of different nucleation phenomena do exist. The classical nucleation theory (CNT) is widely used as the basis for the development of a model of other nucleation mechanisms. CNT can be divided into three types: Homogeneous, Heterogeneous, a combination of two which has been referred to as mixed mode. When nucleation formation takes place in fully homogenous melt without any impurities or additives called homogenous nucleation. On the other hand if polymer gas mixture contains impurities, additives or blowing agent then nucleus formation occurs on the surface between particles and solution is called heterogeneous nucleation. [5, 6, 7]

Classical nucleation theory is based on three basic principle outlined by Kumar:

- The probability of nucleation is directly proportional to an exponential function,  $\exp(-W^*/kT)$ , Where  $W^*$  is the minimum work required to make the system unstable and to generate large number of bubbles in a continues phase. Einstein first proposed this relationship in 1930.
- Fluctuation that create a stable nucleus form and decay by the same path.

- In 1931, Onsager developed an idea that applies microscopic laws to microscopic entities such as bubble embryos containing cluster of gas molecules.

Based on these principles the steady and transient rates of nucleation are given as:

$$J_s = Z\beta^* N \exp\left(\frac{-\Delta G^*}{kT}\right)$$

$$J(t) = J_s \exp\left(\frac{-t}{T}\right)$$

Where,

J= Nucleation rate (nucleus/cm<sup>3</sup>-s)

S= Steady state

T= Transient state

Z= Zeldovich non- equilibrium factor

$\beta^*$  = Rate at which gas molecules are added to the critical nucleus

N =Number of nucleus sites per unit volume

$\Delta G^*$  = Gibb's free energy of forming a critical nucleus

kT= Boltzmann's constant times absolute temperature

$\tau$  =Induction period for establishing steady state nucleation condition

These variables change based on the type of nucleating system and process condition. All variables must be checked on an individual basis to fit real life application [8].

- **Homogeneous Foam Nucleation:**

Homogeneous nucleation characterizes the formation of second phase (e.g. a gas bubble) in the primary phase. Homogeneous nucleation starts when a sufficient number of dissolved gas molecules form cluster for a long enough time to make a critical bubble radius to cross over the resistance path. As shown in figure 1.

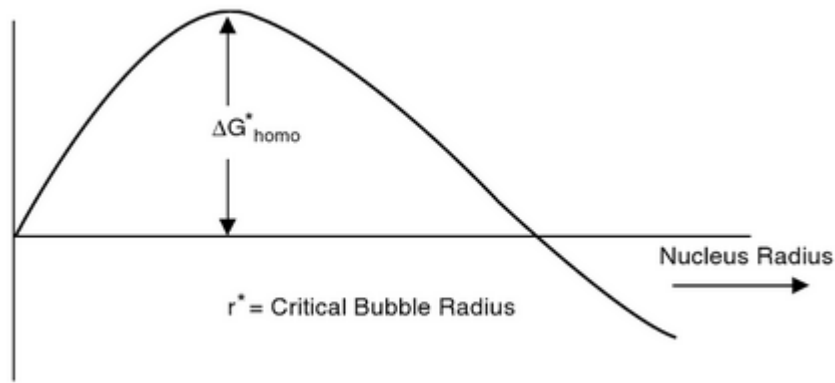


Fig.1: Homogeneous bubble nucleation

Figure 2.A shows single phase containing molten polymer saturated with gas at certain pressure. Figure 2.B Shows the formation of second gas phase when the pressure is reduced from  $P_o$  to  $P_s$ .

Thermodynamic instability is responsible for the nucleation of tiny bubble. Due to the bubble formation new surface with certain volumes generates. Generally, the nucleus are in spherical in size because if this easier mathematical expression can be derived based on thermodynamic principle [9]

The homogeneous nucleation, as per the equation of Gibbs free energy,

$$\Delta G = \frac{-4}{3} \pi r^3 \cdot \Delta P + 4 \pi r^2 \sigma$$

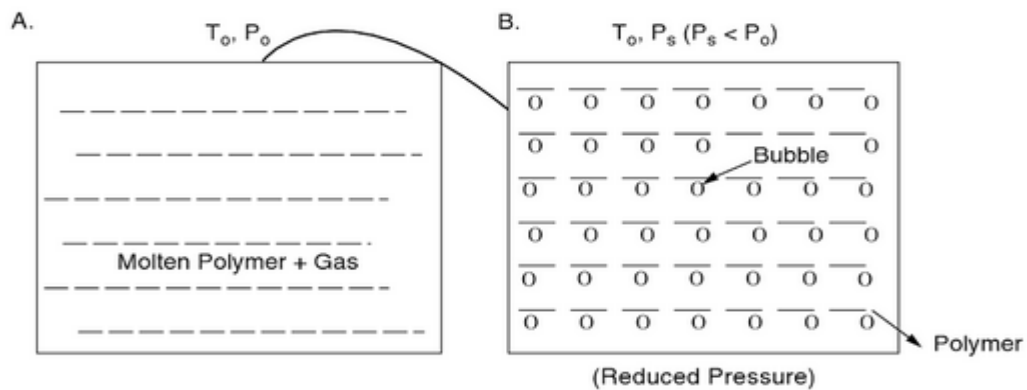


Fig.2: Typical nucleation process:  $T_o$ = temperature  $P_o$ = Initial pressure (Higher than surrounding pressure)  $P_s$ = Final pressure or surrounding atmospheric pressure

Where  $r$  is the bubble radius;  $\Delta P$  is the pressure drop,  $\sigma$ = Surface tension of polymeric matrix, the maximum value of  $\Delta G$  is denoted as  $\Delta G^*$ , occurs at critical size  $r^*$  or when there is a critical number of gas molecules in the embryos and represent the free energy of formation of the critical nucleus. If we differentiate free energy term with respect to radius and set it equal to zero, the result becomes,

$$\frac{\partial \Delta G}{\partial r} = 0$$

Which gives an expression of critical radius,  $r^*$ :

$$r^* = \frac{2\sigma}{\Delta P}$$

The shape of nucleus assumes to be spherical to represent minimum resistance for a given volume. In general such an assumption is reasonable. But in polymeric system nonspherical geometries might be encountered. The activation free energy for homogeneous nucleation of critical nucleus is derived as,

$$\Delta G_{\text{homo}} = \frac{16\pi\sigma^3}{3\Delta P^2}$$

Where  $\sigma$  is the surface tension of polymer,  $\Delta P = P_{\text{sat}} - P_s$  is the super saturated pressure. For batch microcellular process system,  $P_{\text{sat}}$  is the gas saturation pressure and  $P_s$  is the gas surrounding pressure at which nucleation is to occur. Generally,  $P_s$  is equal to atmospheric pressure.

It is assumed that gaseous foaming agents often makes polymer soften and because of this surface tension of polymer may decrease or increase based on the foaming agent dissolved in it. So that such effects must be taken in to account when predicting real life example. Since the activation energy term has been calculated, the nucleation rate expression can be calculated based on the classical nucleation theory equation. According to Colton and Suh, the homogeneous nucleation in gas polymer system is given by,

$$N_{\text{homo}} = f_o C_o \exp\left(\frac{-\Delta G_{\text{homo}}^*}{kT}\right)$$

Where  $f_o$  is a frequency factor for the rate at which gas molecules join a critical nucleus, and  $C_o$  is concentration of gas molecules. We can see from the equation that when the degree of supersaturation is increased both critical radius and critical free energy decreased. Physically this means that a greater amount of gas in the polymer makes it easier for bubbles to form. Similarly higher the pressure drop, the higher the nucleation rate of bubbles [8].

- **Heterogeneous Foam Nucleation:**

The most common type of nucleation found in polymer systems is heterogeneous nucleation which contains additives. The efficiency of producing bubbles depends on several factors such as type and shape of nucleating particles and interfacial tension of solid and solid gas interface. In 1975, Blander and Katz proposed a simple heterogeneous nucleation models for liquids. The primary benefits come from the interface, which act likes a catalyst for



nucleation. For achieving stable nucleus, the presence of tiny particles and cavities helps to reduce the activation energy. Figure shows reduction of Gibbs free energy associated with the heterogeneous nucleation process [8].

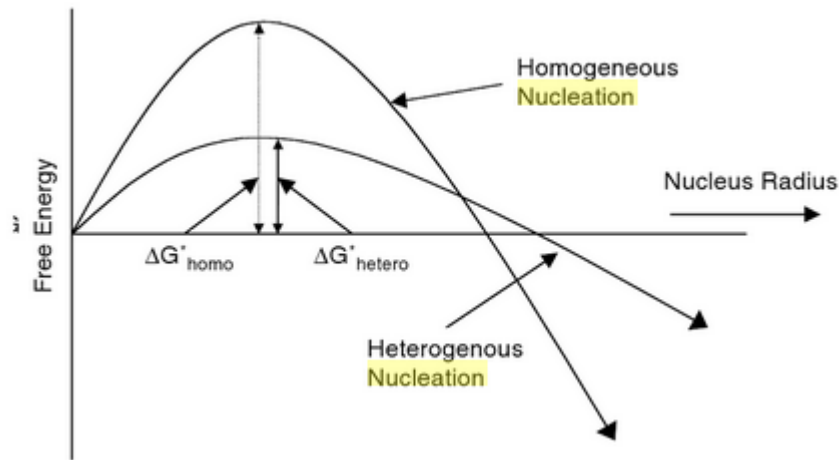


Fig. 3: Heterogeneous bubble nucleation  $\Delta G^*_{hetero} < \Delta G^*_{homo}$

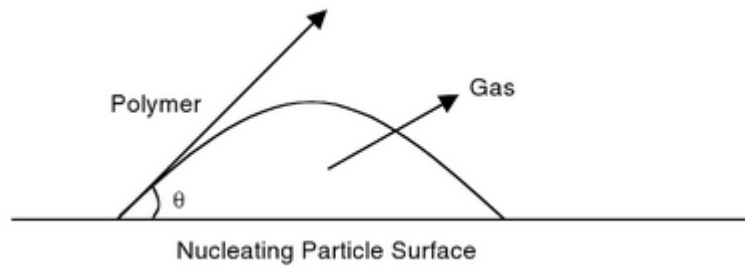


Fig.4: Schematic of nucleating particle interaction with gas and polymer

The thermodynamics of heterogeneous nucleation and its mathematical analysis are given in Uhlmann and Chalmers. The heterogeneity factor can be used to correct the activation energy term derived for homogeneous nucleation as showing in following:

$$\Delta G^*_{hetero} = \Delta G^*_{homo} f(\theta)$$

For the configuration shown in figure Uhlamm and Chalmers derived and expression for  $f(\theta)$  as

$$f(\theta) = \frac{(2 + \cos \theta)(1 - \cos \theta)^2}{4}$$

$$\Delta G^*_{hetero} = \frac{16\pi\sigma^3}{3\Delta P^2} f(\theta)$$

Where  $\theta$  is the wetting angle,  $f(\theta)$  is the heterogeneity factor and  $\sigma$  represent the interfacial tension of polymer gas bubble [9].

### 2.2.3 Growth of cells:

Bubble growth is the dominant step in polymeric foaming processes. The mechanical properties of foam polymers are closely connected with the size of the bubbles created inside the material. However, cell growth is a phenomenon that is not fully understood. Considering the classical theory, it suggests that the growth is controlled by diffusivity of the gas and by the stiffness of the substrate. The critical size of the bubble is relying on the temperature because of the vapour tension. In general, critical size of the bubble is inversely proportional to the difference between the vapour pressure and the liquid pressure. The critical size of bubble decreases with increasing the temperature because of the increased vapour pressure. Due to this reason, small bubbles are created and begin to grow at high temperatures of polymer melt. Another phenomenon occurs simultaneously with the opposite effect. The viscosity will also fall down with increasing of the temperature, increasing the diffusivity of the gas in the polymer. As a result of this effect, the possibility of a collapse of the bubbles increases (cell density decreases).

According to the Laplace's law, the gas pressure required to maintain a small bubble is higher than that of a bigger bubble. Therefore, the gas tends to diffuse from the smaller bubble to the larger one. Because of this small bubble will collapse and confirming the tendency that if they have enough time, the small bubbles will disappear. During the year 2009, Moon et al. found a theoretical framework to improve bubble growth rate and size predictions during microcellular injection moulding process. Most general method of analysis, use a constant viscosity and surface tension to predict the size of the bubbles. But Under actual situations, however, when the polymer contains gases, changes occur in the viscosity and surface tension that cause disparity between the estimated and observed bubble sizes. Moon and co-workers showed that a model using variable bubble properties predicted bubble sizes that were closer to actual observations compared to results obtained from standard analysis tools [10].

### 2.2.4 Cell stabilization:

In order to obtain a homogeneous foam structure, the foamed melt must be stabilized at the right point in time. Foam stabilization means the fixation of the foam structure. This will occur if the viscosity of the polymer melt is so significantly increased that the pressure in cells is no longer sufficient for the further extension. The viscosity of the polymer increases due to the gas diffusing out and cooling in the tool. There are two cooling effects in the injection

moulding process, the one is the external cooling which means the temperature controlled inner surface of the mould, the other additional cooling effect is the isentropic expansion of the gas [5, 6].

If the foam stabilization is very rapid, the cells have only very short time to grow, so that the formed cells are very small. Only a part of gas can diffuse into the cell due to the short growing time and the porosity of the foamed structure will therefore be low. However, if the duration of the fixation is prolonged, a large part of gas can escape from the foamed structure into the environment due to the low pressure outside and the formed cells can also collapse. How fast the foaming polymer melt is stabilized largely depends on the wall thickness of the foam injection moulded part and the tempering of the tool. If the foam injection moulded part is very thin and the tool temperature is low, relatively thick skin layers result, which lower the maximum achievable density reduction. In thick-walled parts and at high tool temperatures, diffusion processes can lead to unwanted pore coalescence in the core layer [5, 6].

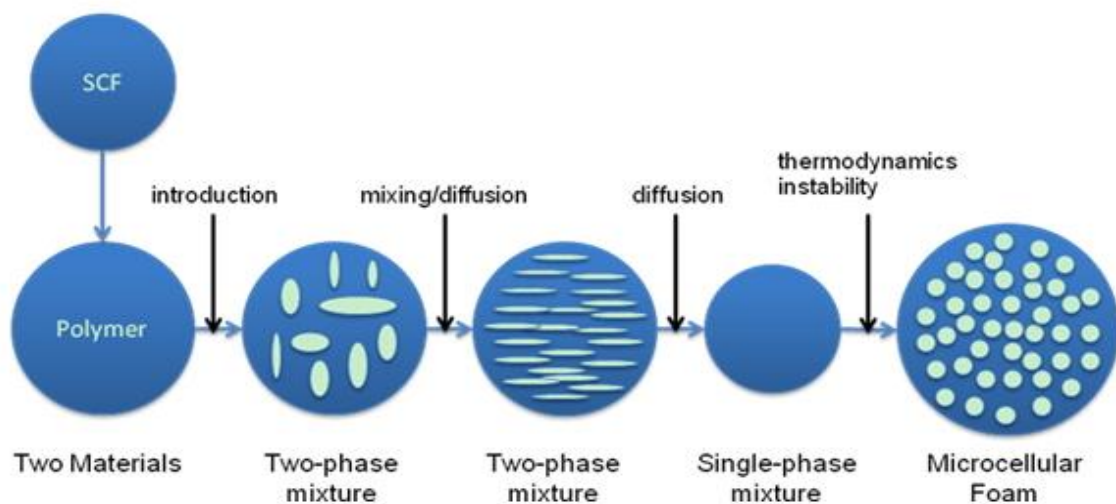


Fig. 5: Illustration of microcellular polymer foaming process [9]

### 2.3. Blowing Agent:

Polymeric cellular is generally characterized by its blowing agent who inhibits and distributed within the polymer matrix. In most cases, they are virtually inevitable in polymeric foam process. There is huge number of blowing agent which is suitable for foaming process. As per the nature of gas formation, it can be classified as two ways first is physical blowing agent and second is chemical blowing agent. Chemical blowing agents are usually solids at standard temperature and pressure (STP) and go through chemical transformation producing gas while physical blowing agents are a liquid or gas at STP and go through either a reversible change of state or expansion. Moreover, these blowing agents must possess high

solubility in the polymer, be easy to incorporate, enable a homogeneous distribution in the melt and produce very small amounts of solid reaction products [4, 10].

### 2.3.1 Physical blowing agent:

During plasticization process physical blowing agents are added in the form of fluid. Foaming is taken place by an expansion of blowing agent when the whole state changes. During the mixing process, they are at supercritical stage because of high pressure and temperature. Due to the intense pressure drop in the cavity they rapidly expand and subsequent transition take place into the gaseous state. This process makes foam structure. Different PBAs are used which are:

- Volatile organic chemicals (VOC)
- Including hydrocarbons (HC)
- Chlorofluorocarbons (CFC)
- Hydro chlorofluorocarbons (HCFC)
- Hydrofluorocarbons (HFC)
- Inert gases, such as carbon dioxide, nitrogen, and oxygen[4,10]

Earlier CFCs and HCFCs were widely used as a physical blowing agent due to its solubility and low diffusivity which helps to make proper foam but it creates high ozone depletion potential because of this reason they were isolated from the market according to Montreal protocol. In the beginning of the year 2010 US were banned the usage of them.

Therefore, now days more and more research is going on using the CO<sub>2</sub> inert gas because of its high solubility and easy handling process. Apart from this N<sub>2</sub> is also good option for its lower cost, abundant and by far the most environmentally acceptable [10, 11].

*Tab.1: Properties of inert gas using as blowing agent*

	Carbon Dioxide	Nitrogen	Oxygen
Chemical formula	CO <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>
Molecular weight	44	28	32
Boiling point (°C)	-78.3	-195.8	-183.0
Critical temperature (°C)	31	-146.9	-118.3
Critical pressure (MPa)	7.38	3.4	5.0
Heat of vaporisation at BP (KJ/mol)	6.8	-	-
Gas conductivity (m W/mk) at 25 °C	16.4	25.8	26.6
Vapour pressure (kPa) at 25 °C	6434	Very high	Very high

## 2.4 Physical Foaming Techniques

### 2.4.1 Cell mould:

This technology was developed by Wittmann Battenfeld to make structured foam parts through direct gas injection with physical blowing agents. The aim of this technology is to make products without voids and keeping them into regular and fine foam structure because small and regular cells give better mechanical performance. To achieve this, they have their own specialised equipment such as gas injector, gas flow regulator module, needle shutoff nozzle.

This technology is used for both thin and thick walled parts. As structural foam part produced with small swirls or streaks on its surface same thing appears with cell mould foamed products. The main focus of this technology is to make products with dense skin, fine and regular cell structure to combine the benefits of not only weight reduction but also high level of product performances.

Cell moulding technology has a separate unit for plasticizing and gas injection sections of the screw. The reason behind this is to sort out the wear resistance problem occurs between two check valves which is the alternative to using an additional sleeve-type check valve. Foaming agent, liquefied nitrogen (pressurized with up to 300 bars) is added to mixing section of plasticising unit during a metering stroke and subsequently diffuses into the melt. The nitrogen is intensified into the mixing section of screw by dividing the melt flow into many separate currents. After that the barrel is kept closed by a needle shut-off valve in the direction of the mould during plasticizing and gas injection, the melt-and-gas mixture is kept under pressure inside the plasticizing unit which in turns gives single phase polymer/gas solution. During the injection process cavity pressure is decreased which in turns reduces the solubility of gas in the plastic melt [12, 13, 14].

### 2.4.2 Ergo cell:

In 2001, Demag Argotech GmbH, schwing, Germany, first developed and introduced a new physical foaming technology for injection moulding. In this technology, blowing agent is injected via an additional module instead of directly add to screw area. This module is placed between injection nozzle and plasticization cylinder. It comprise with separate introduction zone for the blowing agent fluid which is a part for homogenization and a connected shot-pot, in which the homogenized polymer-blowing agent mixture is kept under pressure until injection begins. The main advantage of this technique is the independent speed of piston pump which is not connected with movement of the screw. It makes this technology differ

from the Mucell technique. Therefore different blowing agent concentration and varying degrees of foaming can be achieved within the component. Polymer which is difficult to foam that are processed with this method because the mixing with gas can be decoupled from the plasticization process. It demands high complexity in plant construction and retrofitting machines therefore it is not economical. The great equipment investment requires to implementing this technique. Now a day the Ergocell technique is not provided by Demag [4]

### **2.4.3 Optifoam:**

This technique first developed at the Institute of plastic processing (IKV) in Aachen. It is similar to the Argo cell method but this method uses a different approach and it was designed as a retrofitting system. The installation of an injection and mixing unit is between the needle shutoff nozzle and the plasticization cylinder. Cantered torpedo system is attached with injection and mixing unit which causes the melt to pass through a narrow annular gap. Blowing agent is injected into the melt through surface shell of torpedo and the inner cylinder which are made of a sintered metal ring. There-after homogenisation of polymer–gas mixture is taken place in a static mixer and then transferred into single-phase solution. In this method the process of addition of blowing agent takes place during the injection process. Currently this technology is no longer available for injection moulding machines [4].

