Prototype Manufacturability of PDC Drill Bit Body using Sacrificial Patterns with Wax Materials and using 3D Printing Technology

by

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Dissertation submitted in partial fulfilment of

the requirements for the

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(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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In partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____

Dr. Khurram Altaf

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK
January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

CHOU ZHI JIAN

ABSTRACT

This project is about application of indirect manufacturing an improved design of Polycrystalline Diamond Compact drill bit body by using Thermojet three dimensional printing and go through investment casting to become a final steel material. Three dimensional printing is also known as rapid prototyping is one of the convenient manufacturing technology since 1980's. It was been promoted in the project due to its advantages and affection in society. The advantages and benefits such as less material required, enable to physicalize a complex structure product, time saving and high efficiency are really attractive to those creative innovator. Besides, within the technology development, the desired of manufacturing rate is keep rising and will be higher in future for sure. This situation make those traditional manufacturing methods harder and harder to keep track with the manufacturing rate required. In order to reverse the situation, rapid prototyping is one of the tool between the manufacturing rate and high precision product. The statement is agreed by the related research team and wish will fabricate a product to support the idea, and this is the reason of the project title. A computer aided design drawing has been modified from the previous model and divided into several parts to ease the three dimensional printing process. Every single divided part is separated within a reason to minimize the support structure and time consumed since the Thermojet printer will build up the model with an additive manner.

ACKNOWLEDGEMENT

Final Year Project (FYP) is an individual two semester project base research to lead student in professional working environment. I would not able to go through without the kind support and help of many individuals and party around. From here, I would like to extend my sincere thanks to all of them.

First of all, I would like to express my deepest appreciation to my supervisor and also as a mentor, Dr. Khurram Altaf for his excellent guidance, monitoring and constant encouragement throughout the research period. With his constant supervision as well as for providing necessary information regarding the additive manufacturing technology that I never touch before, I successfully completed this course with experiences.

Moreover, I take this opportunity to express my profound gratitude and deep regards to both internal and external examiners who did the evaluation. Thanks to their sacrifice in terms of time and caring, the project became more complete and professional. Nevertheless, a million thanks to those people who commit themselves in the project with their abilities. Their constantly encouragement and blessing are the factor to succeed the project.

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ABBREVIATIONS AND NOMENCLATURES

Those terms will appear in the report more than one time.

3D	Three Dimensional
AM	Additive Manufacturing
ANSYS	Analysis System
CAD	Computer Aided Design
CATIA	Computer Aided Three-dimensional Interactive Application
FYP	Final Year Project
IC	Investment Casting
PDC	Polycrystalline Diamond Compact
R&D	Research and Development
RP	Rapid Prototyping
STL	STereoLithography
UTP	University Technology PETRONAS

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The project title is to manufacture a sacrificial patterns for PDC drill bit body by using wax material within the AM technology in University Technology PETRONAS (UTP). In the sentence, there have two terms are conducting the main roles in the project, which are AM technology and PDC drill bit body. Further discussion as below is to ensure the reader understand their roles in the project.

Additive manufacturing (AM) technology is also termed as direct manufacturing, or commonly referred to as “3D printing” in public. It sounds not so familiar with since it is consider a new invented technology in late 1980’s. The manufacturing technology is different with previous traditional manufacturing method due to the manner of additive process. It is a manufacturing technique of producing product with a manner of layer by layer without any subtraction of bulk material. For the earlier stage, it has been invented to improve the industry performances. Since the technology brings multiple advantages especially environmental friendly, it gave attention to the researchers to invest the technology and invented the following additive manufacturing machines such as Laser Sintering, Fused Deposition Modelling (FDM) and Binder Jetting. This manufacturing technology actually unintentionally covered fields in our daily life. Many applications like prototyping, biotechnology, and automotive are using additive manufacturing nowadays.

In Oil and Gas field, drill bit is the important part attached in the foremost of drill string when drilling a wellbore. Its performance is the main factor how well the wellbore can be drilled. Due to the consequence, well drill bit manufactures and R&D are brainstorming on how it can be improved in terms of dynamics and stresses by changing the features and configuration. Latest research development shown that well drill bit body are variety in shape and thus have specialize properties, like tricone rock bit and vertical drill bit are working in different areas. To advance the development, the project will indirectly fabricate a functional metal prototype for PDC drill bit body to aid the further research.

