FABRICATION OF MOLD PARTS USING FUSED DEPOSITION MODELING AND VACUUM CASTING

AYAZ ASIF

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
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ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: AYAZ ASIF

Matric No: KQG160016

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ABSTRACT

Molding the part is a conventional technique that is highly adopted in industries to produce plastic & metallic parts. This huge demand urged to use several automated CNC machining processes (material subtraction technique) to produce mold parts that is fast and accurate. Nowadays a lot of research is being conducted to produce metal parts by sintering the powder or binding the resin using laser or UV light (rapid prototyping) but it seems very difficult to achieve required mechanical properties under cyclic loading so a combination of latest fused deposition modeling (FDM) and conventional vacuum casting processes are used to produce mold parts as these processes are accurate and reliable. This methodology adopted is designing the mold using Solidworks (drafting, creating partition surface, building core & cavity and tools splitting), printing using fused deposition modeling printer (CAM at highest resolution), casting the part (preparing slurry mixture, filling in conical flask containing part, vacuum to remove bubbles, curing, dewaxing and filling) and finishing (refining edges, sand blasting, grinding and polishing) to make it presentable. Part produced is being inspected using microscopy and surface roughness test to highlight the efficiency and drawbacks in this process. For that purpose, 3D Scanning using Sense Scanner is done to look at all the dimensional changes and compared with CAD Drawing, so this process is so far 70-80% accurate and can be improved further by using specialized equipment (accuracy in printing, machine-based casting like investment casting), choosing the suitable part & size as downsizing and uneven surface are difficult to grind and polish and selecting the right material (SS 420). This process can have an impact on several industries like Automotive,

Plastic based industries and can be expanded to producing parts in investment casting for Aviation Industry with the requirement of mold.

FABRIKASI BAHAGIAN MENGGUNAKAN MENGGUNAKAN PEMODELAN PEMENDAPAN YANG DIGUNAKAN DAN CASTING VACUUM

ABSTRAK

Mencetak bahagian adalah teknik konvensional yang sangat diterima pakai di industri untuk menghasilkan bahagian-bahagian plastik & metalik. Permintaan besar ini digesa untuk menggunakan beberapa mesin pemesinan CNC automatik (teknik penolakan bahan) untuk menghasilkan bahagian acuan yang pantas dan tepat. Kini, banyak penyelidikan sedang dijalankan untuk menghasilkan bahagian-bahagian logam dengan mengintegrasikan serbuk atau mengikat resin dengan menggunakan laser atau uv light (rapid prototyping) tetapi nampaknya amat sukar untuk mencapai sifat-sifat mekanik yang diperlukan di bawah beban kitaran supaya kita menggunakan kombinasi terkini proses FDM dan proses pemutus vakum konvensional untuk menghasilkan bahagian acuan kerana proses ini adalah tepat dan boleh dipercayai. Metodologi yang digunakan adalah merekabentuk acuan menggunakan kerja pepejal (penggubalan, membuat permukaan partisi, bangunan core & cavity dan pemisahan alat), mencetak menggunakan pencetak FDM (CAM pada resolusi tertinggi), peletakan bahagian (menyediakan campuran slurry, mengisi flask conical yang mengandungi bahagian, vacuum to remove bubbles, curing, dewaxing and filling) dan finishing (edging edge, blasting sand, grinding and polishing) untuk membuatnya rapi. Bahagian yang dihasilkan sedang diperiksa menggunakan mikroskop dan ujian kekasaran permukaan untuk mengetengahkan kecekapan dan kekurangan dalam proses ini. Untuk tujuan itu, Pengimbasan 3D menggunakan Pengimbas Sense dilakukan untuk melihat semua perubahan dimensi dan dibandingkan dengan Lukisan CAD, jadi proses ini sejauh 70-80% tepat dan boleh dipertingkatkan lagi dengan menggunakan peralatan khusus (ketepatan pencetakan, mesin pemutus yang berpusat seperti pemutus pelaburan), memilih bahagian dan saiz yang sesuai

sebagai pengurangan dan permukaan tidak sekata sukar digiling dan menggilap dan memilih bahan yang betul (SS 420). Proses ini boleh memberi impak kepada beberapa industri seperti industri Automotif, Plastik berasaskan dan boleh diperluaskan untuk menghasilkan bahagian dalam pemutus pelaburan untuk Industri Penerbangan dengan keperluan acuan.

ACKNOWLEDGEMENTS

Thanks to Allah Almighty for my passion, energy and responsiveness towards this Project.

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Special thanks to Lab Assistants, especially in Surface Lab, Workshop and Furnace Lab who has helped in good execution of difficult processes like Casting, Machining and Heat Treatment.

I must be thankful to all Department of Manufacturing Engineering Faculty Members for making me enough skillful to smoothly execute this project and most of the Administrations for helping in regards to important quarries about submission deadlines.

Finally, Many Thanks to My Parents who has been supportive throughout my Life and Education, It's a great blessing from Allah Almighty. Thanks to my rest of the Family Members and Friends for giving kind support to achieve this.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
ATR	Aerei da Trasporto Regionale (French-Italian Company Aircraft)
CAD	Computer Aided Design
CAM	Computer Aided Modeling
CLIP	Continuous Liquid Interface Production
CNC	Computerized Numeric Calculation
DPT	Die Penetrating Testing
FDM	Fused Deposition Modeling
HDPE	High Density Poly Ethylene
HDPP	High Density Poly Propylene
ISO	International Standard Organization
NURB	Non-Uniform Rational B-Spline
NDT	Non-Destructive Testing
OSHA	Operational Safety and Health Analysis
PLA	Poly Lactic Acid
PET	Polyethylene Terephthalate
PS	Polystyrene
PC	Polycarbonate
RP	Rapid Prototyping
RC	Remote Control
SLA	Stereolithography
TVF	Tip Vortex Free
VC	Vacuum Casting

CHAPTER 1: INTRODUCTION

1.1 Background Study

Mold making is 6000 years old technique. It was called copper age in which basic technique of metal extraction and processing was developed. In the era of Roman and Greek empires, these techniques are improved to build tools, religious artifacts and jewelry. During industrial age of 19th century, a lot of techniques like precision casting, forging and hot/cold metal forming techniques were developed. Nowadays a lot of casting processes *(die casting, vacuum casting, investment casting and sand casting)* has been developed. (Burner Felton Barrie, 1992)

Vacuum casting is most widely used for producing both metallic and non-metallic parts in several industries. In this process, part in the chamber is filled with investment *(silicon/plaster of paris)* depends on part to be produced. It is also called lost wax casting process because it melts the wax/plastic based part inside the mold and filling it with molten metal to make the part. On the other hand fused deposition modeling/3D printing (Rapid Prototyping) is relatively new technology used to quickly fabricate the layer by layer model by utilizing computer aided design (CAD/CAM). It uses several types of polymer based filaments by melting and depositing it on the surface.

In literature/industry, there are several different types of molds (cold & hot) which are utilized in various processes like injection molding, blow molding, metal and ceramic die casting etc. All types of molds are mounted with sprue, runner and gating system to enable smooth flow of molten material in die. Each mold has two important parts separated by parting line/surface core and cavity that are credited as upper and lower side of the product. Some other parts are ejector pins, cooling pins, injector and ejector plate, clamping and connecting systems to make it flexible and fully automated. Our focus is on main parts (core

& cavity) using recent modeling and prototyping techniques to observe its efficiency while considering time and cost.
Solid works is also an important software to design 3D models and in this project it is being utilized to design mold by following important steps like draft analysis, drafting, parting line, parting surface and tool split. These steps are being done in a sequence to make the mold from the part itself.

The part that is being selected for mold is tip vortex free (TVF-5) propeller. It's being used at the front side of engines of ATR aircrafts. 5 wings attached to a single piece and separate tip is helpful in generating more aerodynamic thrust. It also provides resistance to crack propagation.

The purpose of this study is to fabricate important parts of the mold (core and cavity) by utilizing solid works, FDM and investment casting which are previously being done by controlled CNC machining, which requires a lot of expertise in precise machining leading towards higher cost and time.

1.2 Problem Statement

In CNC operations for mold machining, a lot of challenges that companies are facing such as low speed operation, huge amount of training and expertise for staff, machine purchasing and maintenance cost, vulnerability to declination of part upon a small mistake, huge amount of machining waste etc. All of these difficulties contribute towards high cost and slow processing time.

This project is helpful in understanding the alternative to conventional mold making industry. As vacuum investment casting process can be made fully automatic and relatively easy leading towards low cost and high production capability with minimal waste.

1.3 Objective of Project

The cost of a mold ranges from USD 2000 – USD 50000, depends upon its material type, sophisticated geometry and post processing. This project aims to understand the efficiency of the methodology adopted to make mold and evaluating the errors causing defects in process to improve it for commercial utilization.

In this project, tip vortex free (TVF) propeller is being selected, used at the front of ATR airplane, creating mold Core and Cavity from 3D model, printing and building up the part using vacuum casting, this process is widely being used in jewelry making

Mold making process will be inspected in terms of time & quality that how much it can be helpful for industry. Quality of mold produced will decide its application where it can be partially or fully utilized. So objectives of this project are

1. To determine the relevant process and parameters for material addition technology for mold making
2. To investigate the efficiency/performance of the addition technology for mold making

1.4 Scope of the Project

The scope of the project is to utilize the process of rapid prototyping for mold making as it is the backbone of several industrial processes. The idea is to make thousand parts out of a single part using reverse engineering and rapid prototyping.

It can save time, cost and more efficient pattern in casting industry for injection mold making.