### **2.4.4 Profoam:**

This technique is also developed by Institute of Plastics Processing in Aachen. In this method the blowing agent is injected in already melted polymer and plastic granulate subject to pressure, heat is preloaded and subsequently plasticized. It is similar to a batch process. It has similar retrofitting solution like the Optifoams system. Primarily, it is applicable for foaming thermally sensitive polymer, which possesses a high gas diffusion rate. This system is placed on the hopper of the injection moulding machine. It possesses pressure chamber which is sealed with two locks. Gas is incorporated into the polymer granulate in this volume by means of diffusion and then kept under pressure until the injection pressure initiate. There must be a seal on the side of the motor of the plasticization screw [4].

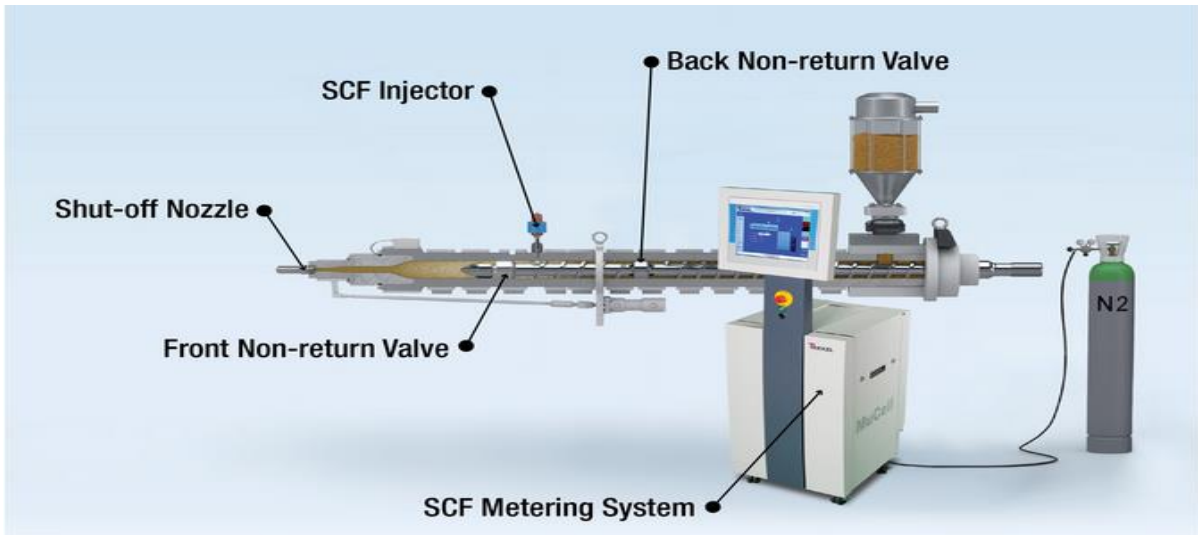
### **2.4.5 Mucell:**

The best known method for physical foaming is Mucell, by Trexel Inc. based in Woburn, Massachusetts. It was first evolved and patented in the 1990s at Massachusetts institute of technology in Cambridge and later was purchased by Trexel Inc [4].

In the beginning, the inert gas carbon dioxide or nitrogen is converted into a super critical fluid or SCF, for precise dosing capability. Then SCF is injected into the barrel during screw recovery process. This is done by SCF interface kit which is mounted to the barrel. A specially designed Mucell screw which helps to disperse the SCF into polymer melt creating a single-phase solution. Here, SCF works as a plasticizer, reducing the viscosity of the resin up to 30%. This improves the filling condition of thin wall sections and flexible members.

Microscopic cell growth occurs within the cavity during filling and cooling process. This helps into creating required internal pressure to fill the part fully which in turns eliminate the holding and packing stage that are contributor for cycle time and major source of moulded in-part stress in conventional moulding process. Moreover, due to lower mould and melt temperature, cooling time becomes shorter and peak cavity pressure is also reduced by up to 80%. Around 20 to 30 percent cycle time reduction directly effects capital cost avoidance and freed machine capacity. The evenly distributed closed microscopic cell structure is created throughout the part with solid screen. Sink marks and stress induced warpage are eliminated without changing chemical structure of polymer. Due to the elimination of holding pressure which lowers the peak clamp tonnage requirement. This gives permission for machine size reduction by up to 50% using Mucell processing [10]

Mucell process makes homogeneous size of the cell and distribution which is the clear advantage of this technology. Nevertheless, it has complex processing condition but it is clearly defined and absolutely reproducible because of the direct gas injection. Moreover, the cost of foaming agents is at least 80 % lower that would be a further advantage of this technology. One disadvantage of MuCell plastication is the shortened plasticising zone caused by the middle non-return valve, which can have an effect the required shot weight, and depends on the material used. However, regarding the choice of material the process is extremely flexible. Nitrogen is used as foaming agent in about 90 % of all applications. Therefore, the process is ideally suited for applications in which subsequent solvent evaporation is undesirable [15].



*Fig. 6: Schematic diagram of Mucell Technology*

## **2.5 Materials for Micro Cellular Injection Moulding:**

Structure of polymers plays crucial role to make proper cells for the foam structure. The molecular weight, molecular weight distribution, number of average molecular weight, crystallinity, and phase transition are the important parameter for foaming process [15].

### **2.5.1 Semi crystalline Materials:**

Crystalline or semi crystalline materials have become more usable for microcellular injection moulding since they have excellent properties for wide application of the industries. The typical materials are polypropylene (PP), polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), and polyamide (PA).

### **2.5.2 Characteristic:**

Semi crystalline materials have the unique characteristics of crystallization during mould cooling. This crystallization creates some kind of issues:

1. Semi crystalline materials do not give uniform cell structure due to crystallization because it expels the gas near crystalloid.
2. Diffusivity and solubility of gas is higher in amorphous materials but for semi crystalline materials due to crystalline region gas diffusivity is lower.
3. One the important proposal was given by Colton that the process must be done above the melting temperature for semi crystalline materials. In the beginning stage, foam must be starts before crystallization.
4. Semi crystalline materials show some unsaturated crystalline region even under the high pressure (34Mpa) at super critical state.



The general methods to improve the cell structure on the moulding part of crystalline materials are:

1. Increase the cooling rate to decrease the crystallinity
2. Addition of fillers or other additives to create more heterogeneous nucleation [15]

### **2.5.3 Polypropylene (PP):**

Polypropylene (PP) is one of the most popular semi crystalline materials widely used in many areas since 1957. PP is a versatile material as it has good mechanical, chemical, physical properties.

Although, PP is difficult to process with oxygen and other gases and it is also fastest burning of the olefins. The flame retardant treatment of PP provides benefit from heterogeneous nucleation for microcellular foaming process. PP gives more advantages from microcellular foam since it is possible to reduce more weight of microcellular PP. The most promising materials for this technology are the heat resistance PP, glass- fibre- reinforced PP, and filled PP. These additional materials with pure PP makes microcellular processing much easier. Moreover, cellular PP can increase the impact strength and resistance of fatigue load with very small cell size [16].

### **Unfilled Homo-PP and Co-PP:**

Generally the unfilled homo- PP is not recommended for microcellular processing since it is hard to get uniform cell structure. The unfilled homo –PP has weak melt strength and melts elasticity at elevated temperature. Nevertheless, unfilled-PP is used in some of the applications where the strength drop is not the major issue for the unfilled-PP microcellular part. During foaming process of PP, the temperature should be maintained higher than the crystallization temperature though it cannot be so high that gas will diffuse out of the cell because of cell wall rupture. The range of processing temperature for unfilled-PP is about 204 – 288°C (400 – 550 ° F). It is believed that the reduction of weight for unfilled PP should not be higher than 10-15% because the strength drop is significant for tensile strength of unfilled PP with microcellular process. The main advantages of microcellular unfilled-PP are the dimension stability with lower warpage and almost zero sink mark. The wall thickness under 2.5 mm and uniformly cooled mould of unfilled-PP microcellular part, the reduction of cycle time may reach 10-15% which directly affect the cost [15].

### **2.5.4 Polyamide (PA):**

Polyamide belongs to the amide group which has an integral part of the linear chain. PA is a very suitable material to use for the microcellular injection moulding process. The experiment shows that the unfilled PA 10 with microcellular structure has good cell structure with uniform average cell size of about 40  $\mu\text{m}$ . Even though, the distribution of cell in PA 10 matrix is not truly uniform, nor is the wall thickness among the cells. The size of cells is similar to the thickness of the thickest wall. Moreover, the thinnest wall has so thin thickness that the adjacent cells are almost touching each other to be an open cell. More experimental results are there regarding the glass fibre reinforced PA6 or PA 6/6. As per the available test result, the microstructure of glass fibre reinforced materials has much more better cell structure than unfilled same materials. Spindle shows the detailed test result for excellent properties of PA6 with 13 wt. % of glass fibres.

American company Rhodia, specialized in chemistry, synthetic fibre and polymers introduced two special grades of Rhodia's Technyl Star polyamide 6 and also introduced 6/6 materials that have relative low viscosity of molten polymer approaching water. These materials have low melt viscosity fitted specifically for microcellular processing. The material has a trade name "X Cell™". Density of these materials is 12% less and can mould thin-walled parts with less injection pressure. The cycle time is reduced by 20 – 30%. The microcellular part of XCell™ shows lower stress, good rigidity, and the ability to withstand high temperatures and impacts. This microcellular part provides benefits of reduction in weight and warpage without creating any effect on appearance like high surface aesthetic part of an engine cover. All polyamides require adequate drying temperature and thorough drying for making good cell structure of microcellular parts. The main reason behind this is moisture in polyamide material may generate big cells. Drying time for microcellular processing is the same that of the solid nylon material [15].

### **2.5.5 Polyethylene (PE):**

Polyethylene (PE) is widely used semi crystalline material in injection foaming industry for a long time. High density polyethylene (HDPE) and low density polyethylene (LDPE) both are appropriate for microcellular injection moulding. Nevertheless, unfilled HDPE and LDPE are identical to unfilled PP. It is hard to make good cellular structure of them. Generally, unfilled HDPE and LDPE require some fillers added to promote the nucleation, and then the cell structure can be improved significantly.

Different techniques are available to improve the microcellular cell structure of PE materials. Among them one method is to bend the different melt indices (From MI=5, to MI=30) of PE materials to increase the transient extensional viscosity. Dicumylperoxide (DCP), a cross linking agent is also utilizing to increase the melt strength. The main purpose of this alteration of PE materials is to reach a good balance between resin viscosity and branching of compound PE. This modified PE comprises both different melt indices and cross linking inducing branch. And this modification allows PE to behave similar like PP to maintain the cell expansion and prevent cell collapse during cell growth and shaping in the injection mould. Compare with PP containing filler as modification with heterogeneous nucleation, filled PE is another amendment measure to make acceptable microcellular structure for all PE materials [15].

### **2.5.6 Amorphous Materials:**

Amorphous materials have different type of morphology than crystalline materials. The unique structure of amorphous materials is having a random array of polymer chain with no regular molecular arrangement. Amorphous materials have no sharp melting point rather than having only a range of soft temperature to determine that they transfer from a solid to an ultra-high viscosity liquid. Typical amorphous materials for microcellular of injection moulding are general purpose polystyrene (GPPS), polycarbonate (PC), acrylonitrile/butadiene/styrene (ABS), and high - impact polystyrene (HIPS).

### **2.5.7 Characteristic:**

Generally, amorphous materials have larger skin area. It can be estimated to be about 15–20% of the whole thickness for thermoplastics. It will be 1.5 to 2 times as thick as that of crystalline materials. Moreover, the gas will uniformly distribute throughout the matrix at supercritical state. Amorphous materials have uniform cell structure and smaller cell size than crystalline materials [15]

### **2.5.8 Acrylonitrile Butadiene Styrene (ABS):**

Acrylonitrile butadiene styrene (ABS) material is a mixture of nitrile rubber and SAN copolymers. There are two most important resins of ABS blends named SAN copolymers with butadiene acrylonitrile rubber (type I) and terpolymers of polybutadiene ,styrene and acrylonitrile (type II). Apart from this many others type of ABS resins are available on the market for injection moulding. Type II resin is a typical ABS which contains a mixture of polybutadiene, polybutadiene grafted with acrylonitrile and styrene and SAN copolymer. The

properties of ABS type II resin depends on graft polymer since blends of polybutadiene and SAN lack strength and toughness. The typical properties of the final ABS polymer are:

- the amount of the elastomeric phase
- the molecular weight of the resin phase
- the styrene – acrylonitrile ratio in the resin phase

ABS resins have lower mould shrinkage, wide melting range and high viscosity. The rubber particle which dispersed in ABS resin provides a good hot strength. The size of rubber particle is dominant factor for microcellular processing. Overall, ABS is an excellent material for microcellular parts since it is a blend of three different components. All grade of ABS is fitted to provide a given property balance. The final morphology of ABS microcellular part will be determined by the rubber phase [15]

### **2.5.9 Polycarbonate (PC):**

PC is generally an easy amorphous material for microcellular injection moulding. It has ability to dissolved large number of gas into free volume at low temperature around  $T_g$  because of limited degree of crystallinity and damping capacity over a wide temperature range. The PC injection moulding machine must require high processing temperature and high melt viscosity of the materials but microcellular processing decrease the cavity pressure significantly. The impact strength of PC relies on its thickness. PC also exhibits excellent creep resistance and excellent optical properties. The heat distortion temperature is in the range of 130–143°C. The melt of PC adhere strongly to metal and, if allowed to cool in a barrel, may pull pieces of metal away from the wall of barrel because of shrinkage. Since PC generally requires to be purged out in the barrel if the machine is going to shut down for a while for microcellular injection moulding process. PC material is essential to be dried before processing if not then it will chemically react with the resin at the processing temperature, decreasing the molecular weight, which can be the cause of loss in toughness and impact strength. During cooling little crystallization occurs and after crystallization has not been observed which is an important feature of PC to make it easy to use for microcellular foaming [15].

### **2.5.10 General purpose Polystyrene (GPPS):**

The commercial general purpose polystyrene is the best known material for microcellular injection moulding process. The foam structure of GPPS is white while it is brittle, clear and colourless in normal condition. GPPS is widely used in the manufacturing of the foams.

Generally, the structure of cell in GPPS is closed cell structure no matter what kind of gas is used. Although, open cell microcellular GPPS can be made by promoting cell growth at a higher temperature than 150°C. It is also possible to make open cell structure by nucleation or by keeping high saturation pressure which helps to maintain the post nucleation cell pressure high enough to break open cells. Usually, N<sub>2</sub> gas has considerably lower solubility than CO<sub>2</sub> gas in GPPS. However, the diffusion rate of N<sub>2</sub> and CO<sub>2</sub> are nearly the same. The processing condition of GPPS is very simple for optimal microcellular structure with extremely low density and high cell density. By comparing the different cell structure of GPPS with different gases, 16 wt % CO<sub>2</sub> gas generates larger cells and thin wall thickness among the cells that is similar to that of the close packed model by Suh. Although, it is not well known model for most of the injection moulding parts and can be used for the applications of an insulator or package [15]

### **2.5.11 Polymer blends:**

Polymer blend is an intermolecular compound where more than two polymers are mixed under defined temperature and shear conditions to processable granulates. Polymer blends consist of two or more phases on a microscopic scale which helps to create excellent heterogeneous nucleation for microcellular processing. Polymer blend prevents delaminating effect during microcellular injection moulding due to coupling of the phase boundaries between poorly compatible polymers. This multiphase system can become ineffective by keeping too high processing temperature or shear rate. Because of this, process parameter must be set up according to phase separation problem for microcellular injection moulding process no matter if the viscosity of the microcellular process is lower than the same material without gas. Many successful blends are available in the market. All blends are easy to process with foaming technology since the heterogeneous nucleation contributes much better cell structure. The typical microcellular blends to be discussed in following;

#### **PC/ABS:**

The blend of PC/ABS material is widely used for microcellular processing. Generally, PC is hard to process and is an expensive resin but the blend of PC/ABS has excellent processing characteristics at relative low cost. Comparing with ABS resins, PC/ABS has a higher heat resistance and impact strength. It has also excellent gloss and surface appearance. Due to heterogeneous nucleation of this blend, it is a very good material to be used for microcellular processing. PC/ABS shows good cell structure with average size of cell 10 µm which is evenly distributed in the part. By keeping same processing condition, an air shot sample is made by injecting the gas rich materials into air, instead of into mould. The result of

morphology shows very fine 3  $\mu\text{m}$  cells distributed uniformly in the whole sample. If a constant pressure drop rate is kept during the whole injection period then better microcellular part can be made [14].

## **2.6 Simulation of Micro cellular injection moulding:**

Simulation is the process of designing a model of a real system and conducting experiments with this model in a digital computer for the purpose either the understanding the behaviour of system or of evaluating various strategies for the operation of the system. In other words, we can define simulation as an experiment of physical scenario on the computer.

The complexity of today's plastic parts as well as the costs, quality and competition makes it necessary to recognize potential errors early, already in the development phase of parts and moulds in order to solve the problems in the design phase. Simulation is most used where complex process needs to understand deeply before the actual process. There are some concrete reasons behind usage of the simulation. According to Nylor, Simulation can help us to make detailed observation of the system which results in better understanding of the system and to suggestion for improving it. It can serve as a “pre service test” to try out new policies and decision rules for operating a system, before running the risk of experimenting of the real system. In other words, when new components are introduced into a system, simulation can be used to help foresee bottlenecks and other problems that may arise in the operation of the system [15].

Real process of micro cellular injection moulding can also be predicted by specialised simulation software. Due to the evolution in the plastic technology, many industries have more advance simulation software through which most problems can be solved. CAD MOULD 3D F, MOLDEX 3D these are the Typical software for foaming of plastic parts.

### **2.6.1 CAD mould 3D F:**

CAD mould 3D F simulation software was first developed by Simcon ,Germany. It uses the highly precise 3D-F method especially developed for injection moulding simulation, making CAD mould 3D-F the superior simulation solution. It is a high-tech software product which is however, easy to use, very fast and precise.

It has great features which makes it more usable. It generates geometry and mesh automatically. It has its own unique patented framework method to make simulation process easy. It also provides high resolution in the areas of high gradients e.g. temperature and shear velocities across the wall thickness. Moreover, it gives very exact simulation results in the volumetric parts areas and areas with discontinuity parts thickness.

Cad mould 3D F foam is an add on software for fill and warp expert of the cad mould 3D F expert line. It offers the possibility to simulate nearly all injection moulding processing with thermoplastic materials. Physical as well as chemical blowing agents can be considered such that all foam injection moulded components can be designed at high accuracy. Some of the features are described in following passage.

Cad mould 3D F are able to do special operation especially for foaming of thermoplastic materials. The special 3D-framework (3D-F) crosslinking method has the advantage, that the 3D-F mesh, which is needed for simulation, is generated automatically.

User can choose thousands kind of materials from the data base and which can be edited and extended. Some of the materials are calibrated which means that during the year it is checked several times by which accuracy can be maintained. Following pictures illustrate the menu of data base:

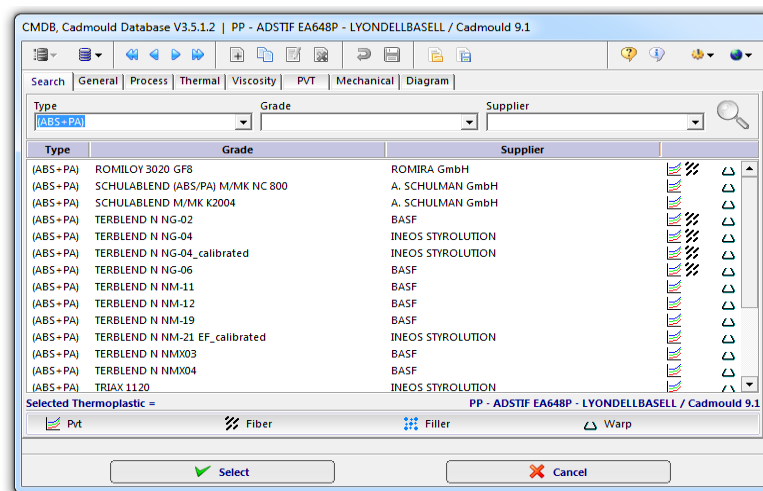


Fig. 7: Data base of Materials

Cad mould 3D F provides to set different process parameter for the simulation. Following picture illustrate the menu of process parameter:

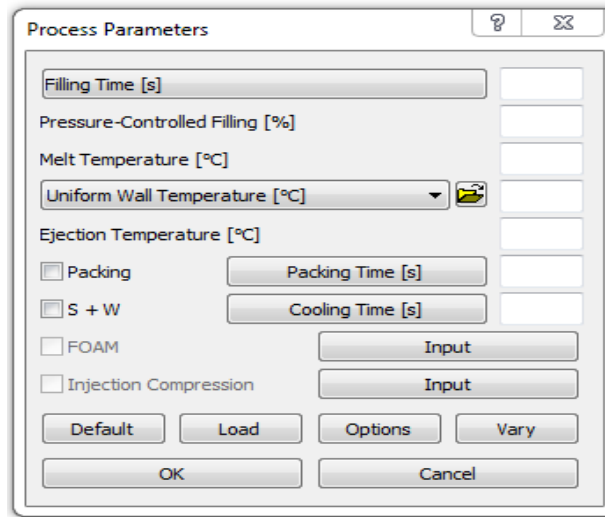


Fig. 8: Set of Process Parameter

After clicking on filling time mode, user will find another screen for setting the value of filling rate or injection speed. By clicking on packing time, user can set the desired value for holding pressure.