1.2 Problem Statement

With the evolution of science and technology, energy extraction technique is improving due to the demand appear. Many research and modifications have been done in Oil & Gas field especially on well drilling. In engineering study, a scale prototype like drill bit body is conducting an important role for real time stimulations or concept understanding. However, it is not easy to produce a high accuracy model with a traditional manufacturing methods like metal rolling, extrusion molding and welding. The situation will be more troublesome if it has an irregular structure or it is a complex design. Production period for a complex structure design like polycrystalline diamond compact drill bit body is counted by weeks. It is consider not economic if time loss in production, purchase expensive tooling, and multiple works required to produce a scale model with the traditional manufacturing methods.

1.3 Objectives

- To modify the PDC drill bit body model by exiting 3D CAD software.
- To manufacture a sacrificial wax pattern of PDC drill bit body by using Thermojet 3D printer.
- To develop a functional prototype of PDC drill bit body in stainless steel material within investment casting technology.

1.4 Scope of Study

- CATIA (Computer Aided Three-dimensional Interactive Application).
- Additive Manufacturing technology.
- Manufacture PDC drill bit body with wax by rapid prototyping.
- Develop a functional prototype in stainless steel material by investment casting method.

CHAPTER 2
LITERATURE REVIEW & THEORY

2.1 Development

According to Park (May 2014), the first 3D printing technology was appeared in late of 1980's due to the evolution of industry and it referred to as Rapid Prototyping. Refer back to May 1980, Dr. Kodama in Japan was the first patent application for RP technology. However, Dr. Kodama was failed after a year deadline as he unable to fill in the full patent specifications. Three years later, Charles (Chuck) Hull has invented the additive manufacturing machine, Stereolithography Apparatus (SLA) and published his product in 1986. Within the success, the first patent was issued to him. Besides, he was one of the co-founder in 3D Systems Corporation. The corporation is another success to bring forward the RP technology, and it is a high rank company in RP sector nowadays.

Besides, Gausemeier (2011) found that twenty to thirty years before, engineers were trying their best to change from 2D slides into 3D drawing in manufacturing processes. In other words, the development of manufacturing was looking for solidification of 3D CAD drawings. Since this invented technology is to build up 2D slides layer by layer into a solid 3D model, it been introduced as AM technology. According to ASTM F2792-10 (2010), the definition of Additive Manufacturing is a process that joining material from layer by layer using 3D modeling data which different with those traditional subtractive manufacturing technologies.

In the early years, AM is only focusing on industry areas for small part applications. The end product were rough in surface finishing and a high tolerance range. Within the improvement that able to produce polymers, it stepped into automotive and aerospace in 2000. And now, the technology had spilled into different career like medical supports, medical implants, nano-manufacturing and architecture. People found its benefits and willing to develop the technology into next level in the future, which is full body organs (Morgan, November 2013). According to Park (May 2014), he was agreed with Morgan. The technology is not only function in engineering, medical and biological fields, but also in some particular design, such as jewelry. Fashion also involved itself with the technology. Numerous of items are printed through it, such as venue decorations, shoes, head-pieces, hats, bags and even dress are able to form.

Figure 1: 3D printing shoes from Continuum (Huang, 2014)

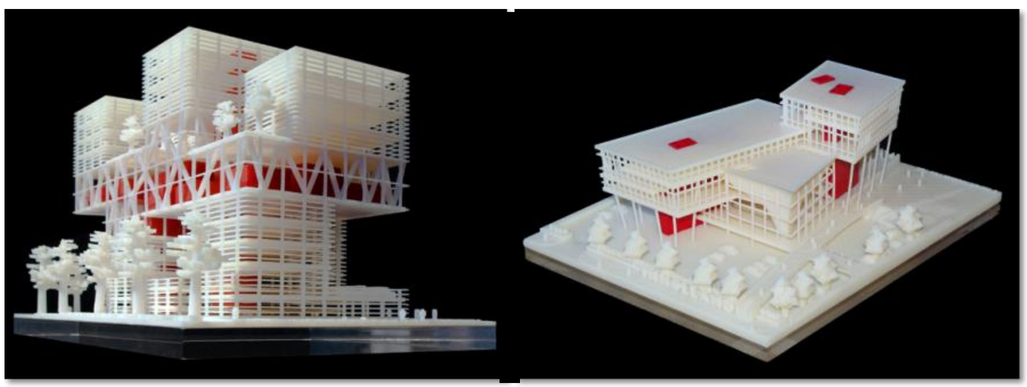


Figure 2: 3D printing and architecture design (Meijs, March 2012)