CHAPTER 2: LITERATURE REVIEW

2.1 Injection Mold

2.1.1 About Injection molding

Injection molding technology started in late 18th century, initially John W Hayat filed a patent to make a billiard ball using celluloid in 1872. Which is then converted into injection mold. Some of the early products produced using this process were combs and buttons. During World War II, its demand increased when he started producing important parts by utilizing recycled polymer with new material. Some of the important processes are blow molding, injection molding, rotational injection molding and compressional molding, widely used in industry.

The main principle is to use a grinded plastic. These pallets passes through conveyer belt, which is two way heated using electric heater, melted and transferred to mold/Cavity to form the desired shape. Our main focus is to fabricate mold for injection molding process.

2.1.2 Designing of Mold

Designing is based on the characteristics of the product itself and several parameters like material to be used, ability of mold, critical temperature and liquidity etc

Several designing and simulation is done on CAD/CAM software to analyze the structural design and to remove the errors in channel system of the mold

2.1.3 Classification of Mold

There is a huge range of molds in several industries but it can be classified into four categories. (Understanding the Basics of Injection Mold, 2000)

- Cold Runner Two Plate Mold
- Cold Runner Three Plate Mold

- Hot Runner Mold
- Insulated Runner Mold

2.1.3.1 Cold Runner Two Plate

There is no further heating of injected material. It uses only two plates (core & cavity) with a clear parting line. The main advantage is, it can easily install runner system on parting line.

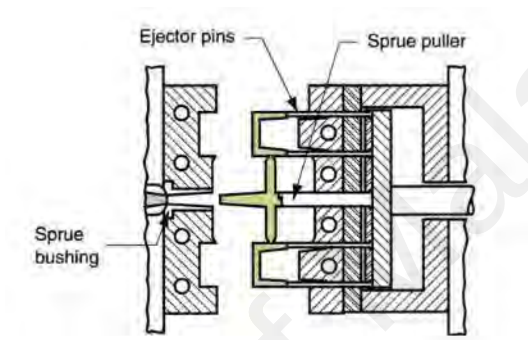


Fig 2.1 Cold Runner Two Plate Mold

2.1.3.2 Cold Runner Three Plate

It also operates at room temperature, consists of three plates, stationary, moveable and middle plate. All sprue and half of the runner are placed on stationary plate, Cavity is on middle plate.

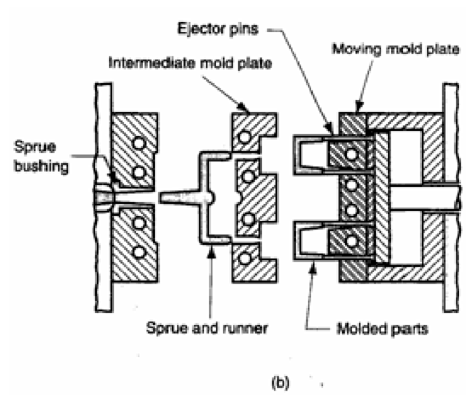


Fig 2.2 Cold Runner Three Plate Mold

2.1.3.3 Hot Runner

The runner system is kept inside the mold itself to keep its temperature higher than melting point of polymer. It can reduce the runner scrap and increase the usage time. Only disadvantage is much higher cost than cold.

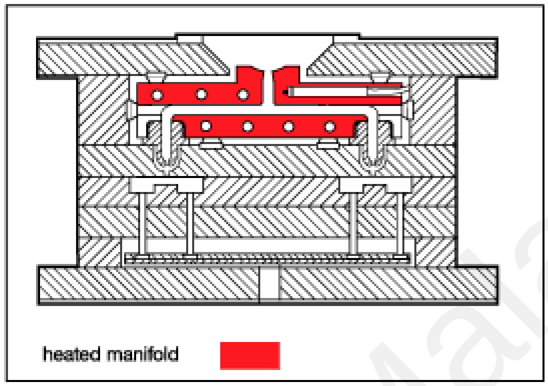


Fig 2.3 Hot Runner Mold

2.1.3.4 Insulated Runner

The runner system is relatively longer and there is the balance between the mold material requirement and runner system size to keep the smooth flow. Consistent flow of high temperature maintains the temperature to prevent freezing with the wall (runner scrap).

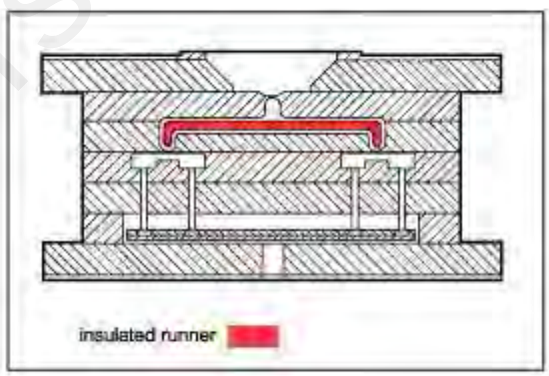


Fig 2.4 Insulated Runner Mold

2.1.4 Parts of Mold

A lot of small parts are assembled to create fully automatic mold. (G Mennig, 2015)

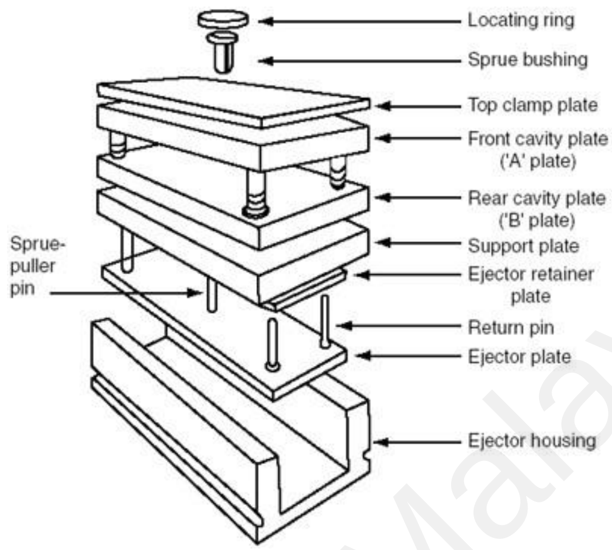


Fig 2.5 Parts of Mold

2.1.4.1 Back Plate

It is the plate used for supporting guiding pins, cavity block and sprue bushings. It can be movable.

2.1.4.2 Injector Plate

Plate containing core (major details of the part), used to inject material. It is stationary.

2.1.4.3 Clamping Plate

It is used to fasten and align different plates and blocks.

2.1.4.4 Cooling channels

It is used to cool down the surface temperature of mold by passing a cooling medium.

2.1.4.5 Ejector pins

At the rear part of cavity a small holes are inserted where these pins are placed and pushed to remove the finished part out of mold. A hydraulic plate is utilized to make injection molding process fully automated.

2.1.4.6 Parting line

A line where flowing media connects after circulating throughout the mold. It is clearly visible in finished product

2.1.4.7 Sprue

Feed opening where material enters into the mold.

2.1.4.8 Sprue bushing

A hard steel inserts before sprue that accepts the nozzle carrying plastic.

2.1.4.9 Runner

Following the sprue, the channel from where material flows towards each part to be produced in the mold

2.1.4.10 Gates

A narrow opening to allow material to enter into the part cavity

2.2 How molds are made in industry?

Nowadays a controlled CNC machining processes (circular cutting, drilling and milling) are being adopted to make mold and each part is manufactured with close precision. In industry all types of molds are made by CNC machining causing higher waste, cost and time. (Beard, 1997)

Several factors need to be considered while making mold, which are:

- Temperature, flow rate, shrinkage of molten plastic to be injected because it leads towards better designing and adding air vents to reduce the temperature
- The cooling vents and cavities in the part should be large enough to avoid defects like warpage, shrinkage and burn marks on the part
- The mold material depends on number of cycles and part complexity (leading to high temperature), steel H13, P-20, SS420 grades are more reliable as compared to aluminum T-6013, T-6061 due to hardness, resistance towards mass production, but its costly and machining cost is much higher. Complexity and material can increase the cost up to 10 to 15 times due to complex manufacturing processes and high level of expertise.
- Core & cavity CNC machining along with placement of ejector pins and cooling lines have a strong impact on finished part.

2.2.1 Why CNC?

CNC is the best repeatable tool for grinding and milling purpose with a fine tolerance and accuracy up to 0.0002 inches that was never possible with manual grinding. It can reduce the labor cost too but the cheapest 5 axis model is available in USD 35000 so the whole cost is incurred into machine itself.

Consistency in terms of cyclic loading is the biggest question from a few to hundreds of cycles per minutes so there is a strong need of having the most appropriate material with cooling channels that can keep it running 24/7. A small flaw in machining can lead to crack propagation and to destruction of whole part so CNC is the most accurate tool to machine with this kind of accuracy requirements.

The challenge related to mold making are (“Kurt & Kaynak” 2009)

- ❖ Expertise in handling the sophisticated CNC machines in which a small mistake can leads to rejection of the whole part.
- ❖ Machining using CNC, makes it more expensive because highly skilled workforce and maintenance of plant
- ❖ Parts size is restricted machine capacity, for bigger sized molds, special equipment increases the cost further
- ❖ Changes in the part once its machined is next to impossible, so customer satisfaction is huge problem
- ❖ New technology adaptation and training of employees.

All these challenges can overcome by shifting to rapid prototyping technologies or material addition technologies if casting processes are improved to this extent.