Now after making a mark on foam section, user can simulate thermoplastic materials with either physical blowing agent or chemical blowing agents. Following figure will pop up once user mark on foam section.

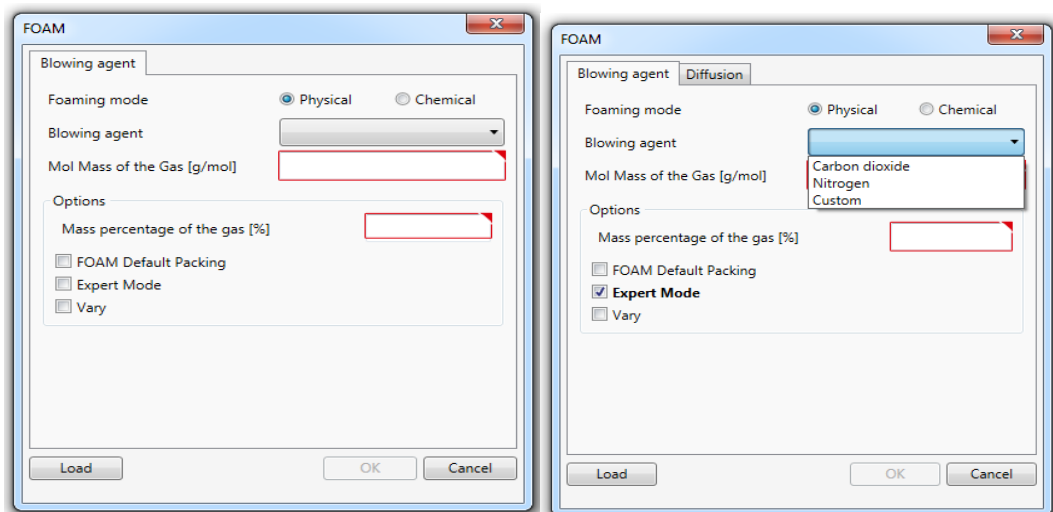
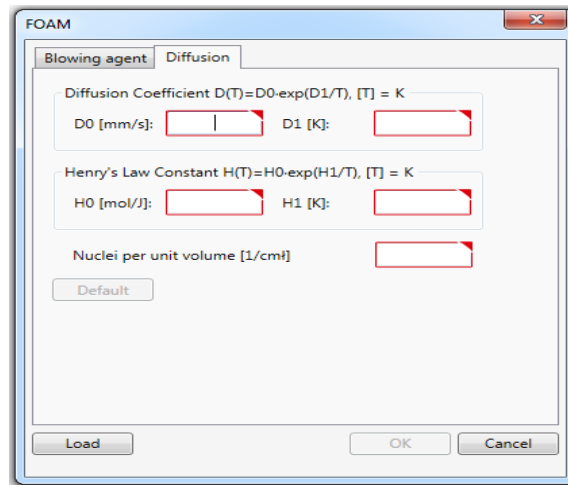


Fig. 9: Icon of foam section and its features

Cad mould 3D F provides three different option to make simulation for foaming product. The initial mode is to do simulation with automatic mode. The first mode is expert mode is foam default packing where it is keep holding pressure on recommend time 0.5 second. user will find another option to set the value for diffusion coefficient and Henry's law constant. If user



knows this value for particular material then it can be worked accordingly. The figure is illustrated below:



*Fig. 10: Details of Diffusion section*

The last mode is VARY where user can set the value of foaming agent in defined range. During my simulation, automatic mode was used since the value for the henry's laws and diffusion coefficient was not known.

Some of the unique features of this software are:

- It can simulate expansion of the blowing agent during the foaming process.
- Simulates all commonly used commercial foam injection moulding processes (MUcell, Optifoam).
- Simulates shrinkage and warpage.
- Simulates both parts with low and high degree of foaming.
- Simulates the bubble growth in the melt.
- Calculate the local change of density and volume.
- Consider the foam on the viscosity during the filling process.
- Display results in animation and 3D cuts.

### **2.6.2 MOLDEX3D MUCCELL:**

Moldex3d F also can perform the similar task like CAD mould 3D F does. Moldex3D Microcellular Injection Moulding (MuCell) is a 3D CAE module to help designers simulate microcellular injection moulding processes. Moldex3D MuCell<sup>®</sup> module can simultaneously simulate the cell nucleation and the growth of bubbles when the molten polymer fills the cavity during the injection process. The module provides the results of cell number density distribution, cell size distribution, etc. Users can benefit from simulating the complex process

to efficiently obtain the optimal processing parameters and prevent manufacturing troubles in the design stage. The main difference between the Cad mould 3D F and MOULDEX 3D is about the cost. It is more expensive and because of this it is not achievable for every company.

### 3. Experiment

The main purpose for this experiment was to compare experimental result of real foaming production process with simulation. MuCell technology was used for real production of the products. It is by far the most used techniques for physical foaming process. Therefore, this technique was chosen for the experiment in order to make proper evolution. The ARBURG, Injection moulding machine was used for the dosage of materials. CAD MOULD 3D F software was used for simulation process. It is one of the most used simulation software in Europe due to its easy operation and economic though it provides very accurate result. Because of the combination of the both ease of process and better result, decision was made to work with it. In the beginning, several operations were done for optimization of process parameter for real production. Once the process was done, the same process parameter was put to the simulation software and comparison was made.

The experiment was done by making Standard injection tensile test specimen according to ISO 527-2 A1. The main purpose behind this was to make evolution of the final result better since analyses of internal structure with complex geometry would not be easy. So it was better to select flat product. The following pictures [Fig. 11] shows the machine which was used during the experiment.



*Fig. 11: Injection moulding machine and Trexel unit for foaming process*

Three different kinds of materials were selected for the evolution of Micro cellular injection process. The first material was from semi crystalline group. It was polypropylene which is most used materials due to its wide application range in different areas. The supplier group name was SABIC PP CX 03 81. This material is also calibrated. It has high impact strength and stabilised to heat & weather.

Tab.2: Properties of PP SABIC CX 03 81

Data sheet: POPYPROPOLYNE SABIC CX 03 81			
Properties	Value	Unit	Test standard
Melt flow index, MFI	10	g/10 min	ISO 1133
Recommended Melt temperature	210-270	°C	-
Recommended Mould Temperature	15-60	°C	-
Flexural Modulus	172	MPa	ISO 178
Yield stress	23	MPa	ISO 527-1/-2
Stress at break	21	MPa	ISO 527-1/-2
Strain at break	>50	%	ISO 527-1/-2
Density	905	Kg/m <sup>3</sup>	ISO 1183

According to the theory, PP alone is not so good material for micro cellular injection process but PP with additives gives better structure. Thus we chose second material SABIC PP G3230 A with 30% glass fibres. Also this material is calibrated. It is chemically coupled and heat stabilised homo polymer polypropylene compound.

Tab.4: Properties of PP SABIC G3230A

Data sheet: POPYPROPOLYNE SABIC G3230 A			
Properties	Value	Unit	Test standard
Melt flow index, MFI	11	g/10 min	ISO 1133
Recommended Melt temperature	200-260	°C	-
Recommended Mould temperature	20-60	°C	-
Stress at break	93	MPa	ISO 527-1/-2
Strain at break	3	%	ISO 527-1/-2
Flexural modulus, 23°C	6900	MPa	ISO 178
Density	1120	Kg/m <sup>3</sup>	ISO 1183

The third material was from amorphous group. It was ABS MAGNUM 3616. ABS is also very common material for micro cellular injection moulding. It is a co-polymer and according to theory is very much suitable for Mucell technology since it is a combination of three kind of monomer.

Tab.3: Properties of ABS MAGNUM 3616

Data sheet: ABS MAGNUM 3616			
Properties	Value	Unit	Test standard
Melt flow index, MFI	5.5	g/10 min	ISO 1133
Recommended Melt temperature	240-270	°C	-
Recommended Mould temperature	40-70	°C	-
Yield stress	38	MPa	ISO 527-1/-2
Yield strain	3	%	ISO 527-1/-2
Flexural modulus, 23°C	2100	MPa	ISO 178
Density	1050	Kg/m <sup>3</sup>	ISO 1183

### 3.1 Process Microcellular injection moulding

#### 3.1.1 Preliminary operation

Before the actual process began, it was necessary to remove moisture from the ABS material due to its hygroscopic nature. So drying was done at 80 degree Celsius for 4 hour in low pressure dryer, MAGUIRE (LPD 100). On the other hand PP was not required to make it dry because it is not hygroscopic in nature. Real production was started with cleaning of the mould and to make proper adjustment of mould in order to avoid any kind of interruption during production stage. The low pressure dryer, Maguire is illustrated below.



Fig. 12: Low pressure dryer

The first stage of experiment was done to make products without using nitrogen gas. After doing several operations, optimal process parameter was obtained for production of foam products. 0.3 % nitrogen gas was added to the materials because it was necessary to reduce the weight under 15% so that the balance can be maintained between mechanical properties and mass reduction. Two variants were compared each time. First product was produced at 0 second holding pressure time while second product was made at 5 second holding pressure time. The different result were compared and made an appropriate conclus

### 3.1.2 Production of PP samples

- The following table illustrate the process parameter of PP for all the variants.

Tab.5: Process parameter

Process parameters	PP without nitrogen	PP with nitrogen variant first	PP with nitrogen variant second
Melt temperature	240 °C	240 °C	240°C
Injection volume (batch)	43 Cm <sup>3</sup>	33 Cm <sup>3</sup>	36 Cm <sup>3</sup>
Injection speed	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s
<b>Holding pressure time</b>	<b>15 Second</b>	<b>0 Second</b>	<b>5 Second</b>
<b>Holding pressure level</b>	<b>350 Bars</b>	<b>0 Bars</b>	<b>200 Bars</b>
Back pressure	0 Bars	100 Bars	100 Bars
Clamping force	1000 kN	1000 kN	1000 kN
Cycle time	60 Second	60 Second	60 Second
Point of switch over	17 Cm <sup>3</sup>	1 Cm <sup>3</sup>	1 Cm <sup>3</sup>
Decompress volume	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>
Water temperature	40 °C	40°C	40°C

### 3.1.3 Production of PP GF samples

- The following table illustrates the process parameters of PP GF for all variants.

Tab.6: Process parameter

Process parameters	PP GF without nitrogen	PP GF with nitrogen variant first	PP GF with nitrogen variant second
Melt temperature	240 °C	240 °C	240°C
Injection volume (batch)	40 Cm <sup>3</sup>	30 Cm <sup>3</sup>	33 Cm <sup>3</sup>
Injection speed	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s
<b>Holding pressure time</b>	<b>15 Second</b>	<b>0 Second</b>	<b>5 Second</b>
<b>Holding pressure level</b>	<b>350 Bars</b>	<b>0 Bars</b>	<b>300 Bars</b>
Back pressure	0 Bars	100 Bars	100 Bars
Clamping force	1000 kN	1000 kN	1000 kN
Cycle time	60 Second	60 Second	60 Second
Point of switch over	13 Cm <sup>3</sup>	1 Cm <sup>3</sup>	1 Cm <sup>3</sup>
Decompress volume	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>
Water temperature	40 °C	40°C	40°C

### 3.1.4 Production of ABS samples

- The below table illustrate the process parameter of ABS for all the variants.

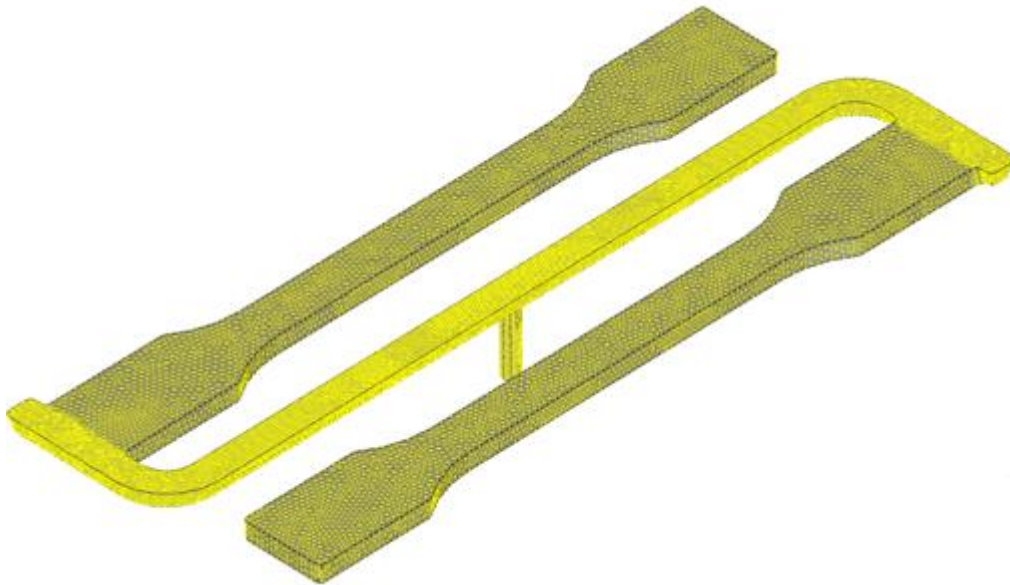
Tab.7: Process parameter

Process parameters	ABS without nitrogen	ABS with nitrogen variant first	ABS with nitrogen variant second
Melt temperature	270 °C	270 °C	270°C
Injection volume (batch)	43 Cm <sup>3</sup>	30 Cm <sup>3</sup>	33 Cm <sup>3</sup>
Injection speed	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s	60 Cm <sup>3</sup> /s
<b>Holding pressure time</b>	<b>15 Second</b>	<b>0 Second</b>	<b>5 Second</b>
<b>Holding pressure level</b>	<b>500 Bars</b>	<b>0 Bars</b>	<b>400 Bars</b>
Back pressure	0 Bars	160 Bars	160 Bars
Clamping force	1000 kN	1000	1000
Cycle time	60 Second	60 Second	60 Second
Point of switch over	11.5 Cm <sup>3</sup>	1 Cm <sup>3</sup>	1 Cm <sup>3</sup>
Decompress volume	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>	0 Cm <sup>3</sup>
Water temperature	40 °C	40°C	40°C

## 3.2 Simulation of microcellular moulding

### 3.2.1 Preliminary operation

In the beginning, CAT model was prepared by using Catia v5 designing software. After that it was converted into STL format for simulation. Simulation requires to follow significant steps in order to full filled whole operation. It starts with importing the STL model in to CAD mould simulation software. After importing STL model, it was necessary to give proper mesh size to the product. Different meshing size was used for runner system and product. 0.5 Meshing size was used for runner system and 1 meshing size was used for the part. The main reason behind this was to done proper filling and to obtain more accurate result. Moreover, according to real process cooling channel was designed to achieve higher accuracy. Drawing of cooling channel, Test specimen and moulds are in the attachment. Following figure illustrate the meshing for the part and runner system.



*Fig. 13: CAD model with mesh*

### 3.2.2 Simulation of PP samples

- As per the aim of my experiment, I put same process parameter in simulation software for all three variants. Following table illustrate the process parameter of PP for all variants.



Tab.8: Process parameter

Process Parameter	PP without nitrogen	PP with nitrogen variant first	PP with nitrogen variant second
Injection speed	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>
Melt temperature	240 °C	240 °C	240 °C
Cooling time	60 second	60 second	60 second
Temperature of cooling medium	40 °C	40 °C	40 °C
Rate of cooling	10 litter/min	10 litter/min	10 litter/min
<b>Holding pressure</b>	<b>300 bars</b>	<b>0 bars</b>	<b>100 bars</b>
<b>Holding pressure time</b>	<b>15 second</b>	<b>0 second</b>	<b>5 second</b>

### 3.2.3 Production of PP GF samples

- Following table illustrate the process parameter of PP GF for all variants.

Tab.9: Process parameter

Process Parameter	PP GF without nitrogen	PP GF with nitrogen variant first	PP GF with nitrogen variant second
Injection speed	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>
Melt temperature	240 °C	240 °C	240 °C
Cooling time	60 second	60 second	60 second
Temperature of cooling medium	40 °C	40 °C	40 °C
Rate of cooling	10 litter/min	10 litter/min	10 litter/min
<b>Holding pressure</b>	<b>350 bars</b>	<b>0 bars</b>	<b>300 bars</b>
<b>Holding pressure time</b>	<b>15 second</b>	<b>0 second</b>	<b>5 second</b>

### 3.2.4 Production of ABS samples

- Following table illustrate the process parameter of ABS for all variants.

Tab.10: Process parameter

Process Parameter	ABS without nitrogen	ABS with nitrogen variant first	ABS with nitrogen variant second
Injection speed	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>	60 Cm <sup>3</sup>
Melt temperature	270 °C	270 °C	270 °C
Cooling time	60 second	60 second	60 second
Temperature of cooling medium	40 °C	40 °C	40 °C
Rate of cooling	10 litter/min	10 litter/min	10 litter/min
<b>Holding pressure</b>	<b>500 bars</b>	<b>0 bars</b>	<b>400 bars</b>
<b>Holding pressure time</b>	<b>15 second</b>	<b>0second</b>	<b>5 second</b>

### 3.3 Evaluation of process Microcellular injection moulding

The evaluation of process micro cellular injection moulding was done by measuring three parameters named mass, density and cell size. After getting the result of each parameter comparison was made.

#### 3.3.1 Production of PP samples

##### Mass of the real production:

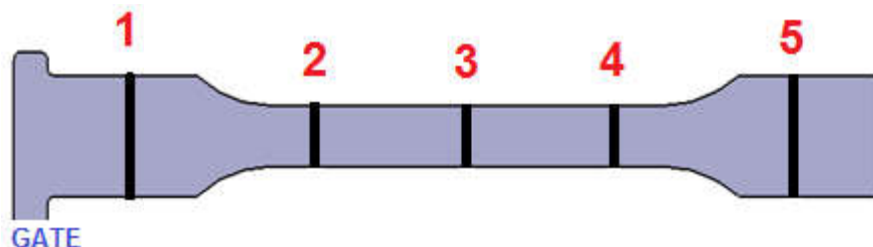
*Tab.11: Weight of the product and percentage of weight reduction with standard deviation*

Parameter	Weight	Standard deviation	Reduction of weight
Without nitrogen	24.17 g	0.02 g	
With nitrogen- first variant	22.02 g	0.04 g	8.9 %
With nitrogen- second variant	23.17 g	0.02 g	4.1 %

After comparing the above result, it seems like the product with lower holding pressure will give higher percentage of weight reduction than the product with higher holding pressure.

##### Density:

Pycnometer method was used to measure density. It was measured by selecting five points on the product/test specimen. These five points were kept at fixed position. The weight of the individual part was kept same each time. Point number 1 and 5 is at 15 mm from the edge of the test specimen. Points 2 is 120 mm from side and point 4 due to having a gate was kept at distance 126 mm because width of the gate was 6 mm. Point 3 was defined in the middle of the test specimen. The pictorial form is illustrated below.



*Fig. 14: Standard Test specimen with location of five points*

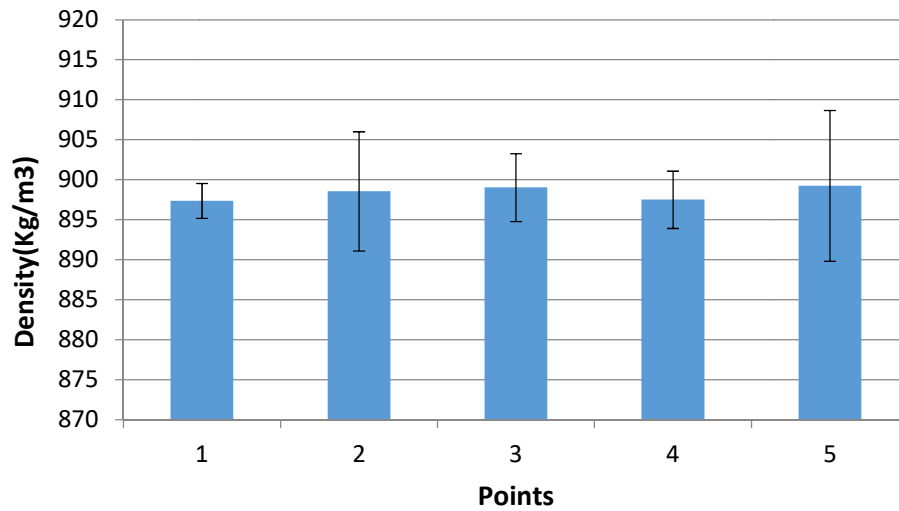


Fig.15: Density of PP without using the nitrogen

The above chart depicts the value of density without using the nitrogen gas. It can be seen from the chart that the density is almost same for every points.