As stated in Khajavi, Partanen, and Holmstrom (2014), the technology has continued to develop in various aspects. For the current stage, it is moving towards the area which required a high precision and quality product for the special application such as the aircrafts turbine components and vehicle gear box structure. Those product are not a prototype anymore, but they are important to be one of the final functional parts in the machine. In the research by Wieneke-Toutaoui and Gerber (May 2003), it stated that RP technology has a high potential for marine researchers and subsea development by producing prototype and unique parts for necessary testing in unknown areas. This technology is increasing its reliability, minimize time consume and lower financial requirement. It helps to assist in identify ideal solution at a reasonable price.

2.2 Advantages

Khajavi et al. (2014) and Park (May 2014) both also stated out that AM is not only for prototype production now. The development of the technology have forward into next area with a wide range of material used by the machine, higher accuracy and reduce the relative cost production. AM is a production method with high potential to over the conventional manufacturing methods in the future due to its characteristics such as no need for tooling in a mass customization, short production time, relatively economic for mass production with complex configuration and able to minimize the material waste formed. It stated out that the product formed by the subtractive manufacturing is mostly 10% of the bulk material, the other 90% are wasted during the process. By using AM, it can utilize all the material without any waste. For the remaining powders above the surface finishing, they are able to recycle and reuse again for next printing. It imposes a less carbon footprint and more environmentally friendly.

There have a limitation for some design always, unable to create a complex structure. Those traditional manufacturing methods are acting like the boundaries for inventor to bring out their own brilliant idea out to the world. It is really a great news that found out AM enable a new forms of mass customization and it is offering a capacity to manufacture any possibilities (Hudson, 2014). In the research by Park (May 2014), the advance of AM is impressing some designers and artists since it is able to build up their desired figure out precisely with level of complexity. Furthermore, final output is able to produce by itself without large number of skilled craftsmen and weeks to months of processing time.

By refer to Morgan (November 2013) study, AM is able to replace machine tooling in coming year. It is a better manufacturing method with low volume production, lower cost investment, high efficiency and able to produce a high level of customize design. Moreover, it has the ability to produce out a product from raw materials into a finished product by itself only, thus it shorten the manufacturing supply chain. If there have another comparison with traditional manufacturing method, it should be the direct manufacturing.

2.3 Materials

According to Kumar and Kruth (August 2009), primary stage of 3D printing is only focus on polymers. As the facility of industry, various polymers are involved as printing material with the different role of plasticizer, tackifier and surfactant. Within some period of development, the technology is involving metals, ceramic and composites as its printing materials. Those materials can be printed with one kind or a combination method. A combination material powders (composite) have an advantage if compare to single material chosen. The situation is easily to discuss with an example of iron-copper as composite for Selective Laser Sintering (SLS) process. The present of copper powder is to bind iron powders to form a desired product with a form of fluid. It helps in merging iron to iron powder only but not involved itself into the product. This point is been mentioned in Gausemeier (2011). For rapid tooling, metal material powders are formed as a compound of two or more for the operation especially in sand casting.

However, the rapid development have moved the technology facing the edge or shortage of material to produce some special product with only metal powders, ceramic and polymers. One of the example is bone, part of the human body support structure, it can be affected by numerous pathological conditions or diseases, and degenerates with age. It previously was build up with metal powders such as stainless steel or titanium. With some disadvantages of previous material, inventors start to figure out the replacement for them. And for now, a bone tissue scaffolds can be printed out with hydroxyapatite (HA) and poly(vingyl)alcohol (PVOH) composite powders (Cox, Thornby, Gibbons, Williams, & Mallick, November 2014). Latest, some of rapid printing technology research is dealing with the fiber-reinforced composites. Among the researches, the few printing techniques used for the fiber-based products are Stereolithography (SL), Fused Deposition Modeling (FDM) are Laminated Object manufacturing (LOM). One of the research is written by Hudson (2014). He posited that the fabrication method is not only focus on the mass customization and configuration, but also employ the new categorize of material. The newest material involved in the technology is a soft fiber (wool and wool blend yarn). The exploration shown that additive manufacturing has achieved into the next level which related to aesthetic of soft objects.