2.3 Vacuum casting

It is the process of producing parts, blends with internal features and several types of shapes and size with perfect surface finish and can reveal unlimited imagination of producing parts in industry. This is shown in figure 2.6.

Several steps of vacuum casting are

- Wax pattern tree preparation *(3D printed part)*
- Slurry preparation
- Vacuum to remove bubbles
- Filling perforated flask with slurry
- Curing & dewaxing
- Filling and shaking out.

Fig 2.6 Step by step guide to vacuum casting process

2.3.1 Advantages

There are several advantages that can be considered while mold making using vacuum casting.

2.3.1.1 Tolerance

It can be minimized to ±0.005 inches, much better when compared to other casting processes.

2.3.1.2 Lower tooling cost

Equipment cost of wax molding, slurry mixture and baking are very low, makes it feasible for mold making.

2.3.1.3 Environment friendly

The wax can be reused again, and part produced by casting is close to the requirements i-e very low post processing and secondary scrap waste.

2.3.1.4 Versatility

It provides maximum flexibility towards complex and multi part products

2.3.1.5 Least defects

Finished part have very minimum defects like porosity, blow hole, inclusion or short pour that can leads towards rejection of part. For that purpose, all processes need to be carried out by following certain standards/patents.

2.4 Fused Deposition Modeling (3D printing)

In rapid prototyping, this is the most famous technology of printing using filament spool that is melted and deposited on the surface layer by layer. There is original material (ABS, PLA, PET, Nylon and TPU) and support material (PLA, dissolvable PVA & Breakaway) that is removed later to get desired product. A heater & cooling fan is attached at printer head called extruder which extrudes the filament and deposit on printer bed.

It can be classified into four types: (Yan, Sun, Qu, 2016)

2.4.1.1 Cartesian printer

It works in Cartesian ne in which each element of the printer (head & surface bed) moves in 01 directions.

2.4.1.2 Delta printer

It is also similar to Cartesian printer, but head is attached to tripod stand, which is movable with stationary bed, makes it more efficient.

2.4.1.3 Polar printer

It's relatively smaller than delta and filament is attached at the back of z-directional movable rod. Only two stepper motors are required to operate in comparison to Cartesian with four. It operates in circular coordinates with arm to move back and forth.

2.4.1.4 Scara printer

It looks and moves like industrial robotic arm which moves in a guided coordinate. It uses 3 servo motors and 02 stepper motors. It is also accurate for sophisticated shapes.

In recent research, Michigan Engineers came up with filtered b-spline algorithm that can double the printing speed without affecting shape by utilizing printer's dynamics to mitigate vibrations on fast speed. It vowed to get shape in half time. This algorithm can be installed in every printer but it's under β-phase. (Jamie D, 2017)

2.5 3D printing Infill geometries

This technology is commonly used to increase the strength and durability of the part. There are two main factors involved in it. (B Siber, 2018)

- Pattern of the infill
- Percentage amount of infill

2.5.1 Infill pattern

Several types of patterns can be used to print the part depends on the application. However, grid, rectangular and honeycomb is the most reliable when it comes to applying pressure on the part. Rest of the patterns are for the sake of fun.

Following picture shows the series of patterns at 15% fill.

Fig 2.3 Types of pattern used in 3D printing (B Siber, 2018)

2.5.2 Infill density

The purpose of increasing the percentage is to make the part denser/heavier, reduce the printing time and increasing the cost of the part. If quality is concerned, then 20% to 25% range is best to keep it durable while keeping the material consumption low. However less concerned structure can be printed at 10% to 15%.

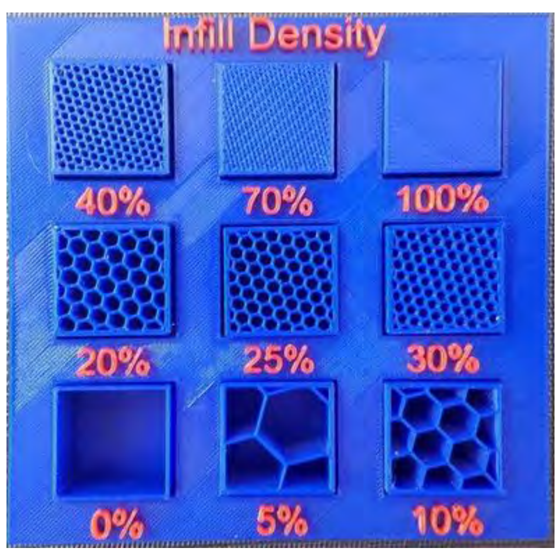


Fig 2.4 Density of part in 3D printing (B Siber, 2018)

2.6 Use of fused deposition modeling in investment casting

Nowadays a lot of research is being conducted on making investment casting process fast and low cost, using 3D printing process to make PLA (poly lactic acid) master pattern and utilizing it as a lost wax to create the part itself.

It involves several steps as per described below (Rupinder & Sunpreet, 2016)

- File designing/scanning using 3D scanners
- Noise reduction and filling necessary gaps
- Creating NURB surface and polygonal mesh
- 3D printing file preparation
- Printing using highest accuracy dimensions
- Part removing and post processing

As investment casting is centuries old material addition process which accumulates the vast range of products in industry. This FDM is helpful in modernizing these kinds of processes to make it more versatile and realistic towards changes in prototypes. So FDM helps in putting some important benefits. ("upgrading a centuries", 2017)

2.6.1 Tooling time and cost reduction

As injection molding is restricted to one-part despite of being quick but FDM is layer by layer method that saves the requirement of tooling which makes it a matter of hours instead of weeks and months.

2.6.2 Design freedom

One of the benefit of RP is producing that kind of parts which were not possible using Injection molding. It is helpful in having uneven surfaces, non-uniform thickness, sculptures and architectural parts with that kind of strength and flexibility in parts according to requirements.

2.6.3 Update patterns

Whenever any part is having some kind of defects, injection molding is constrained to tool modification leading to delay in production but FDM is helpful in doing hundreds of modifications within that time.

2.6.4 Durability of patterns

Wax patterns that are produced with injection molding are not that much durable when moving the part to another place, a small defect can lead to rejection of whole part. On the other hand, thermoplastic based patterns produced by FDM are more durable and long lasting in harsh environment

2.6.5 Smooth finish

Some of the secondary processes are adopted to make the part smooth

- Sanding (finishing around corners and extra filament removing)
- Vapor smoothing (to remove stepping error)

It is helpful in getting injection molding type of finishing with minimal cost and time.

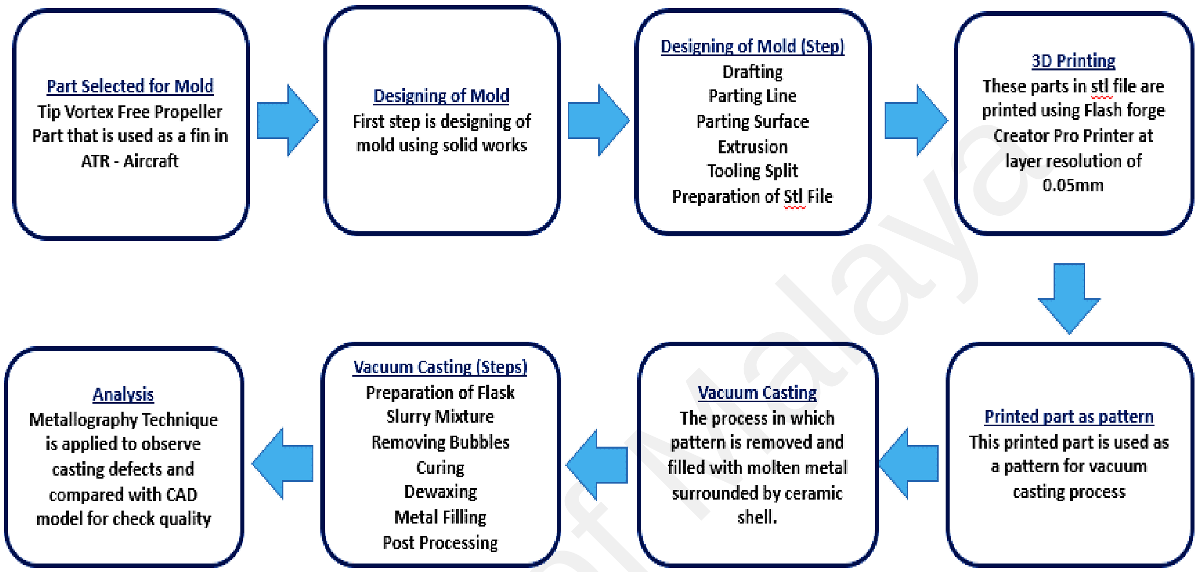
2.6.6 Drawbacks

After all these processes, part can be used to do casting. Therefore, it is helpful in producing the part without mold. The problem associated to it is FDM has limited options of materials, mostly related to thermoplastic, it can be melted into the furnace, but layered filament catches fire at a certain temperature. However, it does really affect the process.

This proposal states towards using FDM process to print the mold parts itself directly from CAD model.

CHAPTER 3: METHODOLOGY

There are series of experiments including designing, printing, casting, machining and analysis. Following flowchart is helpful in understanding the methodology.



3.1 Designing of mold

Solidworks mold tools is used to design the mold from the selected part by following series of steps. These steps are helpful in understanding the feasibility of part geometry and changes required to make it perfect for the required process of Molding. Further simulation processes enable us to do required changes in sprues and gating system to avoid defects like premature solidification & high stress areas.

3.1.1 Drafting

Draft analysis is used to differentiate the outside core and inside cavity. It uses a face and axis at a certain angle to cover majority of features. Solidworks shows number of areas that are not covered and these are either being removed or aligned according to drafting axis.