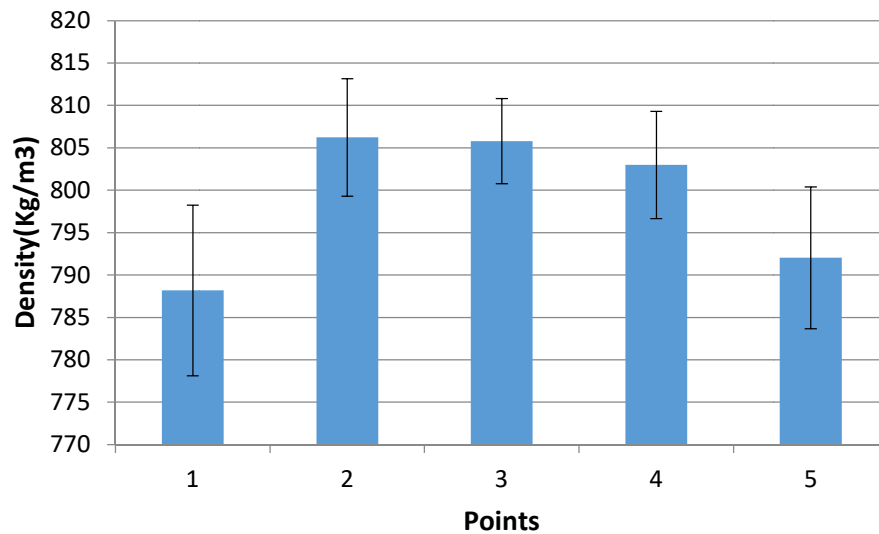
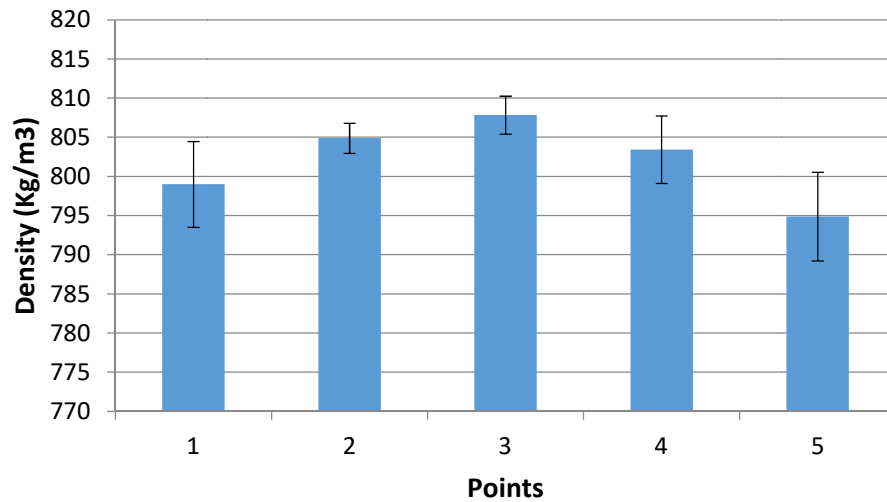


Fig.16: Density of PP with nitrogen variant first

The above chart shows the value of density for PP with nitrogen during the holding pressure time was kept 0 sec. It is clearly seen that density was lower near the gate and at the end of the test specimen while in narrower part of the test specimen like point 2, 3, 4 densities was observed higher.



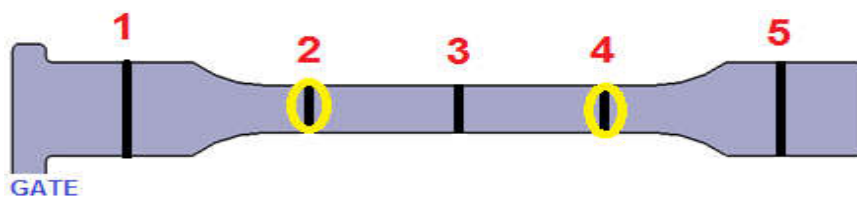
*Fig.17: Density of PP with nitrogen variant second*

The above chart reveals the value of density for PP with nitrogen gas during the holding pressure was kept 5 sec. As it is obvious like in previous case density near the gate and end of the test specimen it is lower than middle section.

By comparing all these three charts, I conclude that according to theory density for foam part should be lower than normal part which is clearly observe from the chart. One more thing, the part produced with 5 sec holding pressure gives lower reduction of density than 0 sec holding pressure it means that holding pressure evoked the structure changes and also according to the theory the structure should be finer.

### **Microscopy:**

The internal structure of the test specimen was analysed by using Scanning electron microscopy. TESCAN VEGA SHB equipment was used for analysing the internal structure. Compact skin layer and core are very essential for the foam part. It must be checked to know size of the cell, and its whole structure. In this experiment, two points were analysed by Electron microscopy. So according to this all the results were measured and mention for each case. Following figure illustrate the yellow point where microscopy was done.



*Fig. 18: Standard Test specimen with indication of points where microscopy was done*

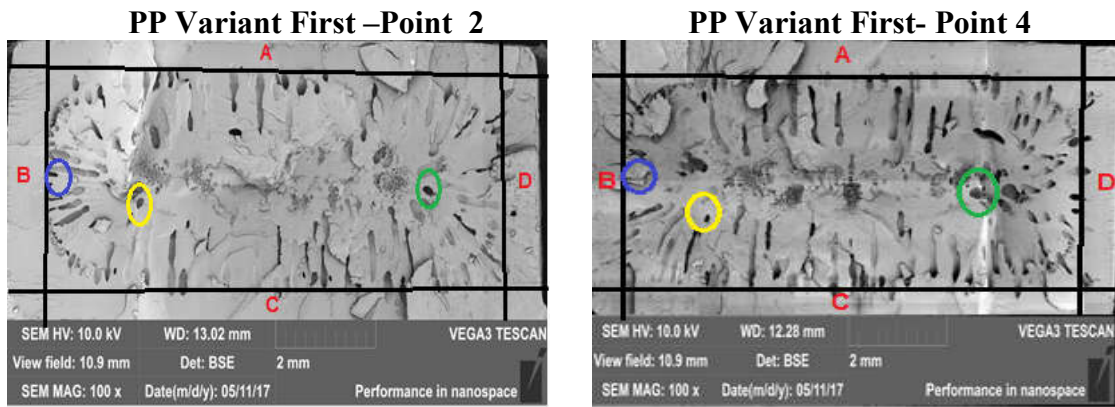


Fig. 19: Microscopic picture of PP Variant first

Tab.12: Value of compact skin layer

Compact skin layer	Point 2	Point 4
A(Length )	0.43 mm	0.33mm
B(Width)	0.69mm	0.52mm
C(Width)	0.41mm	0.42mm
D(Length )	0.50mm	0.57mm

Tab.13: Value of cell size

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.02 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.17 mm	0.13 mm
Green	0.02 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.15 mm	0.11 mm
Blue	0.01 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.12 mm	0.10 mm

The above pictures illustrate the cell distribution in structure of PP during where the holding pressure was kept 0 second. According to theory, PP is not so good for foaming due to agglomeration of the bubble which makes size of the cell bigger. So exactly the same result was found during microscopy. The three circles green, yellow and blue are indicating the cell and size of these cells are shown in the table number. And, it is seen that values are nearly same at both the points. Apart from this, the values of compact skin layer at both the points are close to each other which are mentioned in table number.

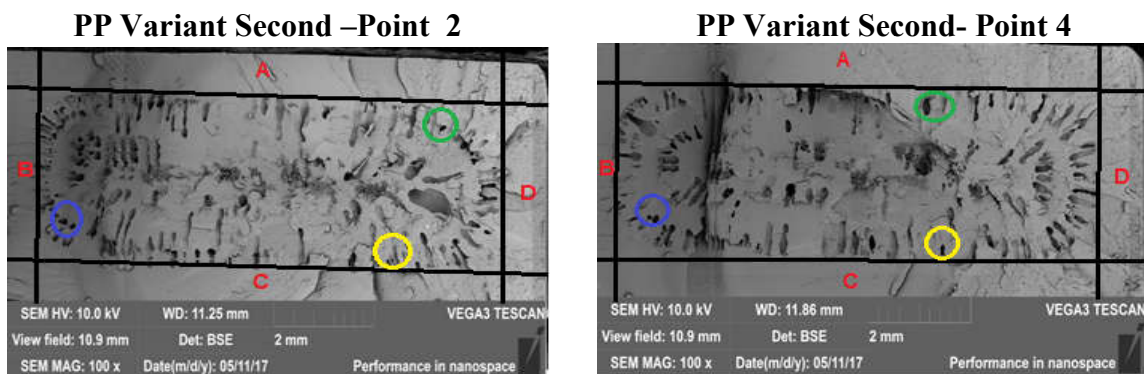


Fig. 20: Microscopic picture of PP Variant second

Tab.14: Value of compact skin layer of PP variant second

Compact skin layer	First Variant	Second Variant
A (Length)	0.74mm	0.75mm
B(Width)	0.53 mm	0.36mm
C(Width)	0.67mm	0.76mm
D(Length)	0.80mm	0.78mm

Tab.15: Value of cell size of PP variant second

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.02 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.11 mm	0.11 mm
Green	0.01 mm <sup>2</sup>	0.03 mm <sup>2</sup>	0.17 mm	0.20 mm
Blue	0.01 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.16 mm	0.13 mm

The above pictures illustrate the compact skin layer of PP during the holding pressure was kept 5 second. Because of this, it can be compare from the table that with increased holding pressure time from 0 to 5 second it gives larger area of skin than with 0 sec holding pressure time. Green, yellow and blue circles are indicating the cell and size of these cells are shown in the table. From the table, it is clearly seen that values are almost same at both the points. Moreover, by visualizing the picture of both the variants, I conclude that Agglomeration of bubbles is higher in first variant than second variant. Due to increased holding pressure second variants shows better distribution of the cell.

### 3.3.2 Production of PP+30 GF samples

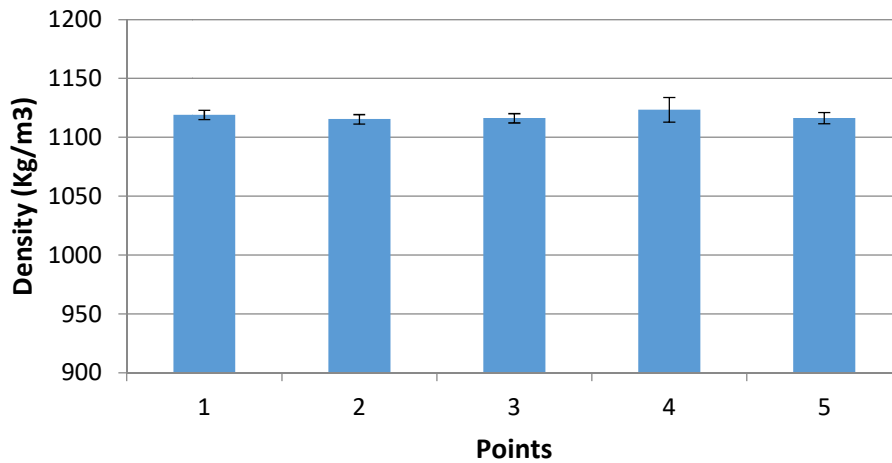
#### Mass of the real production:

Tab.16: Weight of the product and percentage of weight reduction with standard deviation

Parameter	Weight	Standard deviation	Reduction of weight (%)
Without nitrogen	30.50 g	0.08 g	
With nitrogen- first variant	27.17 g	0.06 g	10.9 %
With nitrogen- second variant	28.97 g	0.08 g	5 %

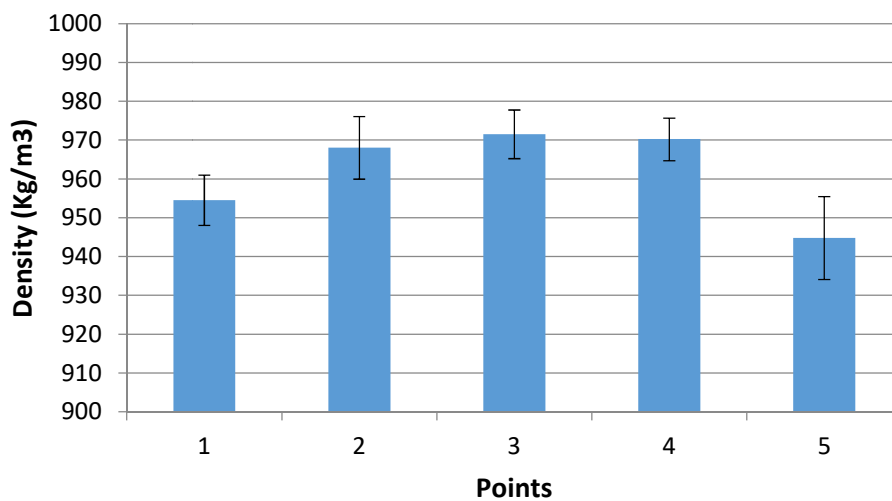
Above table illustrate the percentage of mass reduction. It is observed that reduction of weight is lower in second variant means higher holding pressure gives lower reduction of weight but probably better mechanical properties.

**Density:**



*Fig.21: Density of PP GF without Nitrogen*

The above chart depicts the value of density without using the nitrogen gas. It can be seen from the chart that the value of density for every point is nearly the same and standard deviation is also very low.



*Fig.22: Density of PP GF with Nitrogen variant first*

The above chart shows the value of density for PP GF with nitrogen during the holding pressure time was kept 0 sec. It is clearly seen that density was low near the gate and at the end of the test specimen while in narrower part density was higher and the values were approximately same.

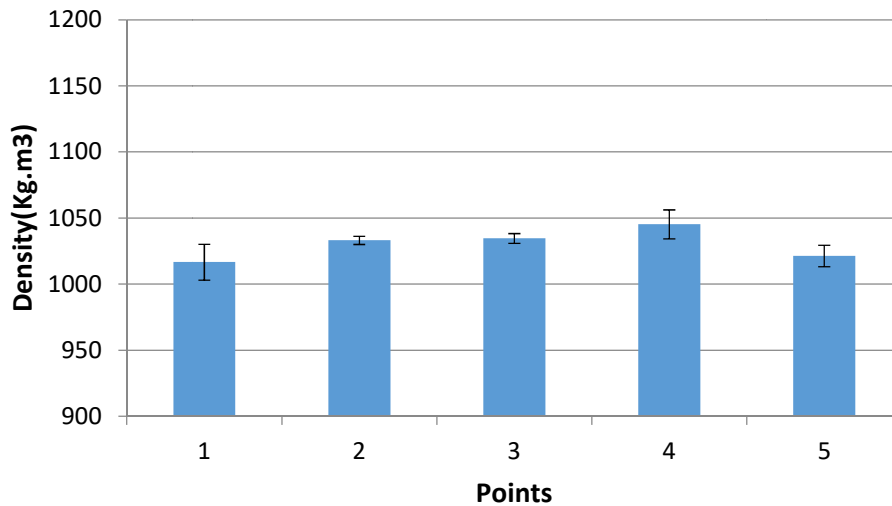


Fig.23: Density of PP GF with Nitrogen variant second

Above chart reveals the value of density for PP GF with nitrogen gas during the holding pressure was kept 5 sec. As it is obvious like in previous case density near the gate and end of the test specimen is lower than in middle section.

By comparing all these three charts, I conclude that according to theory density for foam part should be lower than normal part which is clearly observe from the chart. Moreover, it is same like previous case, the part produced with 5 sec holding pressure shows lower reduction of density than 0 sec holding pressure since holding pressure evoked foam structure changes.

### Microscopy:

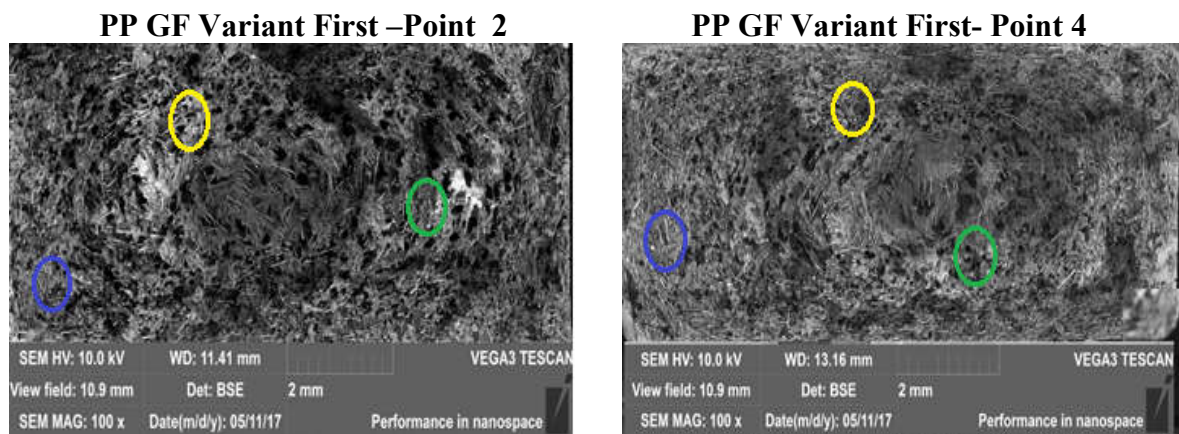


Fig. 24: Microscopic picture of PP GF Variant first



Tab.17: Value of cell size

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.01 mm <sup>2</sup>	0.004 mm <sup>2</sup>	0.12 mm	0.08 mm
Green	0.02 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.14 mm	0.11 mm
Blue	0.002 mm <sup>2</sup>	0.003 mm <sup>2</sup>	0.05 mm	0.06 mm

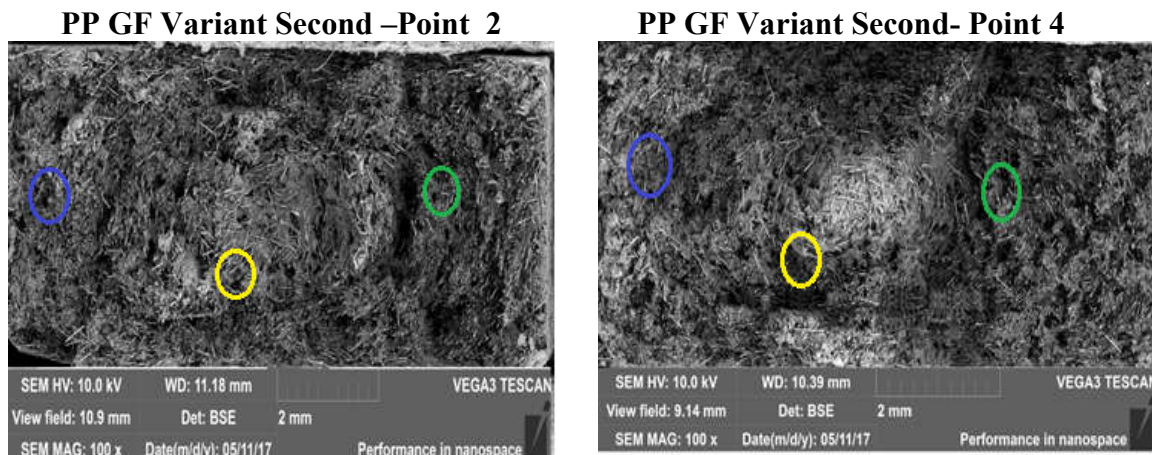


Fig. 25: Microscopic picture PP GF variant second

Tab.18: Value of cell size

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.02 mm <sup>2</sup>	0.04 mm <sup>2</sup>	0.18 mm	0.19 mm
Green	0.01 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.11 mm	0.08 mm
Blue	0.004 mm <sup>2</sup>	0.003 mm <sup>2</sup>	0.08 mm	0.06 mm

According to the theory, material with additive helps to make nucleation process easier and give more fine structure. PP with glass fibre also reveals the same kind of structure and it evoked very small compact skin structure because of heterogeneous nucleation bubble are going very close to the surface. It was observed same for the both variants which are shown in above pictures.

By comparing both variant, I conclude that second variants reveal more uniform structure than first one due to even distribution of cell but compact skin layer is same for both cases.

### 3.3.3 Production of ABS samples

#### Mass of the real production:

Tab.19: Weight of the product and percentage of weight reduction with standard deviation

Parameter	Weight	Standard deviation	Reduction of weight
Without nitrogen	29.15 g	0.04 g	
With nitrogen- first variant	26.80 g	0.17 g	8.1 %
With nitrogen- second variant	28.08 g	0.07 g	3.7%

Above table demonstrate the value of weight and percentage of reduction. It can easily observe that lower holding pressure helps to achieve higher weight reduction. Besides, after comparing the value of standard deviation, product without nitrogen shows very lower value than with nitrogen and this could be the reason that final quality or mechanical properties are changed, if nitrogen is used.