2.4 Operations

Actually, AM or RP technology is just acting like an ordinary printer. An ordinary printer is able to print out any information with only two dimension forms such as words, diagram, figure or picture. In the other hand, rapid prototyping machine is more advance and able to produce out a three dimensional digital model into an object. According to Wieneke-Toutaoui and Gerber (May 2003), it is a manufacturing technology that helps to direct physical realization from 3D digital model format. The RP technology is so convenient for all kind of designer. First of all, construct out a 3D CAD solid model, then convert the reading format into STL (reading format in 3D printing machine). Within the dedicated software, STL file will slice into thin cross-sectional layers. The machine will start to construct out the model layer to layer as the desired solid model design. In short, it converts the 3D drawing data into a dedicated reading format, and it will form accordingly layer by layer with a satisfy level of accuracy. Designer usually do not really generate a new model with the CAD system. However, they will revise the existing design with some modifications of angles, curvatures and dimensions to adapt the requirement in drilling a specific field area (Southland, Mar 5, 2002).

There have few CAD software that we can choose for the design project, such as AutoCAD, SolidWorks and CATIA. For the current project, CATIA been chosen as the drawing tool for 3D modelling since it is a provided software in UTP. As Park (May 2014) stated, the starting point to function a 3D printing machine is the 3D software programs. In order to make sure consumer feels convenient to use the machine, engineers invented the 3D scanner. It is a device that analyses an object and collect its appearance in shape or color by two dimension scanning from bottom to top or vice versa. Those collected data can used to build up an object accordingly layer by layer with 3D printing machine. Thus, the outcome object is approximately the same as the object been scanned. However, it only can be duplicate with 3D scanner which unable to modify or change the figures.

2.5 PDC Drill Bit & Body

Since PDC drill bit body is involved in the project, it will be briefly discuss for a further understanding. From Scott (2006), it stated out the disadvantage of traditional manufacturing method to produce a PDC drill bit. In 1971, General Electric (G.E) had invented the carbide supported polycrystalline diamond cutter. Since it is not really economic and due to the technologies, it only been introduced commercially in Oil and Gas field after three years of massive development and researches done in 1976. The early cutter was a carbide disc with the specifications of 8.38mm diameter by 2.8mm thick, with a 0.5mm thick PDC layer.

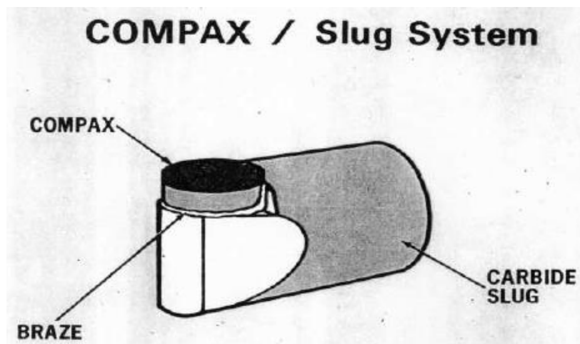


Figure 3: Schematic of early PDC diamond layer (Scott, 2006)

However, many issues had been identified in the early stage and testing. Several figures of the PDC cutters were changed accordingly due to the researches and testing been done to ensure the stability of the PDC bit. As previous decades, people keep modify the PDC drill bit by manufacturing the product and go for real time testing in different platforms. If the result is dissatisfy, new design need to manufacture again for another platform test. It is totally different nowadays, we can use computational fluid dynamics (CFD) as a part of bit hydraulics design process. The way we doing now is more time saving and relatively economic in overall.