3.1.2 Parting line/surface

The area where the resin meets after flowing from both halves of the mold. It is being drawn on the part to form a closed loop using spline curve surface tool. This line area can be easily identified in draft analysis. A planar surface is drawn on parting line to divide the part. Figure 3.1 and 3.2 shows the Solidworks schematics of drawing parting line and planar surface.

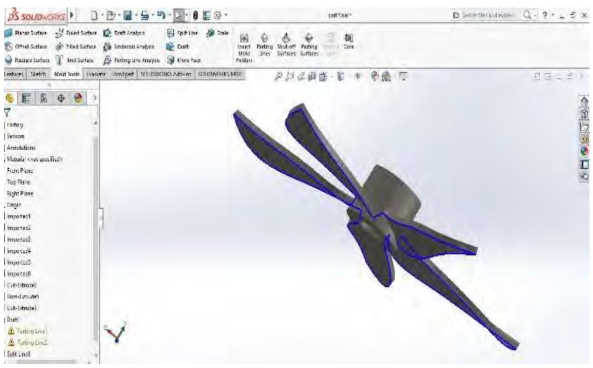


Fig 3.1 Parting line on spline surface

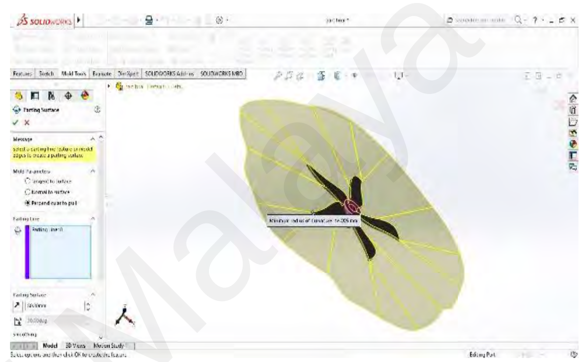


Fig 3.2 Parting surface on line drawn

3.1.3 Extrusion of Core and Cavity

Once the parting surface is developed, it can form a plane upon which two divided sides can be extruded. It also keeps the parts and extruded surface separate to form an impression that is visible in tooling split. Figure 3.3 shows the blocks extruded on the parting surface.

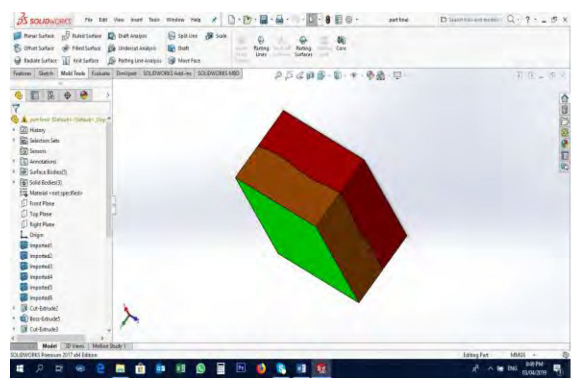


Fig 3.3 Extrusion of tools on surface

3.1.4 Tooling Split

The outer shape of the mold is drawn on parting surface and extruded to certain requirements. This tool is being used to make impressions on die/mold by keeping it separate from the part. These upper and lower part (core and cavity) can be split for further processing. Figure 3.4 shows the separated blocks with impressions.

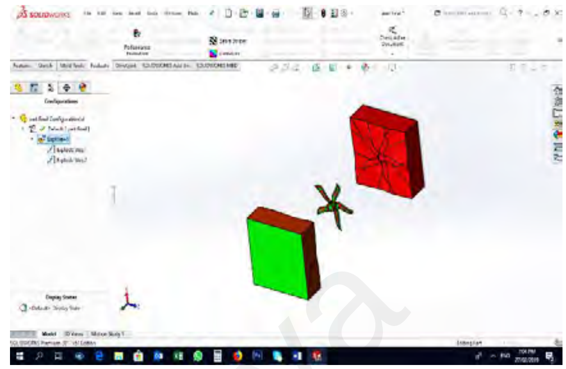


Fig 3.4 Splitting of tools from parts

3.1.5 Downsizing & file preparation

Once all parts are complete, they are being downsized and transferred to stl. format for printing. As cavity and core impressions are on one side of the parts so thickness and width is reduced to *(3 x 3 x 0.3) inches.* It helped in reducing 80% of the printing cost and time.

3.2 Fused deposition modeling

The second step is printing the core and cavity using fused deposition modeling.

3.2.1 About printer

Flash forge creator pro 3D printer is used for printing. It is a Cartesian printer with capacity of producing part and support structure at the same time such that certain type of geometries can be easily printed.

Most of the important parts are replaceable. Some important features are SD Card slot, cooling fans, automatic filament loading and pause ability during

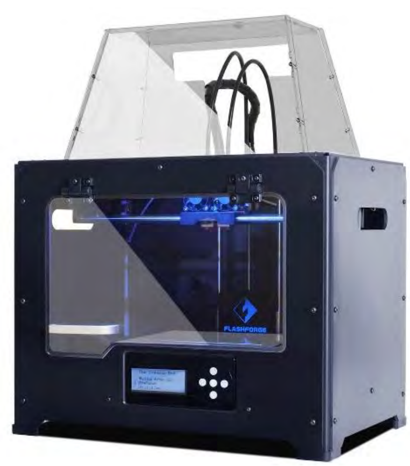


Fig 3.5 Flash Forge Creator Pro

printing. Figure 3.5 shows the Printer used for fused deposition modeling. Following table shows the specifications of printer. ("flash forge creator pro", 2014)

Table 3.1 Specifications of Flash Forge Printer

Number of extruders	2
Printing technology	Fused filament fabrication
Build volume	227*148*150 mm
Layer resolution	0.05-0.4 mm
Tolerance	±0.2 mm
Position precision	Z axis: 0.0025 mm xy axis: 0.011 mm
Filament diameter	175mm (±0.07)
Nozzle diameter	0.4 mm
Device size	526x360x403mm^3
Net weight	14.8kg
Support format	3mf/stl/obg/fpp/png/jpg/jpeg output: x3g
Software	Flash print

3.2.2 Printing

It involves converting the solid work part file into rectangular mesh based SLS file then this file is transferred to Cartesian based FDM printer. The filament used to print the part is PLA (*poly lactic acid*), melted and deposited layer by layer on the surface/bed.

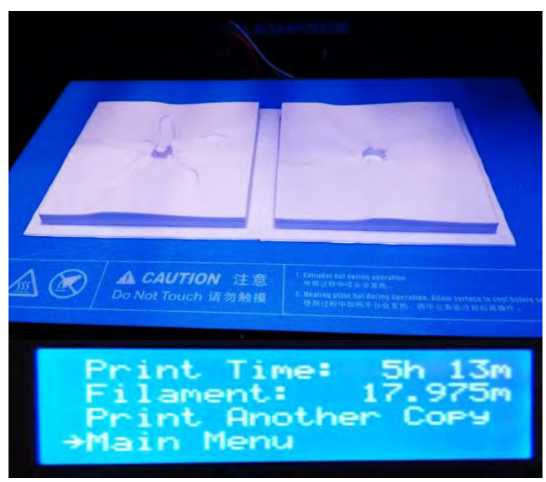


Fig 3.6 Printing Specifications.

3.2.3 Part finishing

After printing, parts are taken off from the surface bed. Base is removed to visualize suitable finishing at the both sides. These parts will be considered as patterns for vacuum casting. Figure 3.7 shows the printed part after removing the base.

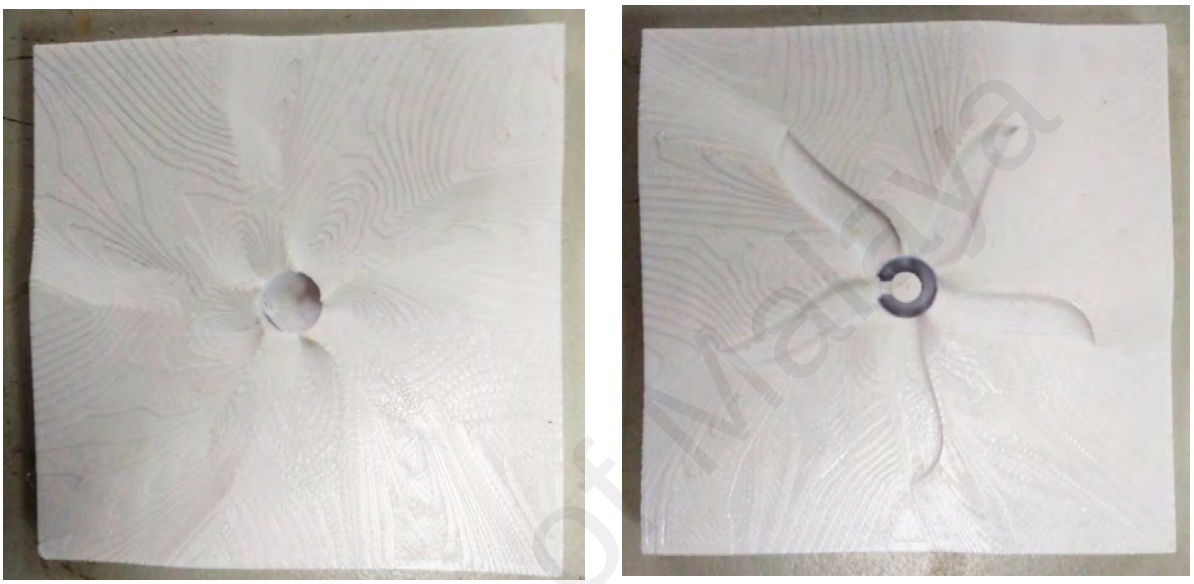


Fig 3.7 3D printed part (core & cavity)

3.3 Vacuum casting

The third step is to utilize vacuum (lost wax) casting technique, where PLA will be acting as wax (completely safe to use in furnace). In this process, candle stearic wax (stearic acid 10%) mixed with additional 30% paraffin wax *(increases hardness)* is used as a base of flask. It's being melted and molded to a specific shape. Some equipment used in this process is

- Weighing balance
- Vacuum pump
- Vacuum chamber
- Electric blender
- Perforated flask

For the experiment, base is attached to cardboard corners to make a flask. 3D printed parts core and cavity are joined to the base using acrylate-based epoxy resin. Figure 3.8 shows the flask joined with wax base using tape.