#### Density:

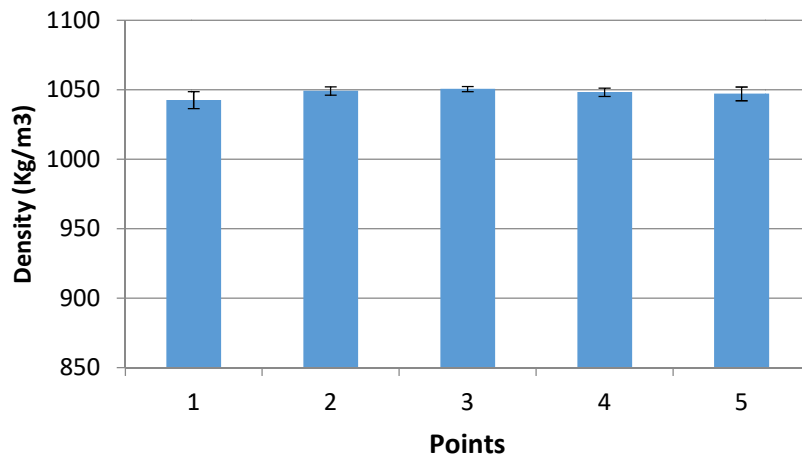
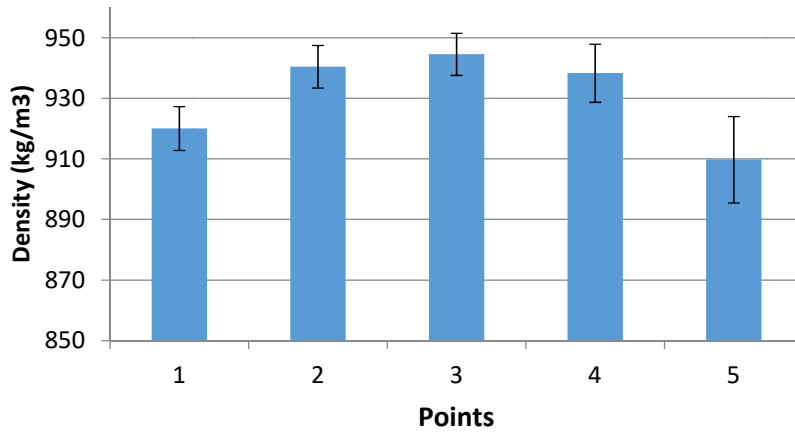


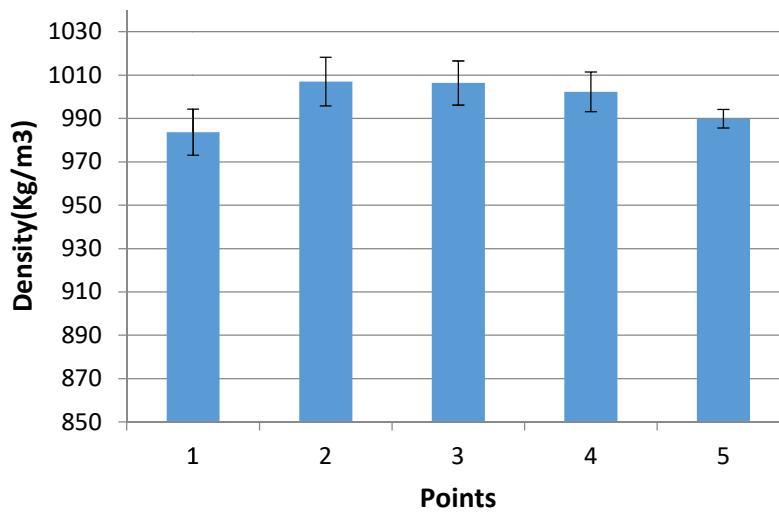
Fig. 26 Density of ABS without Nitrogen

The above chart depicts the value of density for ABS without using the nitrogen gas. It can be seen from the chart that the density is almost same for every points.



*Fig. 27 Density of ABS with Nitrogen variant first*

The above chart shows the value of density for ABS with nitrogen gas during the holding pressure time was kept 0 sec. The same characteristic as for previous material was detected for this variant. Density was lower near the gate and at the end of the test specimen while in middle part density higher. The values in these areas were approximately same.



*Fig.28: Density of ABS with Nitrogen variant second*

The above chart reveals the value of density for ABS with nitrogen gas during the holding pressure was kept 5 sec. As it is obvious like in previous case density near the gate and end of the test specimen is lower than middle section.

By comparing all these three charts, I conclude that as per the theory foam part possess lower density than part without foam structure which can be observed from the chart. One more

thing, the part produced with 5 sec holding pressure shows lower reduction of density than 0 sec holding pressure it means that holding pressure do influence the internal structure.

## Microscopy

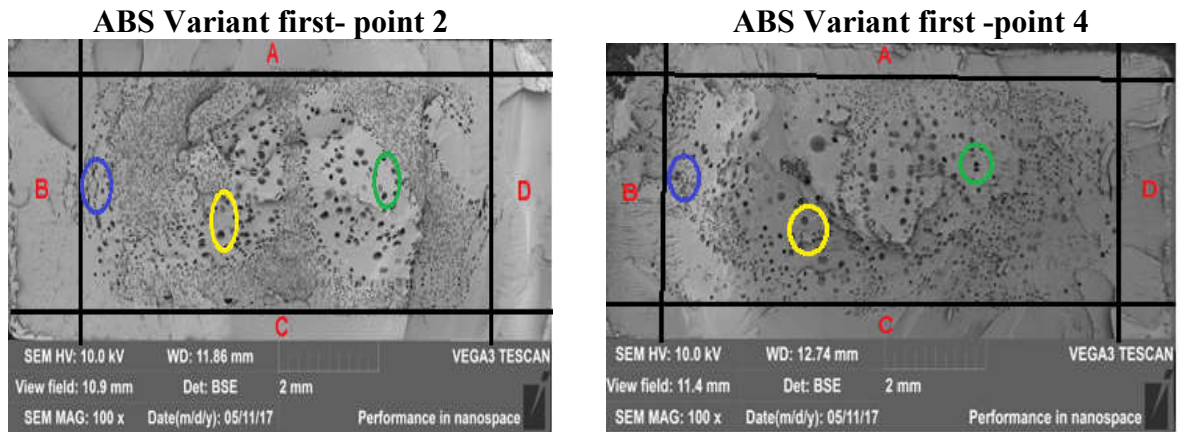


Fig. 29: Microscopic picture of ABS Variant first

Tab.20: Value of compact skin layer

Compact skin layer	Point 2	Point 4
<b>A(Length)</b>	0.45 mm	0.45 mm
<b>B(Width)</b>	1.33 mm	0.87 mm
<b>C(Width)</b>	0.44 mm	0.47 mm
<b>D(Length)</b>	1.66 mm	0.88 mm

Tab.21: Value of cell size

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.03 mm <sup>2</sup>	0.08 mm <sup>2</sup>	0.10 mm	0.11 mm
Green	0.01 mm <sup>2</sup>	0.02 mm <sup>2</sup>	0.06 mm	0.08 mm
Blue	0.03 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.07 mm	0.06 mm

The above pictures illustrate the compact skin structure of ABS during the holding pressure was kept 0 second. According to theory, amorphous materials are very much suitable for micro cellular injection moulding process due to its internal structure which helps for heterogeneous nucleation. The microscopic picture of ABS for first variant shows quite good distribution which is similar to theory. From the picture, it is observed that size of the cell is bigger in the core area and lower size is in the compact skin area. The highlighted area indicates the size of cell and values of it are shown in above table which is very close to each other.

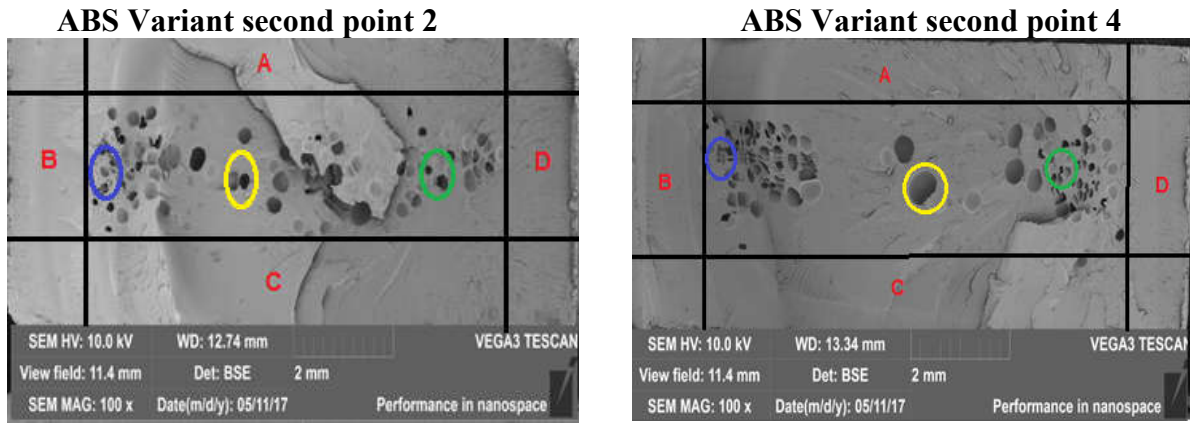


Fig. 30: Microscopic picture of ABS Variant second

Tab.22: Value of compact skin layer

Compact skin layer	First Variant	Second Variant
A(Length)	1.08 mm	1.20 mm
B(Width)	1.33mm	1.34 mm
C(Width)	1.33 mm	1.40 mm
D(Length)	1.43 mm	1.24 mm

Tab.23: Value of cell size

Indication of colour	Point 2	Point 4	Point 2	Point 4
	Area		Cell size(Equivalent Average)	
Yellow	0.01 mm <sup>2</sup>	0.01 mm <sup>2</sup>	0.20 mm	0.38 mm
Green	0.001 mm <sup>2</sup>	0.008 mm <sup>2</sup>	0.13 mm	0.16 mm
Blue	0.004 mm <sup>2</sup>	0.003 mm <sup>2</sup>	0.13 mm	0.12 mm

The above pictures illustrate the compact skin structure of ABS during the holding pressure was kept 5 second. In previous case, the holding pressure helped to make more fine structure but during the actual process of second variant, microscopic pictures reveal totally different result. Structure with lower diffusion of gas and larger compact skin layer was detected. The values for size of the cells are shown in table. Apart from this, distributions of cell and its size are not uniform which can directly influence on mechanical properties.

By comparing both the variant, according to me ABS does not give same structure all the time but it is true achieve the same in some cases like first variant.

### 3.4 Evaluation of Simulation for microcellular moulding process

Evaluation of simulation for microcellular moulding process also did like the previous manner. Weight of the product, Density at fixed points and cell size were measured.

#### 3.4.1 Production of PP samples

Tab.24: Total weight and percentage of weight reduction

PP	Weight	Weight save
Without Nitrogen gas	23.30 g	
First variant	19.96 g	14.33 %
Second variant	21.59 g	7.33 %

By comparing the total mass of each three cases, it seems that first variant gives higher reduction of mass than second variant which is probably the effect of 0 sec holding pressure.

#### Density:

Following pictures illustrate the distribution of average density of both variants of PP. The values of evaluated 5 locations the same as real process are shown in graph.

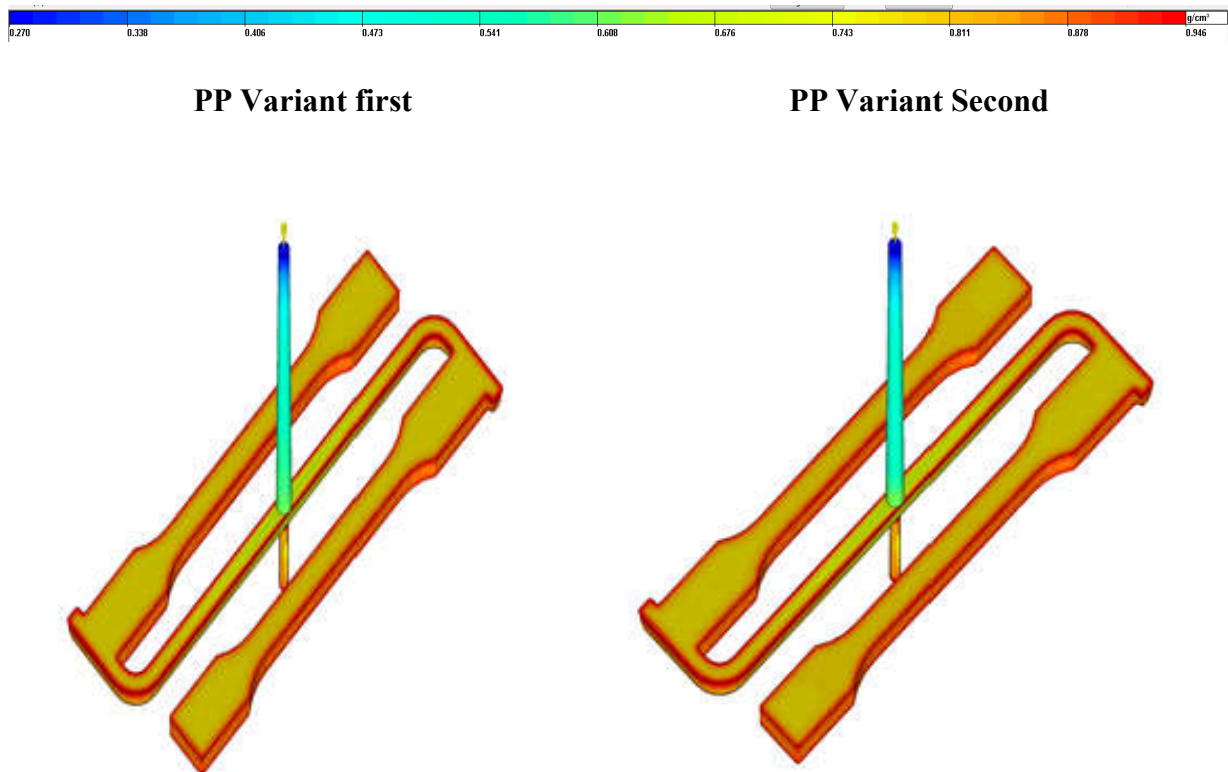


Fig. 31: Distribution of average density of PP variant first and second

From this picture it looks like distribution of average density is similar but from the individual point there was observed some differences which are illustrated in below graph.

### Graphical representation:

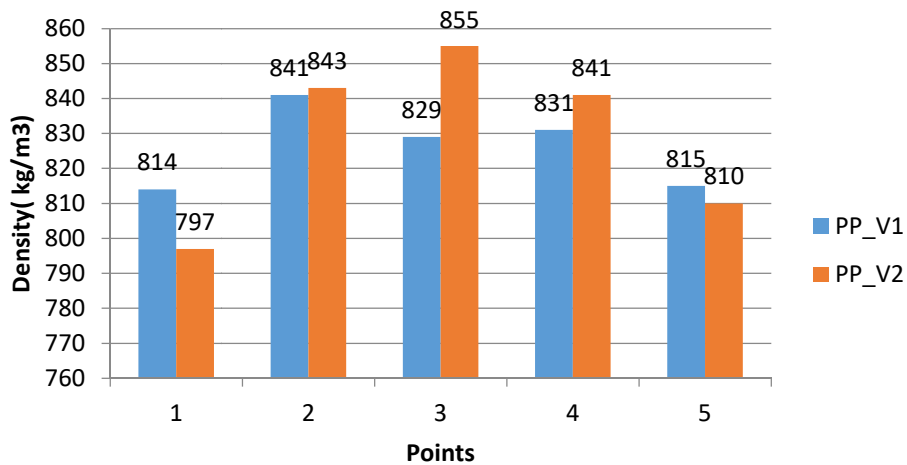


Fig.32 Density of PP variant first and second at five points

The above graph depicts the value of density at 5 fixed points. The average value at particular point was considered. The characteristics are completely similar like real case. At the point 1 and 5 density is lower than rest of the points. Also simulation gives higher value than real process for most of the time.

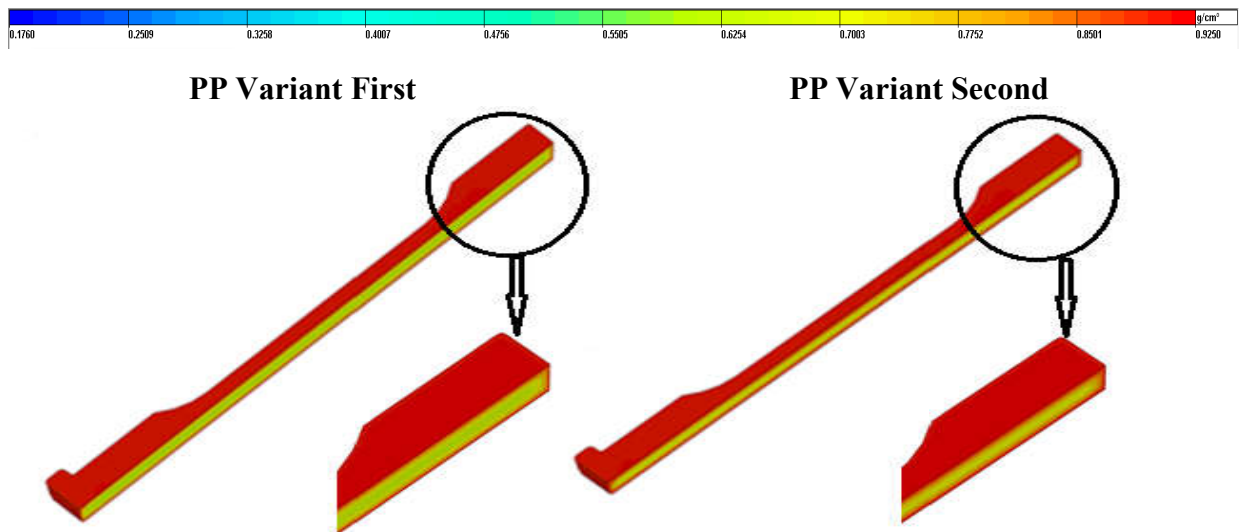
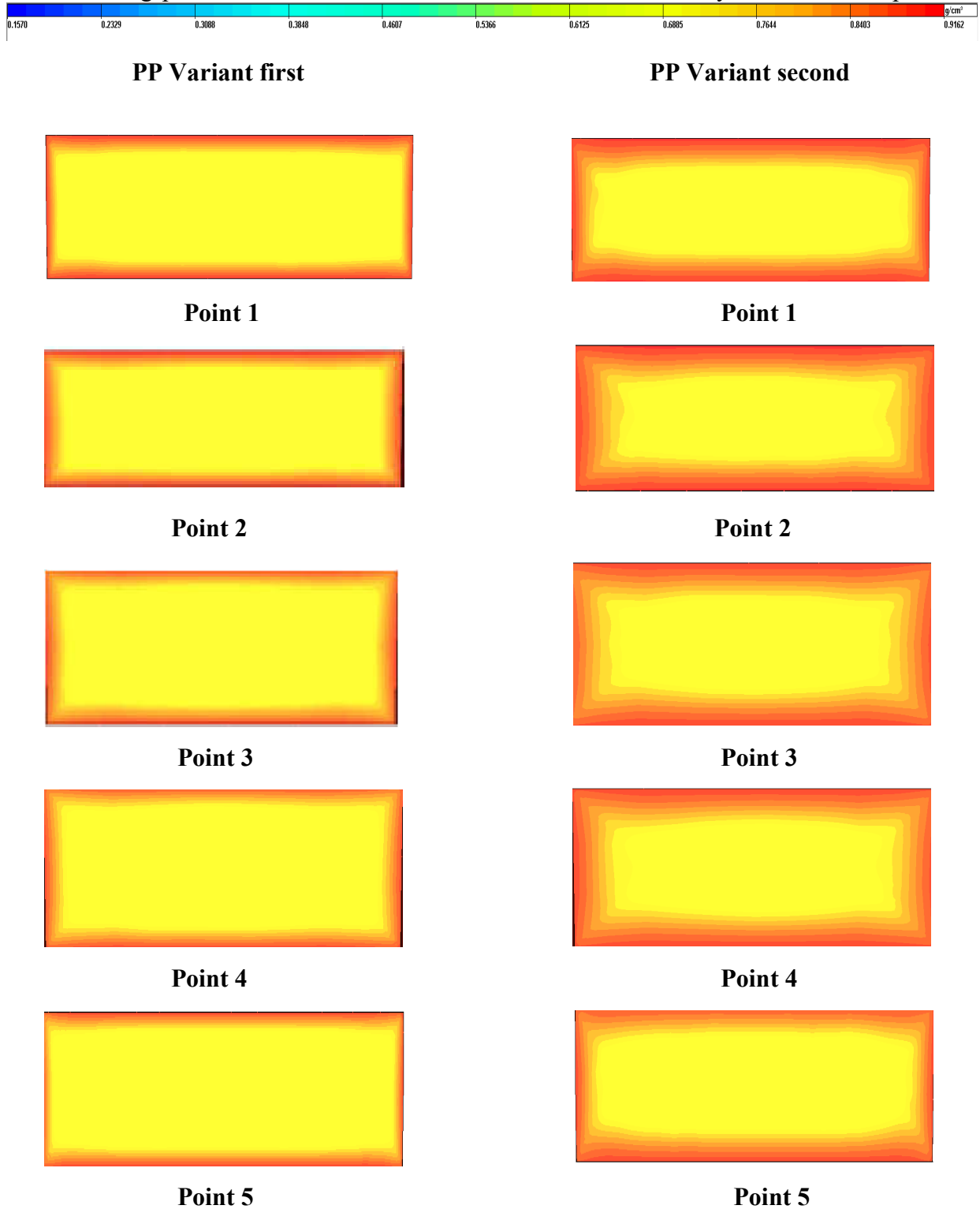


Fig. 33: Distribution of packing density in cross section area of PP variant first and second

The above picture illustrates the density of distribution in cross section throughout the part and the densities at 5 points are shown in below pictures.