According to (Jones, Sugiura, & Barton, 2008), PDC cutter is steadily developing after the first production in 1976. In latest, polycrystalline diamond materials, part of the PDC bit is becoming important factor to consider for oil drilling tools. There have two structurally dissimilar design for PDC bits, which is matrix-body bit and steel-body bit.

In the project, structural design of steel body bit was chosen to indirectly manufacture with the rapid prototyping machine.

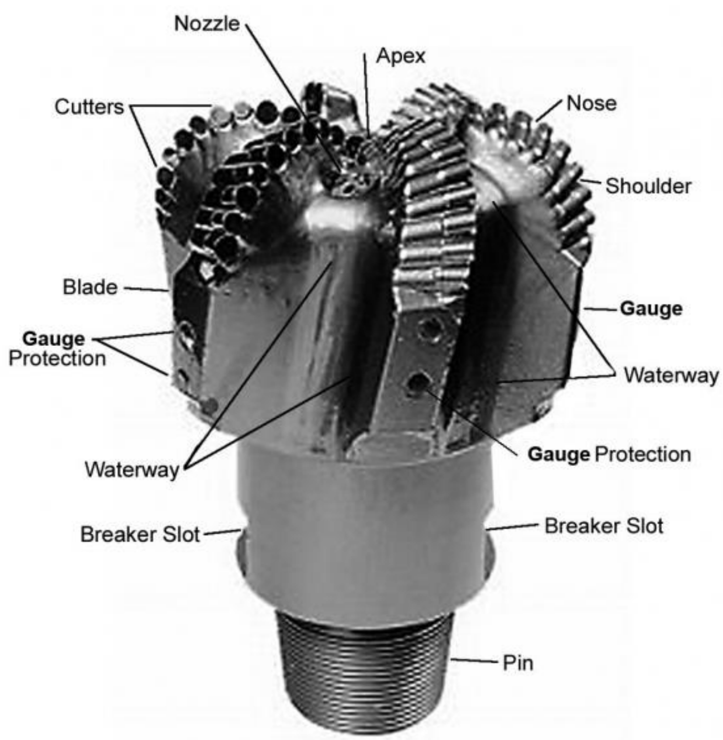


Figure 4: PDC bit nomenclature (SPE, 29 August 2012)

Blayton, Chen, and Lefort (2005) found that PDC bit is designed for hard rock drilling. In order to optimum the drilling efficiency and bit life to minimize the costs and ease risk in rough operation environments, a series of PDC bit had been designed by using the combination of modeling system and sophisticated analytical tools. By changing or matching the specific rock properties and drilling parameters, it can be more advance than other, thus replace the previous design. Bit design is complex in features such as physical shape, cutter rake angles, impact arrestors, and cutter type chosen are highly inspected for optimize axial, lateral and torsional forces in drilling hard and transitional environments. By using some software like Thermal Mechanical Integrity (TMI), it can be more easily to understand the failure of PDC bit in abrasion and impact damage. At the same time, we clearly know which characteristics have to be modify for a better performance.

2.6 Production

This segment is to compare the ordinary manufacturing process and AM for casting a steel-bodied bits. According to (Symonds, 1999), the present drill bit designs are complex in configurations. Between all the fabrication methods, provide a multiple patterns for casting is chosen always to eliminate the associated time and finance required in the creation of a new pattern mold. Besides, clients are able to require in design and manufacture a drill bit with different in specifications to match the relative fields. The basic sequence to produce a steel bit pattern is machining multiple bulk metal into a desired form by using axis computer numerical control (CNC) machine. The pattern can be two or multiple pieces of molds or dies for further process a reproducible complex pattern body. Complex multiple patterns has its advantage without intermediate, which is reusable for next production. The variation of the patterns are able to replace by another modified parts after correction is done. Then, this combination of patterns in a desired form will proceed to installation of molten steel. Break the shell mold from casting at the end of the cooling period, and proceed to substantial reduction in machining for the final bit form. Amongst the steps, process of casting is about few percent of time consumed and a low investment over the entire fabrication only. Most of the time and investment were used for the pattern preparation since it included those expensive tooling machine and high load of material used.