Fig 3.8 Paper based conical flask

3.3.1 Slurry mixture

Normally the plaster of paris is widely being used as a slurry mixture because of low setting time to much better finishing, so as per context the water to powder ratio depends on the weight of investment itself. (Carter, 2001)

Slurry mixture used in this process is 50% plaster of paris *($CaSO_4.1/2H_2O$)* and 50% zirconium silicate (*$ZrSiO_4$*) as it acts as an anti-oxidation agent when metal is being poured into the ceramic shell. According to powder to water ratio mixing guide, 1000ml water and 1400 grams of powder mixture is most suitable for slurry.

3.3.2 Removing bubbles

The slurry mixture is then placed in vacuum desiccator and pump to bring the bubbles to the top of the surface and pop up. It creates a pressure of 40-60 psi on the vacuum chamber until whole mixture rises up and bubbles stop. This is helpful in removing bubble entrapment casting defect in the next stage. Figure 3.9 shows the slurry mixture is placed into vacuum chamber to remove bubbles.

Fig 3.9 Removing Bubbles

3.3.3 Pouring

This mixture was then poured into flask containing the 3D printed part and allowed to solidify. The flask was again placed into vacuum chamber to remove bubbles entrapped while pouring mixture. Figure 3.10 shows the paper flask filled with slurry mixture.

Fig 3.10 Pouring into paper based flask

3.3.4 Curing

The curing/setting time is around 20 to 30 minutes. This part is being placed overnight to make it perfectly hardened and to reduce the temperature.

Fig 3.11 Cured plaster shell

Once part is cool, the outer cardboard layer is removed to get ceramic shell with wax base and part inside. Figure 3.11 shows the cured ceramic shell that is ready for dewaxing.

3.3.5 Dewaxing

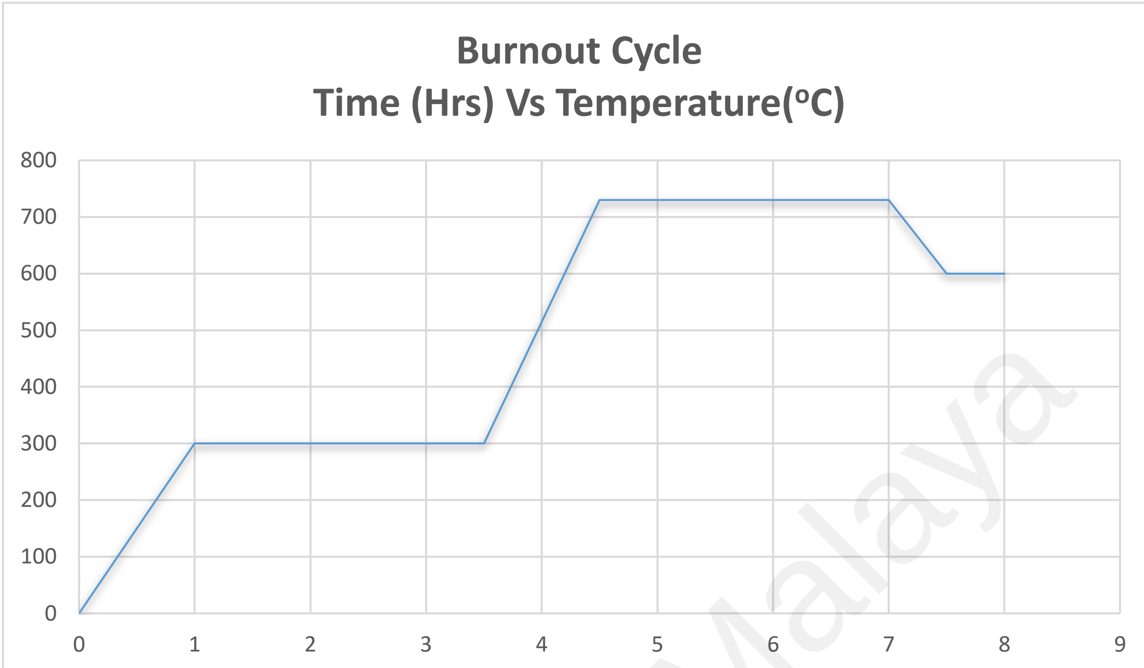
The ceramic flask is then put into the furnace to dewax the part inside, the temperature of the furnace is maintained. All ISO standards related to lab safety has been followed along with OSHA standards to tackle any fire hazards. Figure 3.12 shows the shell placed into Electric Furnace.

Fig 3.12 Dewaxing of PLA part

Following table shows the burnout cycle that is adopted in industry to melt down the wax inside the shell

Table 3.2 Burnout Cycle for Dewaxing

Condition (temperature)	Temperature (ºC)	Time
Increasing	0-300	1 hour
Constant	280-300	2.5 hours
Increasing	730	1 hour
Constant	730	2 hours
Decreasing	600	30 minutes
Constant	600	30 minutes



3.3.5.1 Benefits of using burnout cycle (Mohd. Nor, 2015)

- Using consistent time for a certain temperature helps in removing residual carbon present in ceramic shell as it reacts with environment oxygen to form CO_2.
- There is a chance of contamination when pouring the reused metal at lower burnout temperature leading to porosity

3.3.6 Molten metal filling

I have used aluminum 6061-T1 grade due to its excellent surface finishing, high corrosion resistance and excellent machining capacity (not so gummy). (Olivier, 2012)

This grade is melted in furnace at 850°C for 30-35 mins and poured into ceramic mold. The molten metal is poured from one side in order to avoid splashing and gases entrapment that can cause defects. Once casting is hardened, shell is dissolved in water to get the part itself.

Aluminum 6061 is widely being used in industry among all 6000 series alloys used in standard or customized shapes, structural pipes and ducts and billets for machining purpose.

It is heat treatable and suitable for welding purpose. It is recommended by machinist because of ideal chips making and easy to handle. It can also be bended using by specialized tempering T1-T4 *(specialized methods for heat treatment and aging).* ("Aluminum 6061-Principle Design Features", 2012)

3.3.7 Post processing

Once the cast is solidified, it's placed in water to remove the ceramic shell. The edges are refined using automatic saw machine. Final casted part is shown in figure 3.13.

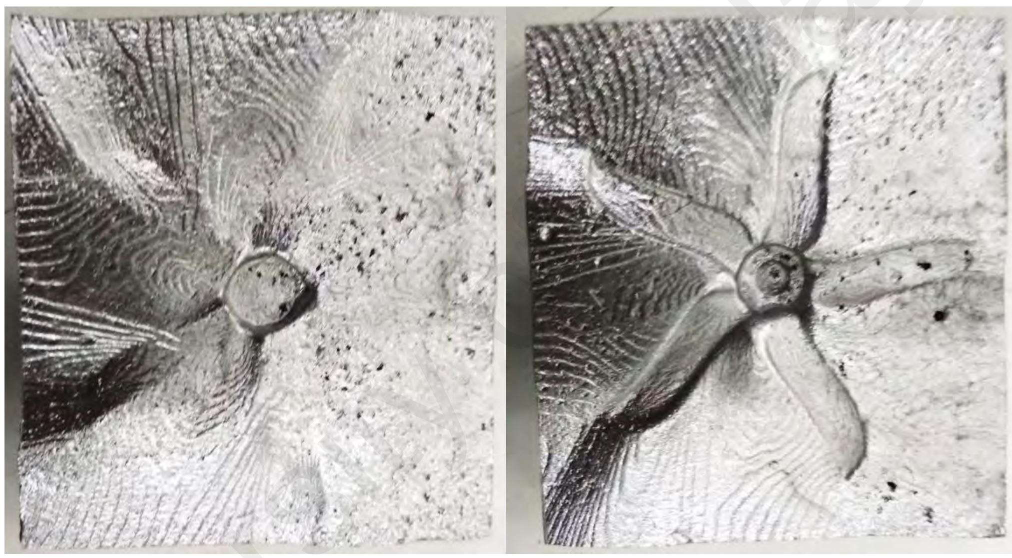


Fig 3.13 Aluminum Casted Part (Core & Cavity)

Once casting is finished, part is analyzed using several metallographic and optical microscopic techniques to deduce the results about its defects and dimensional accuracy.

3.4 Sand Blasting

It is an important process to make metallic rough surfaces smooth by spraying the sand particles of specific size under high pressure. It removes the oxidized, corroded or contaminated layer by abrasive action in which each and every particle participates in removing the debris. This process is simple and effective for grinding of parts.

Drum based manual machine with the following features.