### Distribution of density:

The following pictures illustrate the cross section distribution density at 5 evaluated points.



*Fig. 34: Average density at five points for PP variant first and second*

After comparing both the pictures, I conclude that the density shows the similar characteristics to the experimental result. It is clearly seen that density is low near the gate and



at the end of the part. Moreover, Second variant reveals higher density than first one since increased holding pressure value it significantly effect on density of the materials. If holding pressure is increased then it will reduce lower mass of the product due to high density.

**Cell size:**

The cell size was measured exactly the same points where real values of cell size was taken. The following pictures provide the information about distribution of bubbles in the cross section and size of the skin layer. Both variants reveal same distribution at both the points.

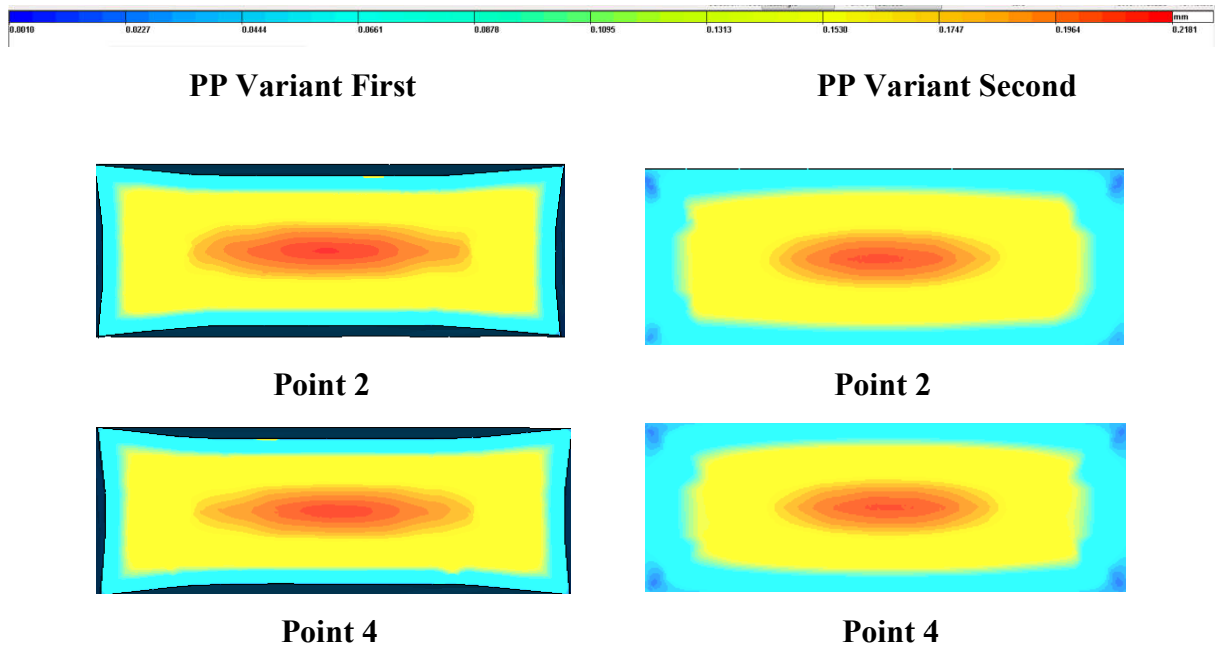


Fig. 35: Distribution of Cell size for PP variant first and second

It shows the same characteristic like a real process. The compact skin layer for first and second variant is same at points 2 and 4. But the second variant shows higher compact skin layer than first variant. The distributions of cells are quite similar at both the point for variant first and second but more uniform structure is achieved in first variant.

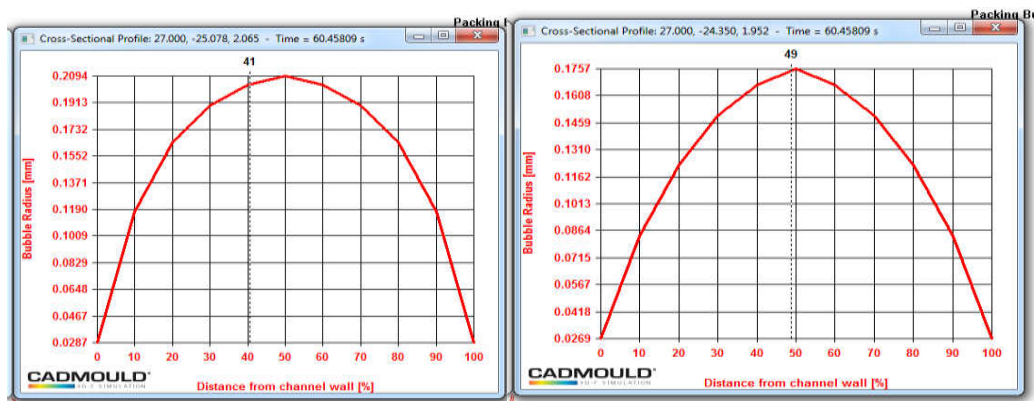


Fig. 36: Graphical representation of Bubble radius for PP variant first and second

Above figure illustrate the value of bubble radius of PP variant first and second. After comparing both the graph, I conclude that Variant first shows higher value of bubble radius than second variant which is obvious according to previous result.

### 3.4.2 Production of PP+30 GF samples

Tab.26: Result of total weight and percentage of weight reduction

PP GF	Weight	Weight save
Without Nitrogen gas	29.55 g	
First variant	24.74 g	16.27 %
Second variant	27.04 g	8.49 %

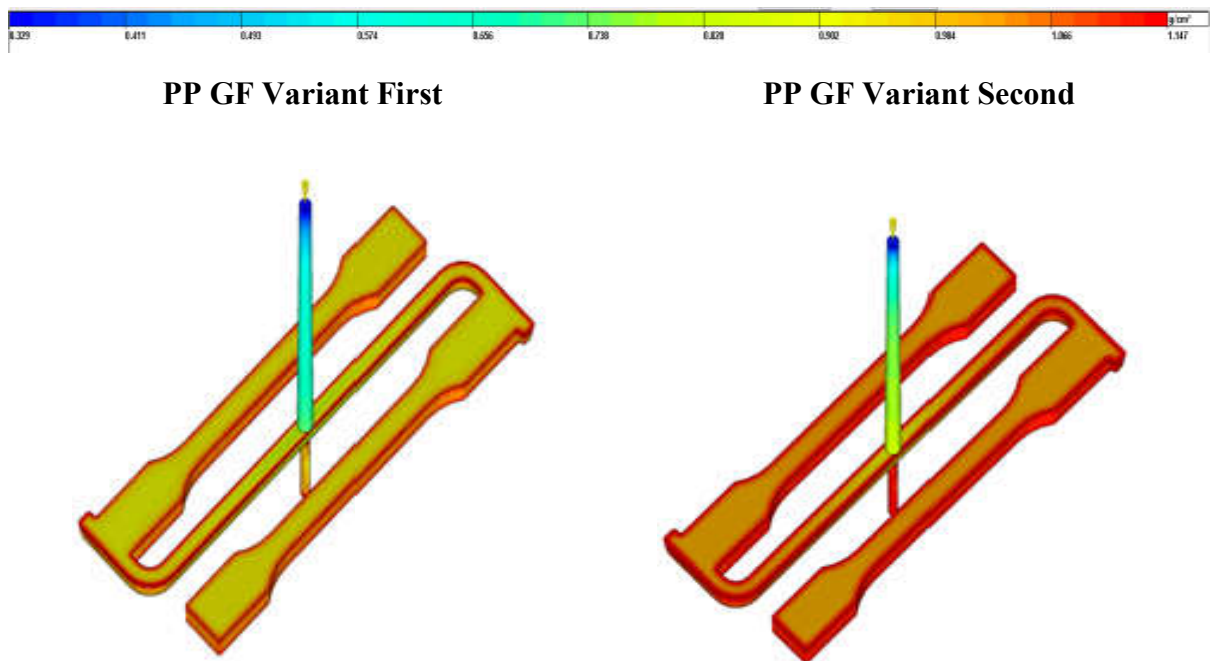


Fig. 37: Distribution of average density of PP GF variant first and second

The pictures reveal that the distribution of average density is higher in second variant while first variant has comparatively low distribution.

### Graphical Representation:

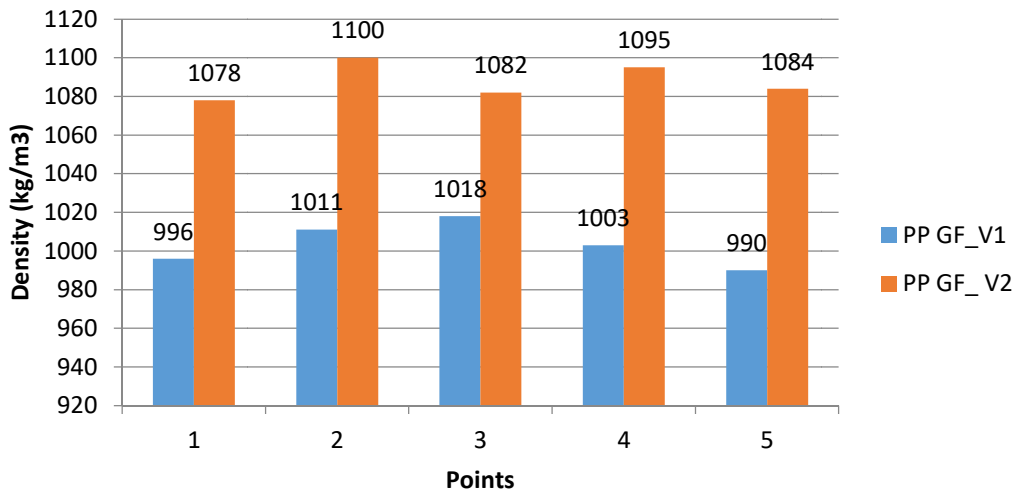


Fig.38 Density of PP GF variant first and second at five points

The above graph depicts the value of density at 5 points. It shows the similar characteristics like real process. Density is lower near the gate and at the end of the part while higher in the middle section. One more thing is found the same like in previous case that simulation show higher values than real process.

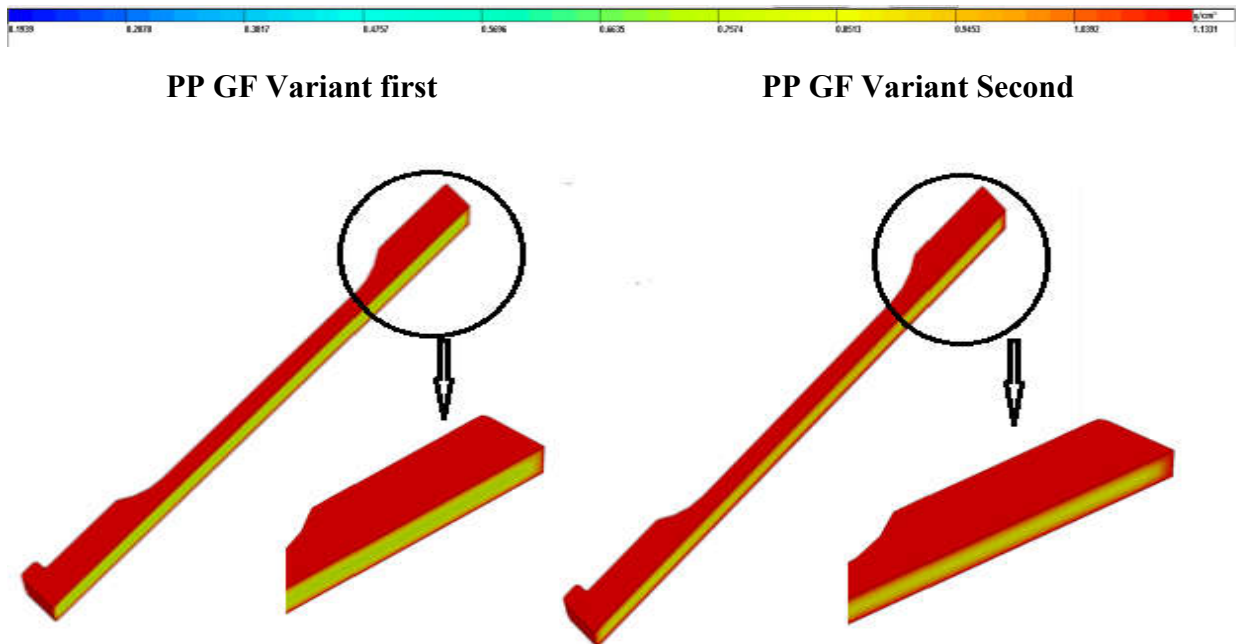
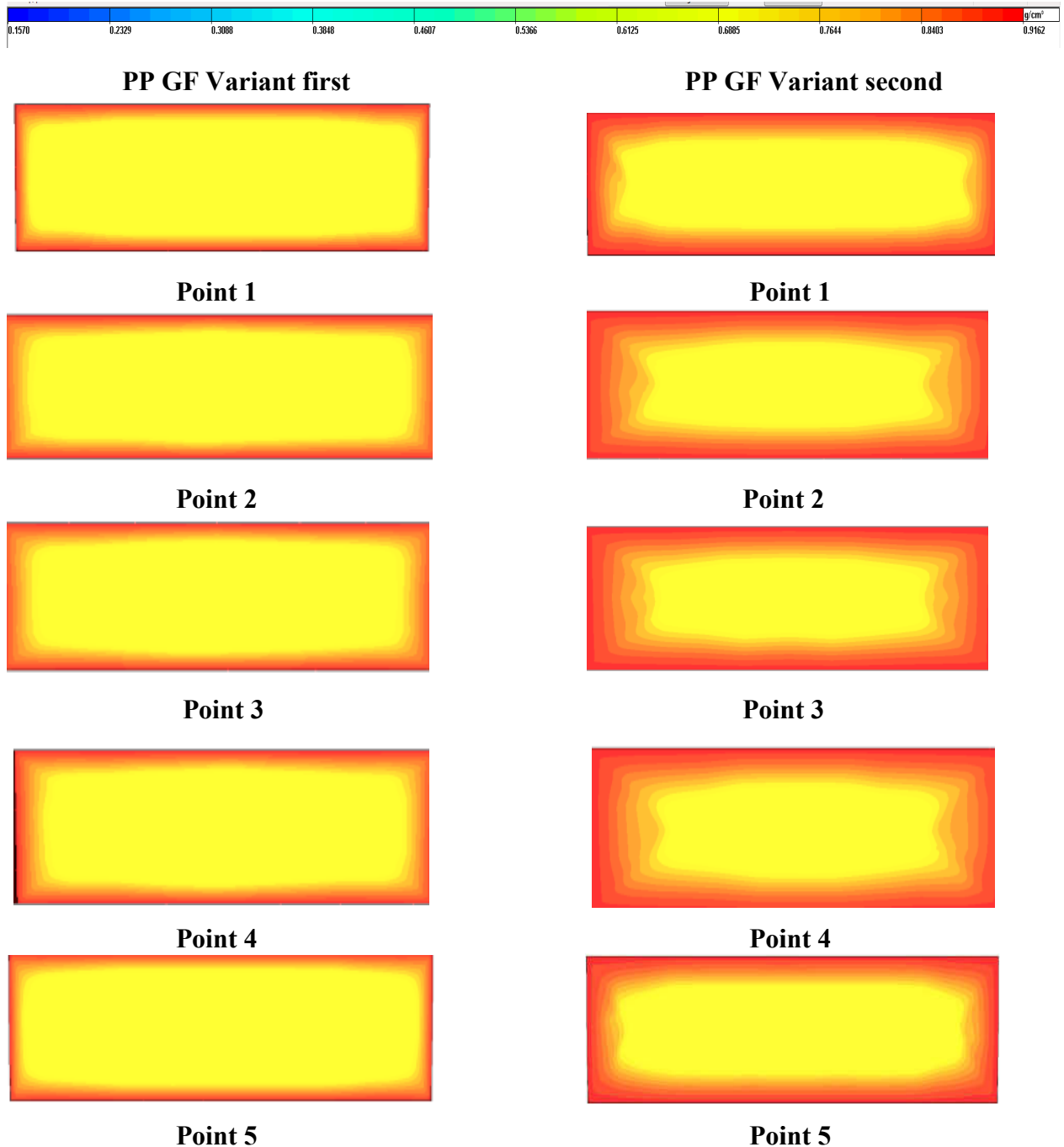


Fig. 39: Distribution of packing density in cross section area of PP GF variant first and second

Above picture reveals the distribution of density in cross section throughout the part and the detailed description of distribution at particular points are shown in below figures.

### Distribution of density:

The following pictures show the cross section distribution density at 5 different points where real measurement was done.



*Fig. 40: Average density at five points for PP variant first and second*

Distribution of density for PP GF, it again shows same characteristics like in previous case. At points 1 and 5 distribution of density is lower in both the case while at points 2, 3, 4 densities are higher. Moreover, increased holding pressure shows higher density which can be seen from the second variant.

**Cell size:**

The following pictures show the distribution of bubbles in the cross section and compact skin layer.

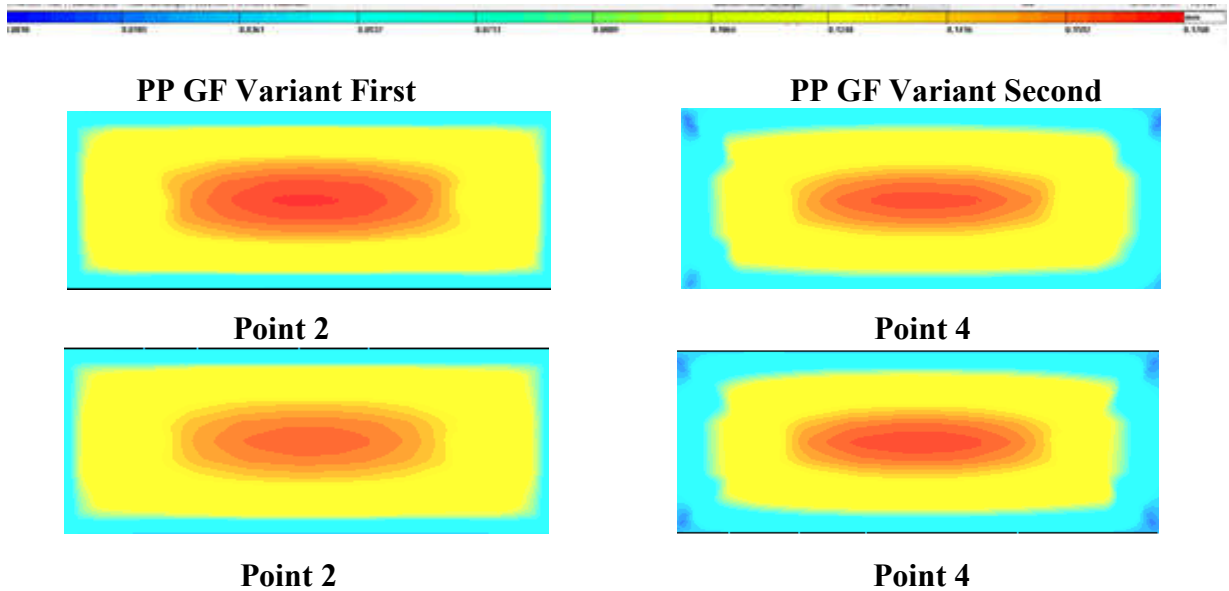


Fig. 41: Distribution of Cell size for PP variant first and second

After making the comparison, it is found that the layer of compact skin is same at both points for both the variant. But it is again followed the similar characteristics like in previous case. Second variant reveals higher compact skin layer than first variant. Moreover, 0 sec holding pressure gives distribution with more similar size of the cell.

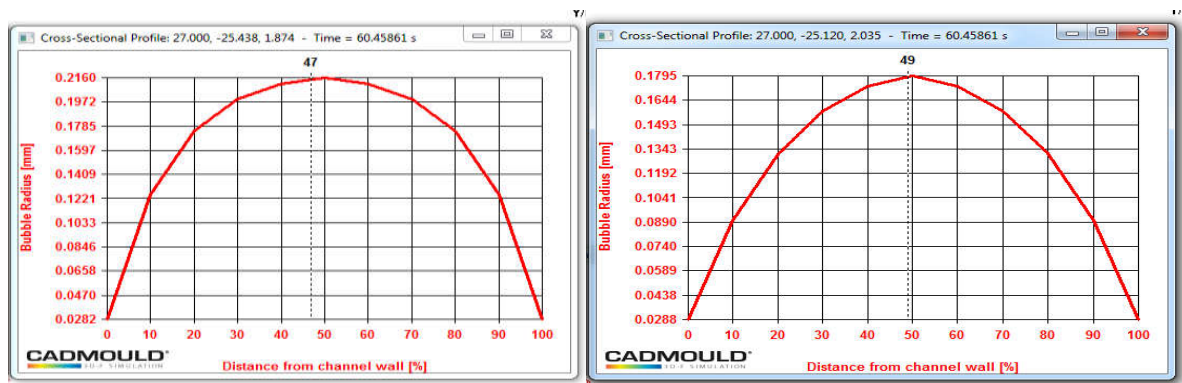


Fig. 42: Graphical representation of Bubble radius for PP variant first and second

Above figure illustrate the value of bubble radius of PP GF variant first and second. After comparing both the graph, I conclude that Variant first shows higher value of bubble radius than second variant which is obvious according to previous result. Higher value of radius means lower density.