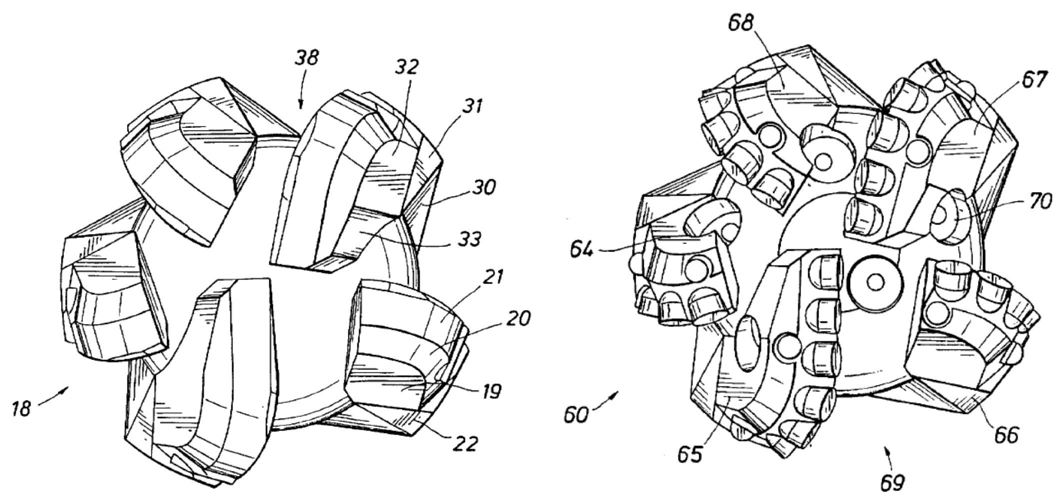


Figure 5: Schematic drawing of bit design (Symonds, 1999)

From the patent prepared by (Southland, Mar 5, 2002), it agreed that using RP technology in the field to produce molds for forming drill bits. First of all, analyze out the configuration of PDC in three dimension and modeling the pattern with CAD system. The geometry data will feed into the device and divides the solid model in thin cross-sectional layers. Then it will proceed to build up the mold by layer at a time with the same definition of the data. Printing materials for the mold can be clay, sand, ceramics, graphite or other flexible properties materials like wax, rubber, and plastic. For those flexible properties materials printing output, they can be coated with a binder or a resin to convert the product into a green state mold. Within the coat of binder or resin, the mold material is able to withstand high temperature and carbon dioxide gas. If the mold material has built by wax and directly proceed to casting, each of its inner layer surface will expose to a high temperature to either fuse or sinter together with molten metal. Consequently, the quality of the product will be disqualify as it is different with the design model. In the other hand, it shown that the printing materials are available for casting process. The similar point is pointed out in (Dickens et al., 1995). The combination of IC and RP is the ideal method to produce a complex part. In 1989, the combination has been tried out by RP parts as sacrificial patterns for IC. It is a problem to overcome the non-wax RP parts inside to proceed into IC. In the project, there have two techniques to be consider for IC, which are block molds or shell molds. Both of the methods have their own disadvantages. For block molds, cast metal is trapped by thick insulator, ceramic shell and this can affect the metallurgical structures of the output since insufficient of cooling. Besides, it able to cause the failure of casting when the solid ceramic inhibits the contraction of product. By comparison, shell molds will produce a better surface finish on casting due to the first layer of fine coating. This is because the methods has invested a wax assembly with several ceramic layers. Wax has a higher coefficient of thermal expansion than ceramic, but it will not make the shell crack as ceramic layers since it can be expand of the main body of wax after the outer layer is melted. However, it is not easy to shell the cast metal with five to eight layers of ceramic slurry and refractory granules depending on the cooling rate.

2.7 Support Material

One of the advantage of using AM in fabrication is enable to manufacture of complex geometries, which are very hard to produce with the traditional methods. In the rapid prototyping technology, there have at least two materials are involved in the fabrication process, the production materials and the support material (Gardan & Schneider, 2014). The final products are generally prefer a least mass of the support material by using honeycomb shape or points supporting product surface only. However, the support materials only can be perform after the overhang structure, hollow volume (porosity), subsurface and flanges have been determined in the computer aided design (CAD) drawing or STereoLithography (STL) files.