- Sealed cabinet and automatic sand extraction system
- Integrated regulator and gauge to choose the desired pressure
- Control panel display and interior lightening to improve visibility
- Gloves chambers for safety operation
- Mobile sandblasting gun with replaceable different sized ceramic nozzles.

For grinding 400 grit size sand at 80-100 psi pressure is used, ideal for aluminum. It is helpful in removing some of the oxidized surface making it presentable. Figure 3.14 shows that stepping error is minimized but a lot of casting defects are visible.

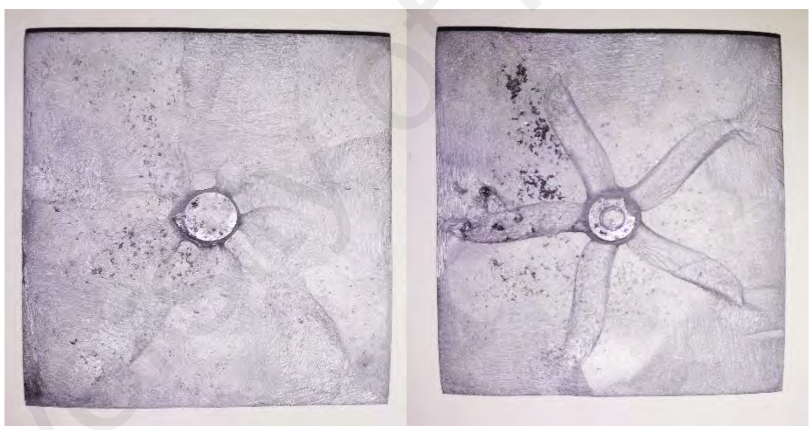


Fig 3.14 Sand Blasted part

Problems associated to this process are

- Damaging the smooth surface by eroding it especially when dealing with soft metals
- Changing the dimensions of the impressions, therefore it needs to be done precisely.
- Using the soft sand for better finishing.

3.5 Metallography/Failure Analysis

Metallography is the study of the structure of metals and alloys. Metallographic analysis can be used as a tool to help identify a metal or alloy, to determine whether an alloy was processed correctly, to examine multiple phases within a material, to locate and characterize imperfections such as voids or impurities, or to observe damaged or degraded areas in failure analysis investigations.

Quality is being analyzed using optical (Somtech & Olympus BX61) microscopes by finding casting defects. This process is also helpful to deeply study grain boundaries and anomaly in solidification of specific phase. It involves series of steps like grinding, polishing, etching and microstructure analysis.

3.5.1 Part Mounting

First step is to mount the part, removing irregular shapes and finishing the edges to make it ready for metallography. This process is helpful in making some of the casting defects visible without affecting the original dimensions.

3.5.2 Grinding

It is the most important part for surface preparation as it allows the operator to reduce mechanical damage. In order to avoid microstructural surface damage, part isn't allowed to heat frequently.

Grinding is done using different grit sized SiC & Al_2O_3 sand papers ranging from 60 to 2400 mesh(details are provided in table 4.1). It starts from 60 mesh which is most coarse in nature and gradually move towards fine grains.

This process is being performed using automatic grinder, sand paper of different grit sizes is placed and part is placed time to time. The orientation of part on one sand paper is kept constant and turned 90^o when using the next grit sized sand paper.

Table 4.1 Grit Numbers & Median Diameters

European (P-grade)	Standard grit	Median Diameter. (microns)
60	60	250
80	80	180
100	100	150
120	120	106
150	150	90
180	180	75
220	220	63
P240	240	58.5
P280		52.2
P320	280	46.2
P360	320	40.5
P400		35
P500	360	30.2
P600	400	25.75
P800		21.8
P1000	500	18.3
P1200	600	15.3
P2400	800	6.5
P4000	1200	2.5

The surface of mold is symmetrical such that it joins together due to which it's not possible to grind it using lab grinding machine. However, all edges are ground to get perfect lustrous appearance.

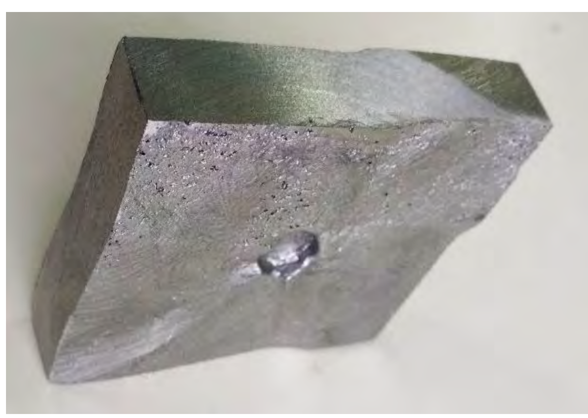


Fig 3.15 Symmetrical Sides (core & cavity)

3.5.3 Micro Pneumatic Grinder

This tool is specially designed to grind small metallic parts which has irregular surfaces, which makes it difficult to grind using conventional tools *(hand grinder/grinding wheels)*.

Fig 3.16 Pneumatic Grinder

3.5.3.1 Benefits

- It is powered by pressurized air generated by compressor, can reach up to 23000 rpm along with no danger of getting electric shock.
- It has high tool power to weight ratio as it can produce twice the horse power than electric ones in much lighter package
- I can increase its productivity by changing the air flow leading to high performance with controlled rpm for different kind of materials
- There is no significant impact of harsh environment on the operation
- It is lightweight, easy to use for different kind of structures.

I have used this grinder to grind and polish the surface of Core and Cavity to remove the stepping error and a lot of casting defects. This tool is quite accurate, efficient and fast. Grinding and polishing is done by using different sized tools attached to the device.

3.5.4 Polishing

This step to make surface flat, mirror like in appearance. Normally Alumina Powder *(0.01 to 0.05μm)* slurry mixture and a fine metal mesh polishing pads are used.

This polishing is carried out in dust free environment and operator is advised to wear gloves to avoid any abrasive particle sticking to surface.

3.5.5 Etching

This is the last step to reveal microstructures by highlighting different type of defects that has been developed throughout the processes.

Etching is done using Nital solution *(5% acidic solution to 95% alcohol)*. Nitric acid or chloric acid is used for this purpose and methanol or ethanol diluted solution are used as an alcohol.

The process is carried out using cotton piece immersed into the solution using tweezer and rubbed onto the surface, hot air dryer is used to avoid any impression on the surface. If surface isn't clearly visible under microscope, etching can be repeated.

3.5.6 Microscopic Examination

Once the sample is ready, it is placed and observed using different magnification lenses ranging from 5x to 100x to closely look at several types of flaws.

The optical microscope *(Olympus BX61)* has following features

- It contains binocular head
- Eyepiece can zoon up to 10x
- Nose piece can have maximum 5 positions
- It has halogen reflected light illumination
- Separate camera that can be helpful in taking defect's pictures.

Sometech microscope is used to take a picture at 10x with any magnification LENS to get the pictures of patches affected by casting. This type of microscope is mainly used for surgical purposes. This is helpful in understanding the defective areas in the part which are closely observed using optical microscope.

Fig 3.17 Sometech surgical microscope

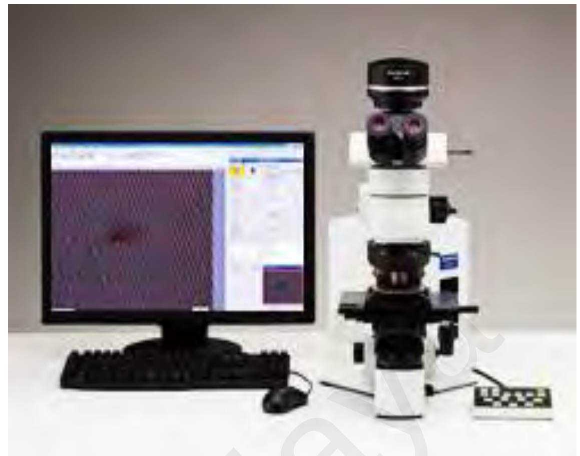


Fig 3.18 Olympus BX61 optical microscope

3.5.7 Safety procedures

It is strongly advised to follow the safety procedures while working in lab by following ISO 23062 (Foundry) & 17025 (Lab) Standards.

- Wearing the lab coat, latex gloves and closed shoes while working in RE&RP and surface lab during 3D printing and investment preparation and pouring.
- Wearing leather apron, leather gloves, mask and safety shoes while doing operations of dewaxing and pouring at more than 800^{o}C
- Having special tools for fire safety to avoid any fire incident, proper exhaust system to prevent smoke.
- Keeping the area clean especially which is being used for casting process.
- Following the emergency procedure for any unforeseen circumstances.

3.5.8 Quality Assurance/Quality control

As quality is the main concern in mold making process, there is a strong need of QA/QC that is going to ensure the following standards are being followed while operation

- ✓ ISO/ASTM 52900:2015 (Additive Manufacturing)
- ✓ ISO UNI EN 20286-i (Accuracy of 3D printed part)
- ✓ ISO 16468:2015 (Vacuum investment casting)

All these standards are helpful in understanding the complexity, reducing the risk and ensuring the quality of parts during these processes.

CHAPTER 4: RESULTS

4.1 Casting Defects

Microscopy is helpful in visualizing the several types of casting defects that affects the quality of the part, some non-destructive test *(die penetration test, magnetic particle inspection)* are used to analyze the quality of the cast.

I have used only microscopic examination and got the following types of casting defects. The casting defects like drop, swell and misrun are being removed by machining all unnecessary parts. Rest of the small casting defects that are important and can affect the whole part. These casting defects are closely observed and evaluated the root causes to make sure it can be prevented.