### 3.4.3 Production of ABS samples

Tab.27: Total weight and percentage of weight reduction

ABS	Weight	Weight save
Without Nitrogen gas	27.43 g	
First variant	25.11 g	8.45 %
Second variant	26.59 g	3.06 %

The above table demonstrate the values of total mass for each three variants of ABS. It shows again the same characteristics like in previous case. First variant gives 8.45 % reduction of mass which is quite more than second variant which is only 3.06%.

#### Density:



ABS Variant First

ABS Second Variant

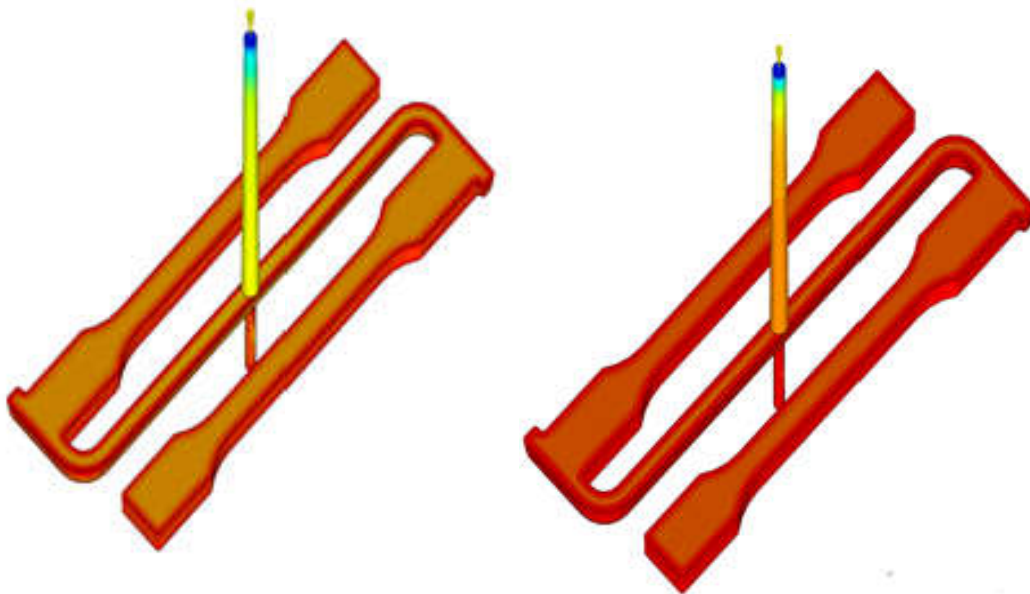


Fig. 43: Distribution of average density of ABS variant first and second

Again ABS also follows the same characteristic like PPGF does. By comparing both the pictures, it is observed higher difference of distribution of average density. Second variant reveals higher value of average density than first variant.

**Graphical representation:**

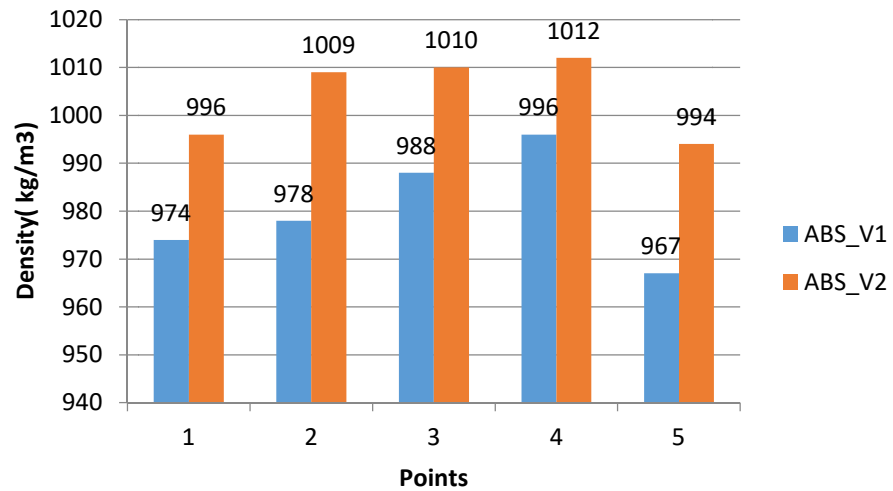


Fig.44 Density of ABS variant first and second at five points

The graph shows that ABS also behaving in same manner like the previous materials dose. Near the gate and at the end of the part the density is lower while higher density can be detected in the middle section, point 2, 3, 4.

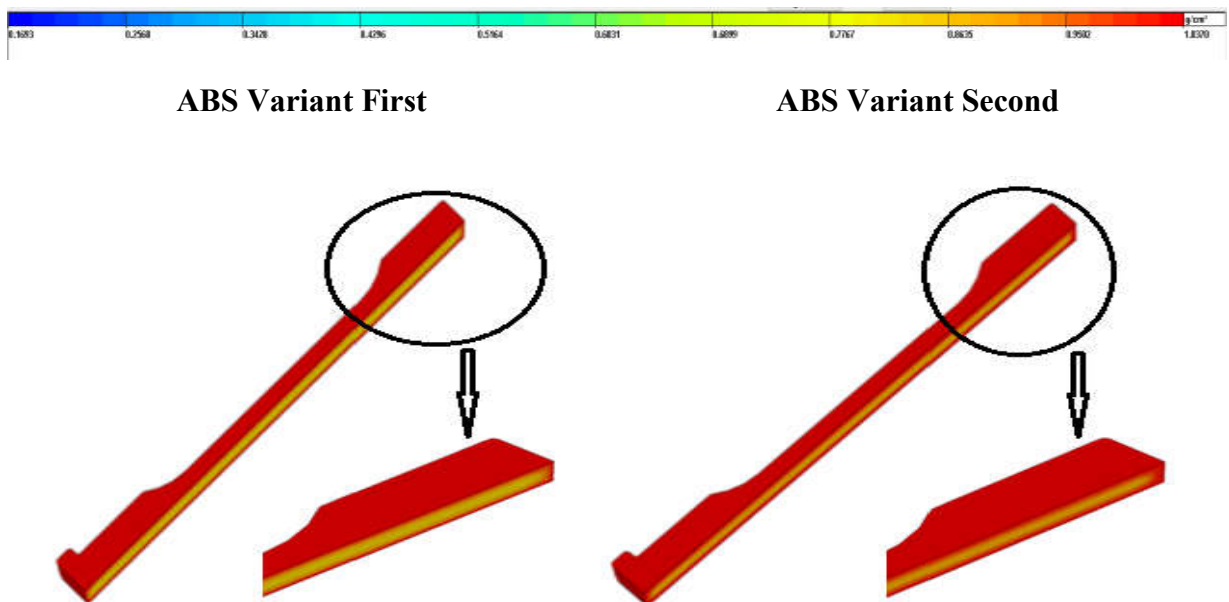
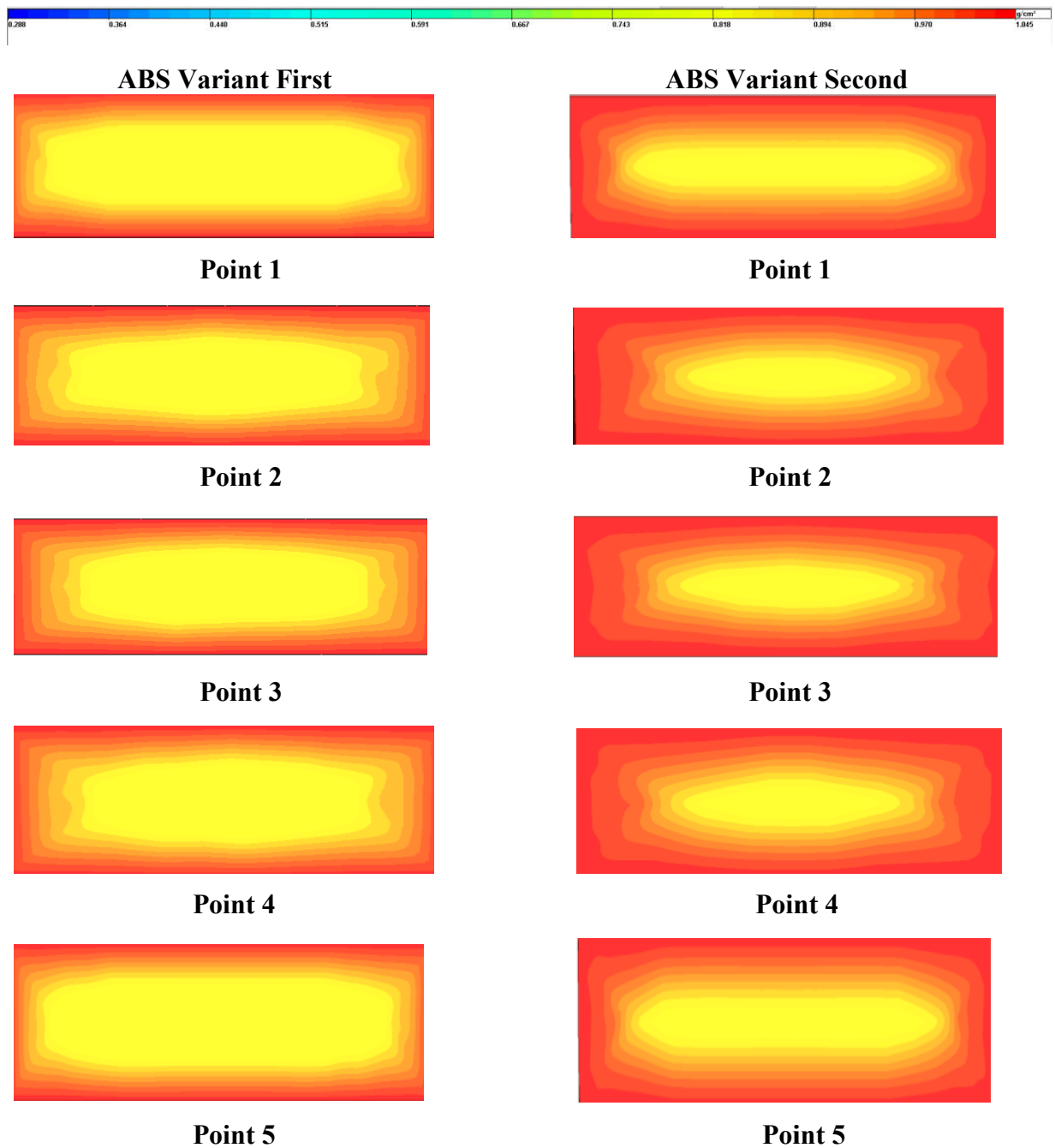


Fig. 45: Distribution of packing density in cross section area of ABS variant first and second

The picture illustrates the distribution of density throughout the cross section area of the part. The second variant of ABS gives larger cross section area of density with higher values close to the surface than the first variant. Below are the pictures of distribution of density at individual points.

### Distribution of density:

The following pictures show the cross section distribution density at 5 individual points for variant first and second.



*Fig. 46: Average density at five points for ABS variant first and second*

The above picture reveals the distribution of density across the part. It has again same characteristics but the distribution shows thicker layer of density than rest of the two materials. Moreover, second variant, 5 sec holding pressure reveals higher value of density than first variant which is also similar with real process.



**Cell size:**

The following pictures illustrate the distribution of bubbles in the cross section and compact skin layer.

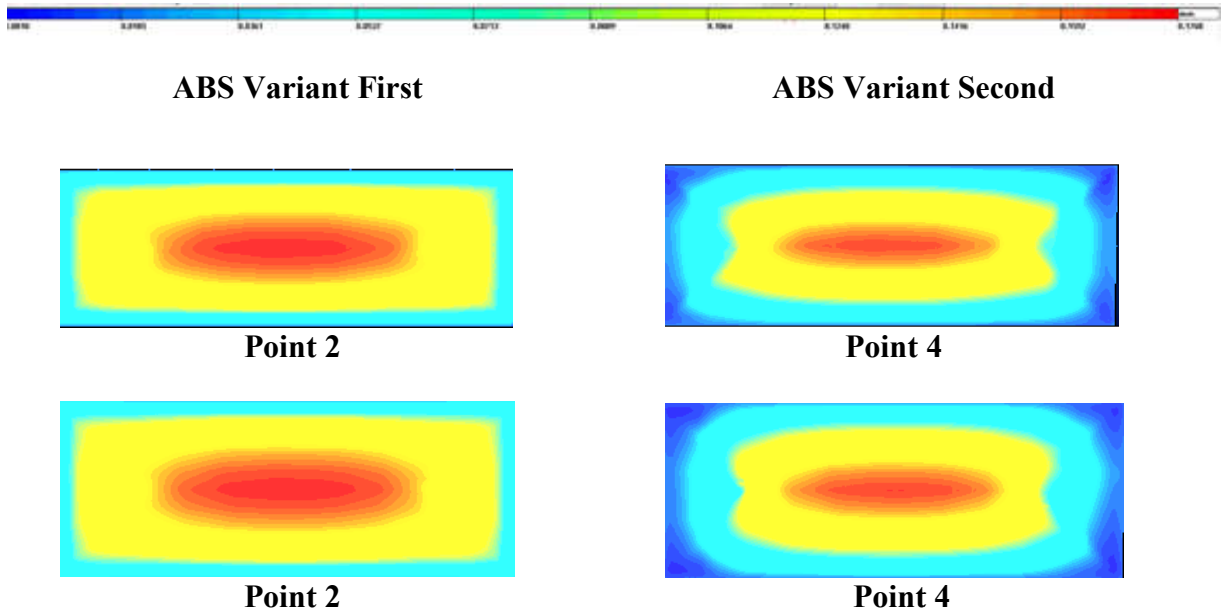


Fig. 47: Distribution of Cell size for ABS variant first and second

By showing this picture, I confirm that variant first and second both have similar compact skin layer but it can be noticed that second variant shows larger layer of compact skin than first one. One more thing is, distribution of cell with higher values is larger in first variant than in second variant.

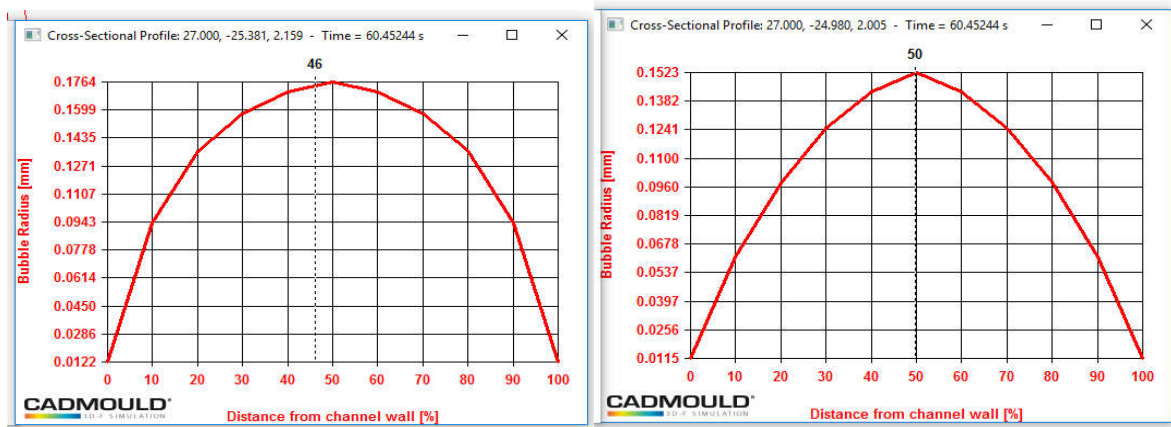


Fig. 48: Graphical representation of Bubble radius for ABS variant first and second

Above figure illustrate the value of bubble radius of ABS variant first and second. After comparing both the graph, I conclude that Variant first shows higher value of bubble radius than second variant which is obvious according to previous result.

#### 4. Discussion

In this chapter the comparison of achieved results between real process of micro cellular injection molding and real process was made. According the experimental steps, three results named total mass, density and size of the cell were compared and conclusion is made.

#### MASS

#### PP

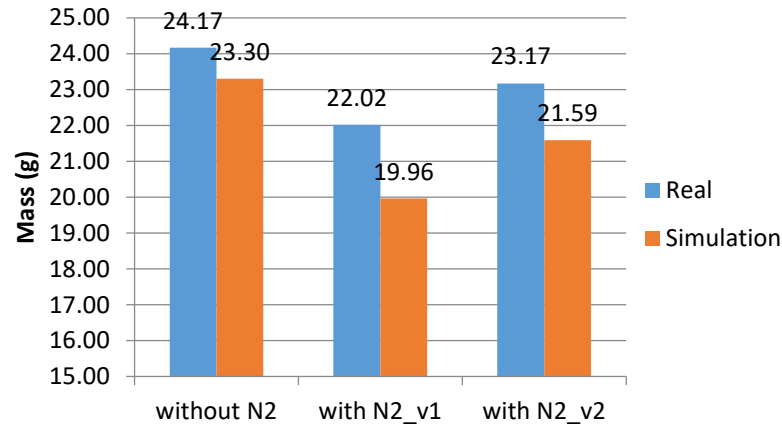


Fig.49: Comparison of PP mass for actual and simulation process

After comparing the both chart of PP, I conclude that simulation predicts slightly lower result than actual process. Apart from this, the product without nitrogen exhibits lower differences that with nitrogen for both real and simulation process. Moreover, with longer holding pressure time achieved higher reduction of mass which follows the characteristics as the simulation prediction.

#### PP GF

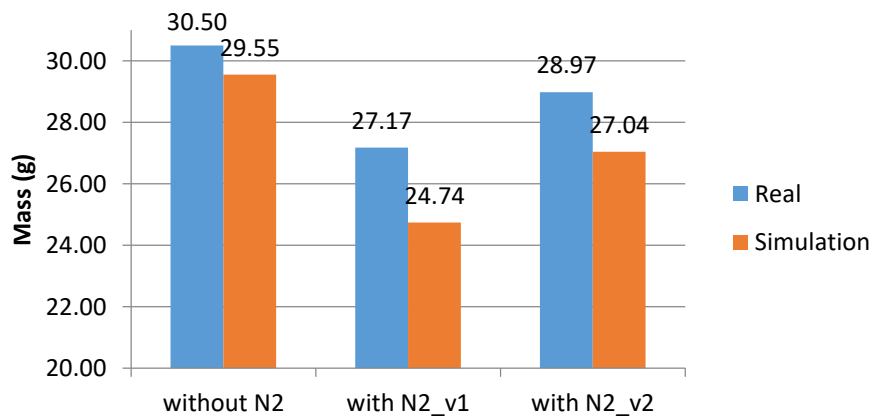
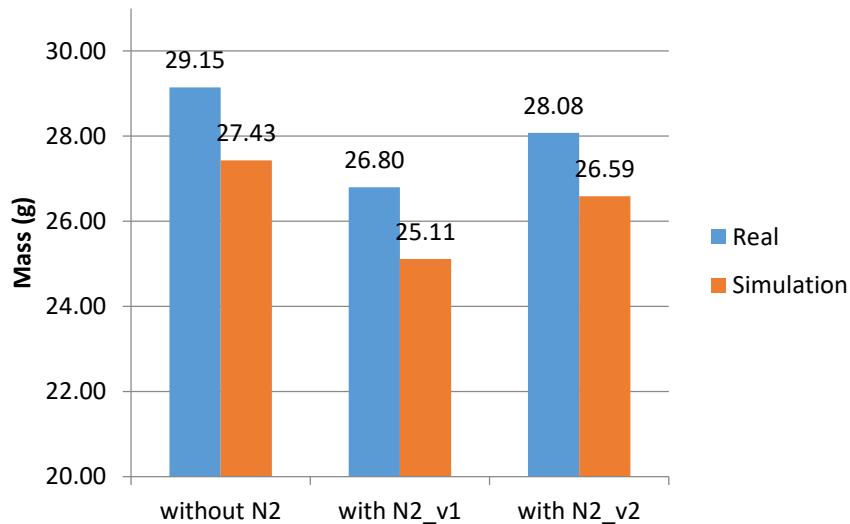


Fig.50: Comparison of PP GF mass for actual and simulation process

The graph of PP GF exhibits similar characteristics like previous case but the differences of the mass between simulation and real process is quit lower accept the variant which was used with 0 sec holding pressure. The prediction of mass by simulation was lower for all the cases than real process. Moreover lower mass reduction is observed during the variant with 5 second holding pressure.