4.1.1 Pin Hole/Blow Hole

This defect arises due to gas entrapped in molten melt while heating and pouring. As aluminum 6061 has much larger capacity of getting oxidized so traces of small pin-hole defect can be clearly seen on the upper side of the cast.

These pin and blow holes are due to

- Gas entrapped in molten metal
- Poor dewaxing and mold burnout
- Molt itself is too hot and it retains gasses while solidification

Figure (4.1 to 4.4) shows the pin hole & blow hole defects observed at 10 times and 40 times to normal eyesight.

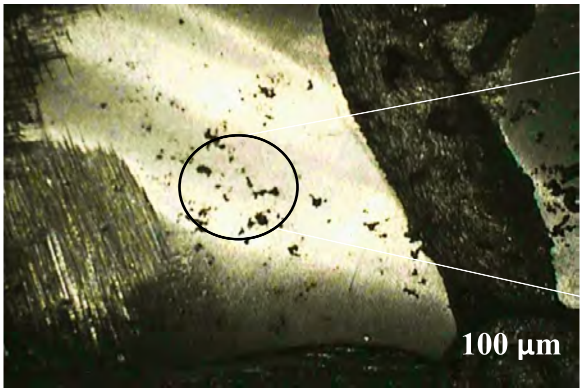


Fig 4.1 Pin Hole defect at 10x Zoom (Sometech)

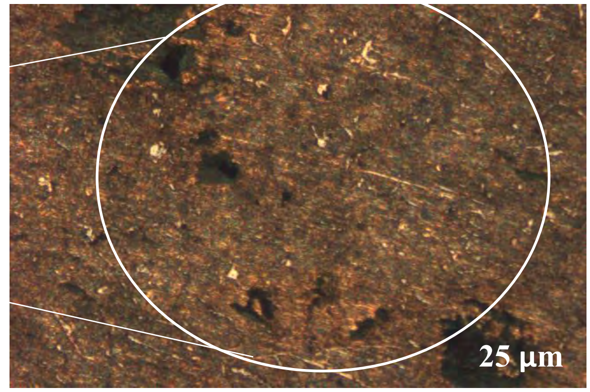


Fig 4.2 Pin hole defect at 40x Zoom (Olympus)

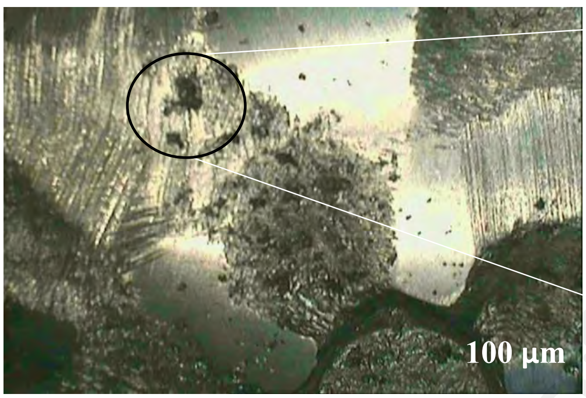


Fig 4.3 Blow Hole defect at 10x Zoom (Sometech)

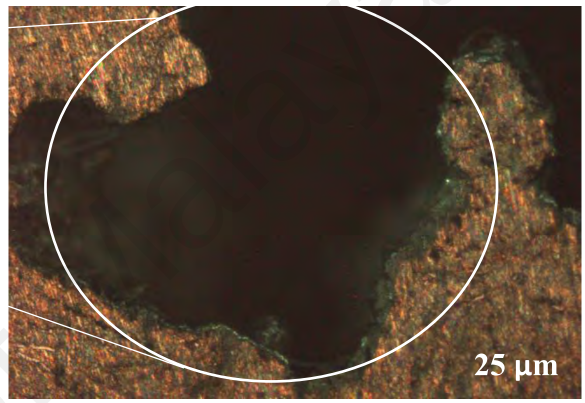


Fig 4.4 Blow hole defect at 40x Zoom (Olympus)

4.1.2 Hot Tears

The reason of hot tear is while pouring the molten metal, some part is cold and starts shrinking while the rest of the part is hot and it causes a contraction on the surface. The liquidus hot metal is trapped in between solidified dendritic structure causing it to contract upon cooling. This can be avoided by retaining the ceramic shell at 600^{o}C to have even cooling throughout the part.

Fig 4.5 Hot tear Defect at 10x (Sometech)

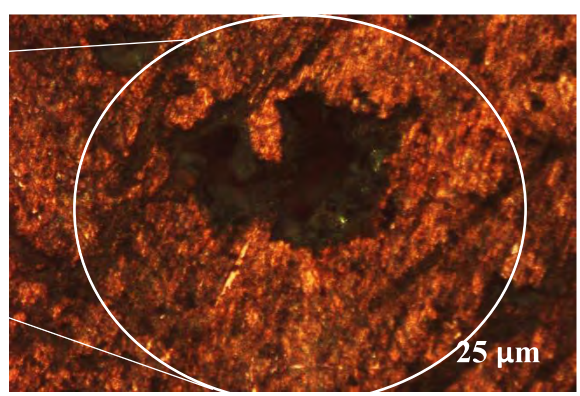


Fig 4.6 Hot tear Defect at 40x (Olympus)

4.2 Stepping Error

In fused deposition modeling *(FDM)*, stl file is being sliced into number of layers that's why it's also called layer by layer technique, when there is a change in the shape of next layer to previous layer, despite of highest layer resolution of 0.05mm. This stepping error can be clearly seen in 3D prototype and final cast. FDM technology isn't improved to that extent where stepping error isn't visible. Figure 4.7 shows stepping error in areas which can not be grinded and polished. It can be reduced by

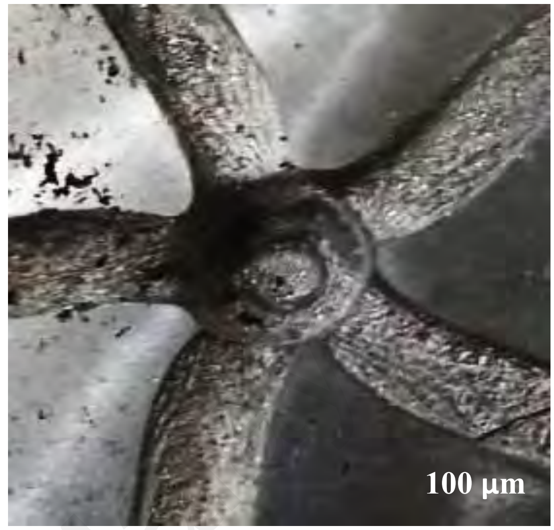


Fig 4.7 Stepping Error at 10x

1. Using the highest resolution, it will slow down the operation and increase the surface resolution
2. Selecting the most suitable printing infill percentage and pattern.
3. Choosing the highest quality filament and suitable material for specific applications

4.3 3D Scanning & Evaluation

Part is rescanned to observe the dimensional changes and to predict the accuracy of the part. For this purpose, Sense 3D scanner is used that uses two cameras and infrared rays to project accurate image by connecting all nodes created while scanning.

4.3.1 Methodology

Object is placed in the Centre of the Table, after configuring the sense scanner with the system, it is slowly rotated around the object by making sure the mesh data is intact thorough out the scan. Once it's scanned, software is helpful in repairing the model to idealize the correct dimensions. Following Figure shows the process of rescanning the model

Fig 4.8 3D Scanning of Model

This scanner uses Kinect 3D scanning technology but it is not so accurate. However, laser scanner are more accurate, fast and reliable for this kind of prototypes.

4.3.2 Dimensional comparison with CAD model

3D model obtained by scanning it is helpful in understanding the dimensional accuracy with respect of CAD drawing.

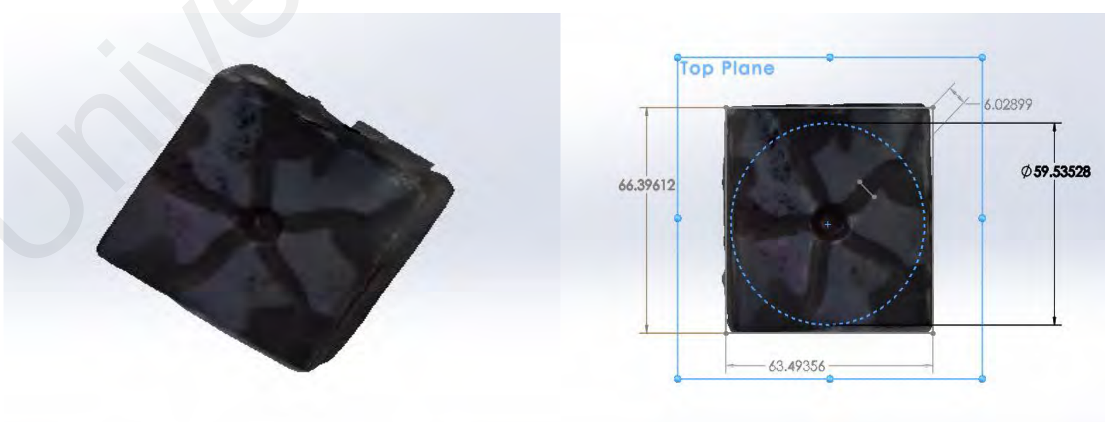


Figure 4.14 3D Scanned Model with dimensions

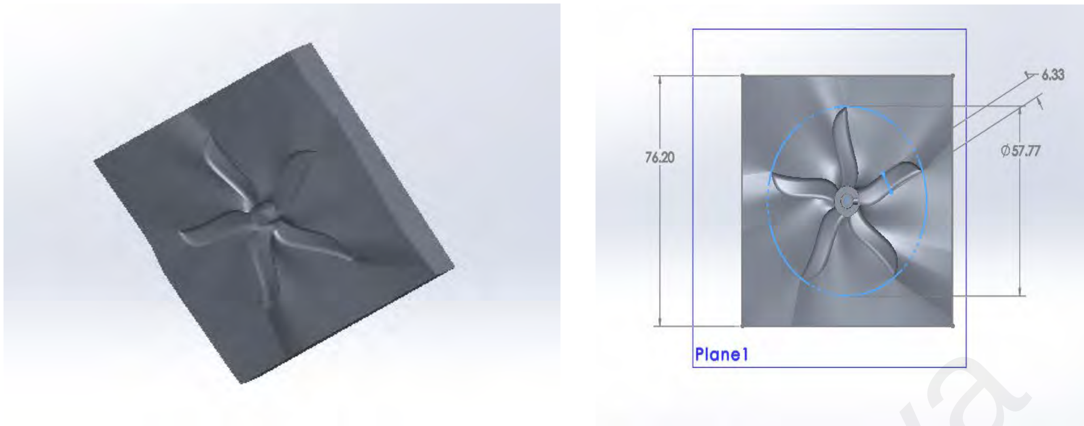


Figure 4.15 CAD Model with dimensions

Upon looking at the dimensions of both parts, it seems to be 70-80% accurate. So there is a room for improvement in this process. Shrinkage is around 5% but machining to remove oxidation layer and extra bulging part reduced the accuracy further. The major change has happened due to less efficient processes and human errors. Dimensions compared with CAD Model are width of the fin, total circumference of the part and edges length.

CHAPTER 5: CONCLUSION

Overall results are evaluated based on casting defects (microscopy) and similarity to original model design in dimensional comparison. This is helpful to idealize the concept of this material addition technology to make molds in industry. As vacuum casting is widely being used in jewelry making and it is similar to investment casting that is widely being used in making turbine blades, motor shells, pump parts, gear wheels, alloy rims and fire arms etc. All these industries demand high quality finishing, desired mechanical properties and huge protection from environment (coating). As far as mold making is concerned, there is a need of these kind of attributes along with highly experienced CNC operator who can generate and execute the exact code for machining of the part. Another biggest challenge is selection of most suitable variant of CNC that can get the job done. All these challenges make it very expensive process.

In this project several aspects for processes are closely observed which can make it suitable for mold making industry. There are several metals forming rapid prototyping processes like selective laser sintering *(SLS)*, laser engineering net shaping *(LENS)* and metal Injection molding (MIM), all these processes are using powder sintering technique which make it less durable for long term cyclic loading. This process is utilizing fused deposition modeling *(FDM/3D printing)* process using flash forge creator pro model with highest layer resolution and surface resolution of 100-200µm *(0.004 inches)*. I have used Polylactic acid *(PLA; 1.75mm)* as a filament because of its high strength & durability and has better finishing than rest of filaments available. The printing symmetry inside the outer layers is honeycomb, helpful in saving 30% of material cost. There is a base that is added to protect the part disorientation and is easily removable.

In industry investment casting is preferred for bigger parts like and sand casting for massive parts. For investment casting, there is a wax part/pattern is being prepared using Injection mold so this process is helpful in preparation of mold without relying on sophisticated CNC operation and experts. Normally it can be helpful in a lot of conventional industries where part accuracy is not questioned. As this process can be considered 60-70% efficient so can be helpful in understanding the alternative and getting one step further in producing cheap molds in industries.

5.1 APPLICATIONS

As injection molding is widely dispersed into medical, toys, kitchen utensils, furniture, automotive, aerospace and electronics industries which demands a huge number of molds requirement along with its versatility in production mechanisms. As investment casting also involves injection mold to produce wax-based patterns so all of its application industries can also be considered.

There are over 18000 different types of thermoplastic, elastomers and thermosetting polymers are being used in injection molding and increasing at the rate of 750 per year so this technology is expanding every day. (Kazmer, 2015)

Complicated 3 plate molds have as much as 100 cavities due to which there is a lot of expertise required to carefully handle and machine using most sophisticated machines, however there are some applications which doesn't demand that kind of accuracy and quality. This project is focused on that applications.

5.1.1 Plastic Industries

There is a huge consumption of plastics worldwide. Global research survey of 2016 shows that plastic Injection molding industry is more than USD 250 billion and it has been increasing significantly in electronics, cables, home appliances and toys sector. (Market Research Report: 978-1-68038-128-3, 2018)

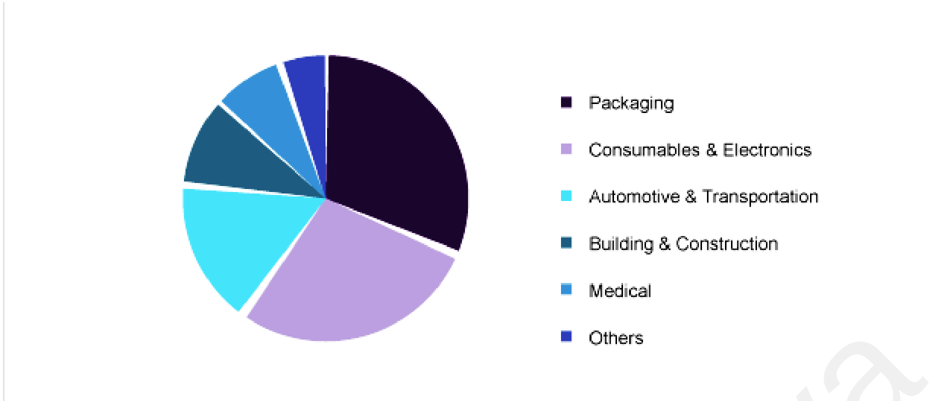


Fig 5.1 Global Injection Molded plastics market volumes (2016)

Most widely used materials are polypropylene, ABS and HDPE. However, PET, PS and PC are used to produce some packaging and cables laminations.

This project can be used to produce molds of: ("resin and types of packaging", 2016)

- PET & PVC food packaging products like trays, cups and boxes.
- HDPP, HDPE & PET based house hold jars, laundry detergents and shampoo bottles.
- Several educational, RC, building blocks and puzzles are made by injecting ABS, HDPP and plasticized PVC.

5.1.2 Automotive Industry

Automotive industry is considered front end in utilizing a lot of casting processes, they are mainly focusing on reducing the weight of the vehicle without compromising its durability and looking for more efficient and less time-consuming process alternatives to meet the demand. Right now, a lot of automotive industries are shifting to MIM process in which molten metal is transferred under high pressure to mold which is removed after cooling down.

The following pictures displays the number of parts that is being produced and projected parts that can be produced in future once its production system is perfect.

Fig 5.2 Automotive parts produced by Metal Injection Molding (Ľudmila, 2012)

The biggest challenges to produce this kind of mold is to have a proper channel to avoid air entrapment and machining the much bigger parts so it might be helpful to cast the part and then machine to get the required dimensions. (Ľudmila, 2012)

Normally automotive industry is focusing more on aluminum cast, converting the most of the automotive part to aluminum using sand, die and investment casting process that is significantly cheap, durable and fit for working environment.

5.1.3 Aviation Industry

As aviation industry involves high precision and durability of parts so investment casting has a great importance in producing parts. The benefit of using this process is that it can produce exact part of nearest part that require small amount of machining along with required mechanical properties.

Some important components produced by investment casting are: ("investment casting for aerospace application", 2017)

- Hydraulic fluid system-based components
- Landing and breaking gear’s components
- Exterior and interior sensors and actuators
- Flight safety equipment
- Bearing cages and cargo systems

As investment casting process involves wax-based Molding of parts and it can utilize the 3D modeling techniques to make sure accurate production of prototype model or even producing much bigger casting for mold parts. Another important factor is, all these part’s quality can be analyzed using NDT methods *(DPT, ultrasonic and electromagnetic etc).*

5.2 FUTURE WORK/IMPROVEMENTS

This project was based on discussing the parameters and efficiency of material addition technology in mold making so following challenges and difficulties are observed that can be tackled to make it ideal for industry

5.2.1 Capabilities of FDM

As FDM is layer by layer filament addition technology and regardless of highest resolution still the problem of stepping error was quite prominent. This can be reduced by hot air blowing but significant enough.

Other RP methods like SLA & CLIP are more significant to avoid this kind of errors with accuracy as low as 50µm. Secondly, these processes are guided by laser or light and cure the resins which can form accurate parts that can be further utilized.

5.2.2 Dewaxing under Controlled Conditions

Regardless of PLA filament is non-combustible but when temperature reaches at 650ºC, it starts catching small fire therefore bricks are placed around it for the safety purpose. Another problem was cluster of melted plastic dropped during dewaxing caused minor change in the shape of ceramic shell.

It is good to use certain process/material which does not get separated in terms of filament to avoid fire and smooth dewaxing.

5.2.3 Non-Oxidizing Metallic Material

P-20 (10) and SS420 Steel *(Chromium, Manganese, Molybdenum, and Carbon)* is the most widely used grade that can be casted and doesn't quickly oxidizes. Therefore, it better option than Aluminum T-6061 which quickly oxidized leading to a lot of defects.

5.2.4 Machine Based Casting

Investment casting is primarily used in industry instead of vacuum casting because it can be made automated, the difference is just coating of slurry instead of filling until it reaches the desired thickness. This process is more accurate and reliable because of bulk manufacturing, idealized filling of molten metal and least casting defects.

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