### ABS



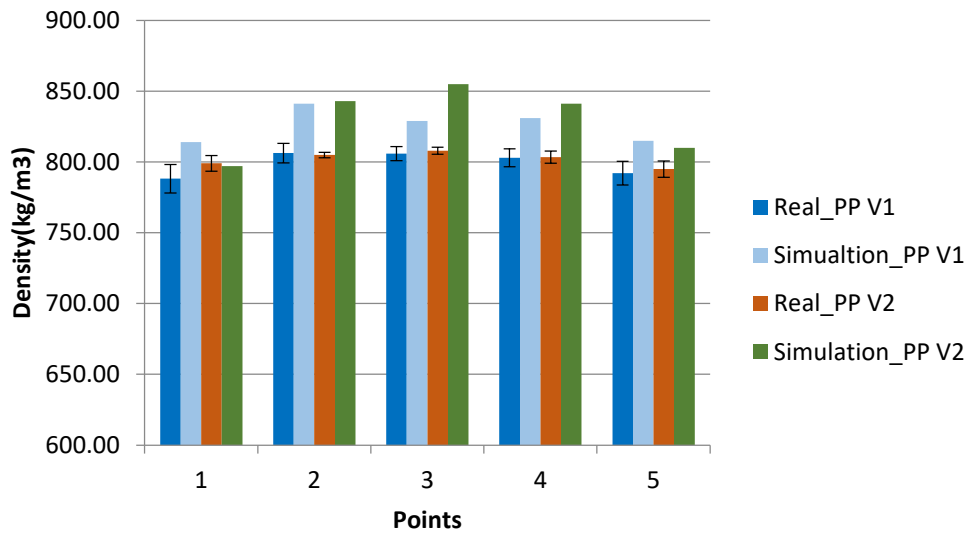
*Fig.51: Comparison of ABS mass for actual and simulation process*

After comparing all the three cases, I confirm that real and simulation process both gives different result with 2 or 3 g differences in all three cases for ABS. Moreover, simulation predicts lower result of mass than actual process. Finally, I determine that the differences are quit same with actual process for all three materials. It means tendency for prediction and characteristics are quite good but the total values are not the same as real process.

## DENSITY

During measurement of density, variant first and second was measured at five points for both the process of real and simulation and according that result were compared by using following graphs.

### PP



*Fig.52: Comparison of density of PP variant first and second for actual and simulation process*

Above graph depicts the values of density of both the variant for simulation process and actual process. Both result shows the same characteristics about the higher density in the middle points and lower near the gate and end of the part. But the dependence is different from the previous information from the mass which shows higher result for real process. The reason behind this is, density was measured at 5 particular points for only one test specimen while mass of the product was measured with gating system and test specimen.

## PP GF

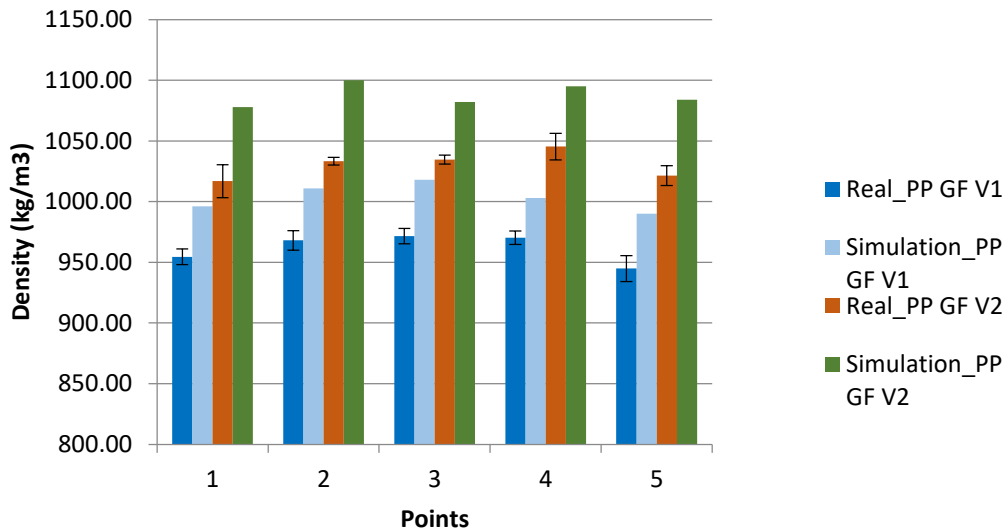


Fig.53: Comparison of density of PP GF variant first and second for actual and simulation process

The above graph represents density of all variant of PP GF for simulation process and actual process. It also follows the same characteristics like in previous case. Density is lower at near the gate and at the end of the part while higher value is seen in the middle part for the both real and actual process. Apart from this, higher value of density was measured than actual process which is similar like characteristics.

## ABS

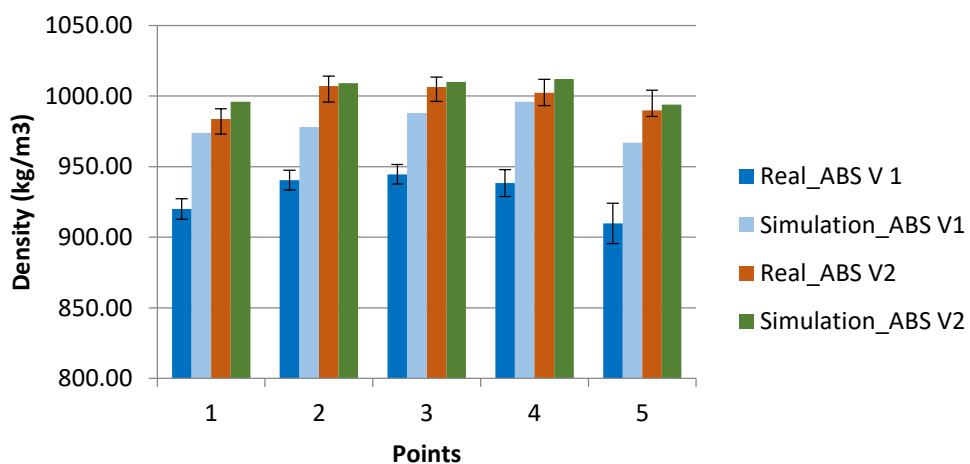


Fig.54: Comparison of density of ABS variant first and second for actual and simulation process

The above graph demonstrates the value of density of ABS for both simulation process and actual process. The similar characteristics can be observed like both previous cases. At points 2, 3, and 4 shows higher value of density for each variants while at points 1 and 5, density is lower. Apart from this, higher values are predicted by simulation than real process. The reason could be the real process experience the agglomeration of the bubbles which cause effect on the structure and final mechanical properties while there is not any prediction of this parameter in simulation.

### CELL SIZE

During the evolution of microscopic cell size, equivalent average and area was measured for 3 possible cells in different location. In simulation same area was chosen to make comparison of the result. The selected area was highlighted by Black dot. Following are the description of all three materials.

### PP

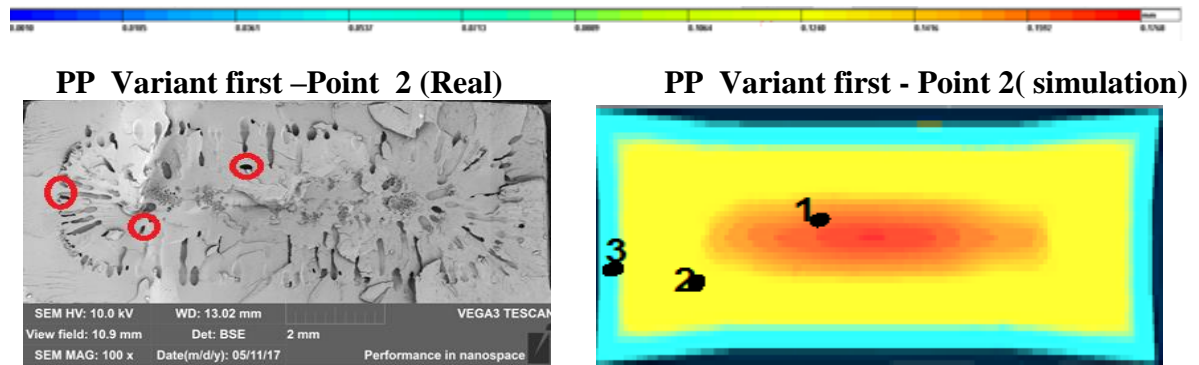


Fig. 55: Comparison of microscopic picture and simulation for PP variant first

Tab. 29: cell size

Points (Red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.18 mm	0.1875 mm
2	0.15 mm	0.1593 mm
3	0.12 mm	0.1192 mm

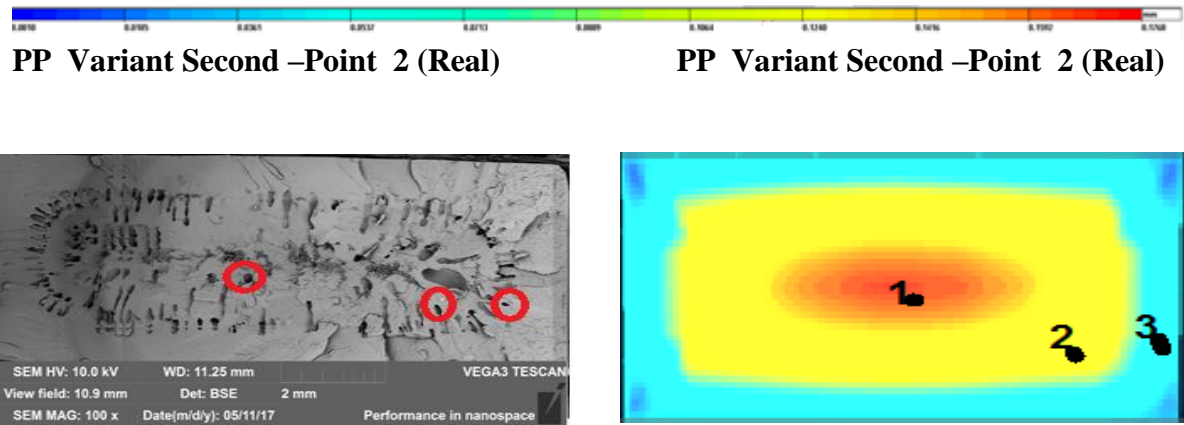


Fig. 56: Comparison of microscopic picture and simulation for PP variant second

Tab. 30: cell size

Points (red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.16	0.1763
2	0.10	0.1226
3	0.09	0.0910

The size of the cell is dominant factor for foam part in order to evaluate the properties of the materials. The above pictures illustrate the internal structure of PP for both the variant. The size of the cell is quite similar in both variant for real and actual process. The values are shown in table 30 and 29. Besides, it is observed that the compact skin layer is nearly the similar in both simulation and actual process. Moreover, the size of the cell, without coalescence, observed quite similar in both the real and actual process. Unfortunately, the coalescence was dominant affected for creation of cell in used PP production. Also the nucleation of cell is not uniform. It is the proof why values of density in the simulation are not the same as in real process. One more thing, the effect of agglomeration and coalescence are not predicted by simulation.

## PP GF

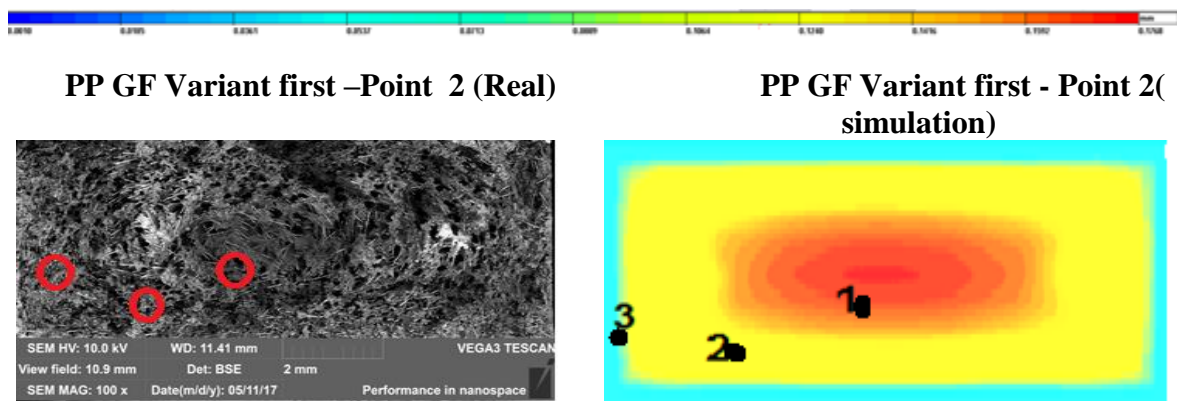


Fig. 57: Comparison of microscopic picture and simulation for PP GF variant first

Tab. 31: cell size

Points (red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.14 mm	0.18 mm
2	0.09 mm	0.09 mm
3	0.05 mm	0.09 mm

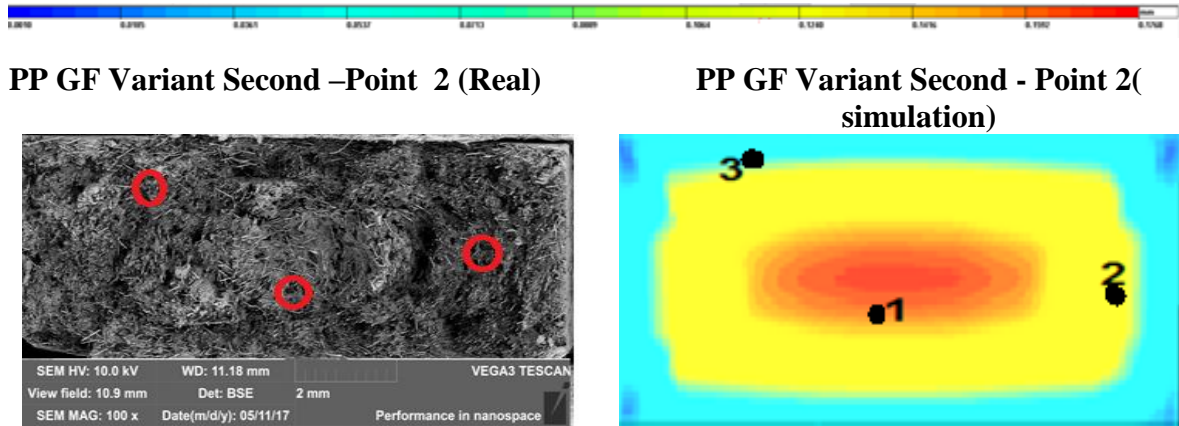


Fig. 58: Comparison of microscopic picture and simulation for PP GF variant second

Tab. 32: cell size

Points (red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.18 mm	0.1785 mm
2	0.11 mm	0.1197 mm
3	0.08 mm	0.0914 mm

After comparing the picture of cell size for both the variants of PP with glass fibre, I conclude that, at location number 1 and 2 the distribution of cell is quite similar with simulation result but the compact skin layer is totally different. It is hard to evaluate compact skin layer especially for PP with glass fibre. Moreover, the higher cells are observed in first variant than second variant which is also quite similar to actual process.

### ABS

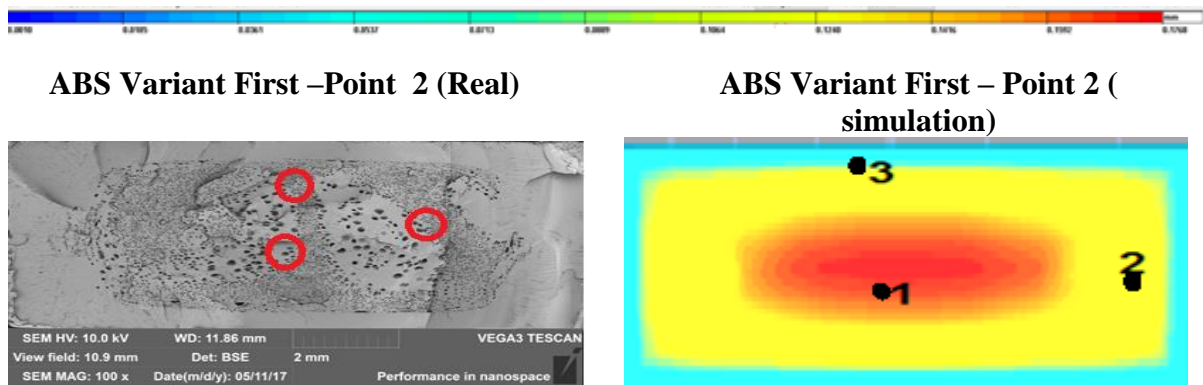


Fig. 59: Comparison of microscopic picture and simulation for ABS variant first



Tab. 33: cell size

Points (red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.12 mm	0.1794 mm
2	0.11 mm	0.13 mm
3	0.06 mm	0.11 mm

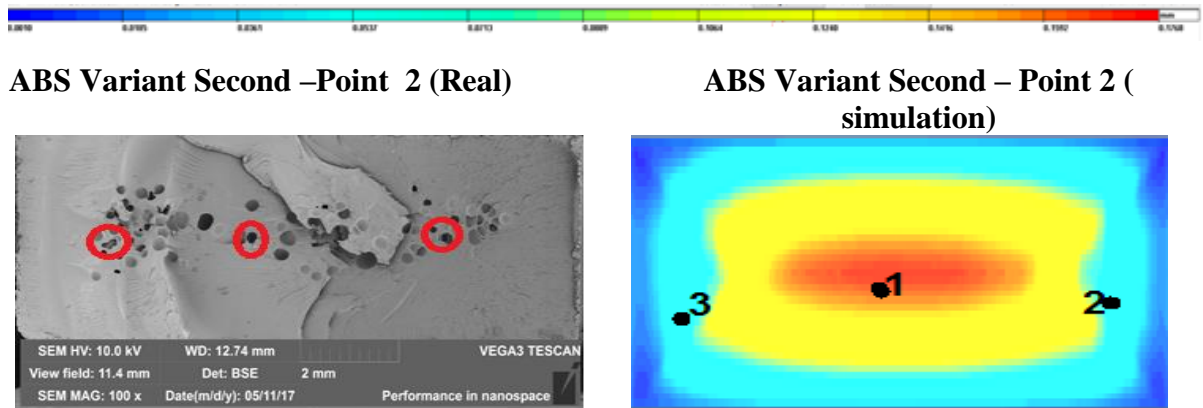


Fig. 60: Comparison of microscopic picture and simulation for ABS variant second

Tab. 34: cell size

Points (red circle)	Equivalent Average (Real)	Equivalent Average (Simulation)
1	0.20 mm	0.1499 mm
2	0.13 mm	0.1139 mm
3	0.09 mm	0.0950 mm

After comparing both the variants, it seems that the area of compact skin layer is close to real process for both the variants. The distribution of cell in first variant for simulation process is uniform but the real process shows some agglomeration effects, especially in the core prediction is not according to it. The real process of second variant shows much more higher differences between predicted cell size distribution and real process due to higher effect of agglomeration.

## 4. Conclusion

Simulation, it is a part of today's technology where everything can be predicted before the actual process happens. But before believing on this virtual result, it has to be checked first whether it works according to the showing result or not.

In the beginning, the experiment was done by using Mucell technology. Standard injection test specimen ISO 527-2 A1 was used for the experiment for getting the transparency into the result. Two materials from different groups named Semi crystalline material PP and Amorphous material ABS were chosen. The main reason behind this was to check the effect on foaming structure for all these different groups of materials. Also PP with 30% glass fibre was used to analyse the effect of it during the foaming process. After getting the result from the actual process, it was observed that according to theory PP is not so good material for foaming which is true because real process shows the problem of agglomeration of cells which can directly influence mechanical properties. But if the same material is used with glass fibres then it gives fine and uniform structure due to heterogeneous nucleation. Moreover, according to the theory ABS is more suitable for micro cellular injection moulding. But during real production, it was detected some problem with non-uniform nucleation and agglomeration. Therefore this theory could not be confirmed.

During real production, two different process parameters were used one with 0 sec holding pressure and second one with 5 sec holding pressure. When there was used 0 second holding pressure, the structure showed smaller thicker area of compact skin while larger thicker area of compact skin was observed with 5 second holding pressure. Moreover, Distribution of cells was found more finer with 0 second holding pressure than product with 5 second holding pressure. Lastly the values of density found lower for the variant with the 0 second holding pressure than 5 second for all three evaluated cases. Because holding pressure significantly affects the structure and makes it more fine which influences the result of density.

After finishing the experiment part of real production, same process parameters were put into the CAD mould 3D F simulation software. The similar parameters were measured also during simulation process and comparison was made.

By comparing both the results, it was confirmed that the prediction of the compact skin for material PP without glass fibre and ABS is similar like real process. PP with glass fibre

showed totally different compact skin layer than actual process. Moreover, distribution of cell size was predicted quite similar at evaluated points. But especially for PP and ABS, there was observed some negative effect like agglomeration, coalescence and non-uniform nucleation which was not detected in the simulation. Therefore, the result of density was obtained different than real process.

Simulation is good for prediction but still there are very some differences which were observed. So it could help to imagine what could happen in the material but my experiment did not exhibit the same result like real process. There was observed some differences in the results between real process and simulation for all the material and all the process variants. So it is still necessary to improve the accuracy. The problem behind this could be, simulation does not allow to set all the process parameter which is used in real production e.g. Like during real process back pressure plays important role for diffusion of the gas. It changes the diffusion of gas but it is not possible to make a change with simulation software. Simulation gives result every time in ideal state while real process is not done in ideal state. Many other process parameters could influence the result this is the reason why simulation cannot predict the same result like real process. During the simulation process automatic mode was used. But there is another mode named expert mode. This mode has two different categories one is for Henry's law constant and second is for diffusion coefficient. So I would recommend to use this mode if the values are known by the user then it can predict result with better accuracy.

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**Attachments:**

**Dimension of the test specimen**