First of all, we have to understand topological optimization since the support material is producing within the concept during the rapid prototyping process together with the production materials. A product can be an innovative complex structure thanks to the topological optimization technique. According to the figure 7, the fork structure was built to support the upper middle load at the two below point. It can be built as the rectangle materials like figure 6, but it is not. For the overhang part like in figure 8, its support materials are not build as a bull solid under the design space to support the overhang part but it was built as rod by rod under the surface for the weight support.

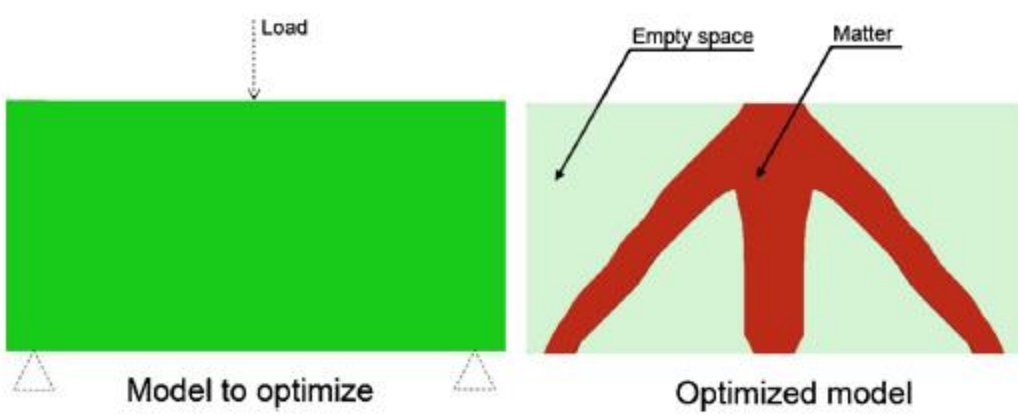


Figure 6 & Figure 7: Topological optimization (Gardan & Schneider, 2014)

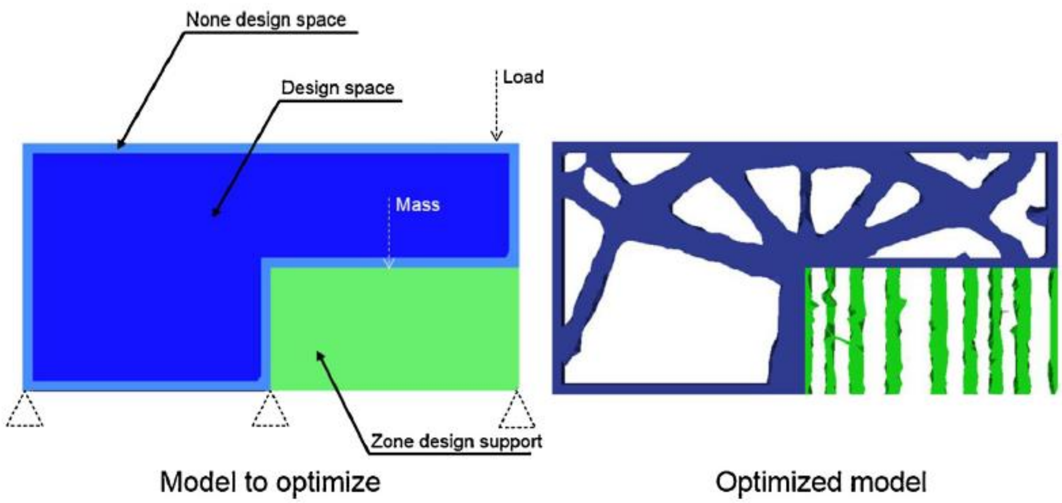


Figure 8 & Figure 9: Overhang part and support optimization (Gardan & Schneider, 2014)

From the examples above, we understand that topological optimization is utilized during the rapid prototyping our product. The reasons of this study been mentioned at the previous session are:

1. Minimize the support material, thus save the cost of production.
2. Ensure the support materials are able to remove easily by chemical or physically.
3. The weight of the structure is supported by extra materials.

The support materials were always built between the surface of workbench and the surface of product in order to support the weight. According to the figure 10, no support material was found at top. However, in figure 11, support material was found at bottom and been removed to achieve the closer surface finishing product.

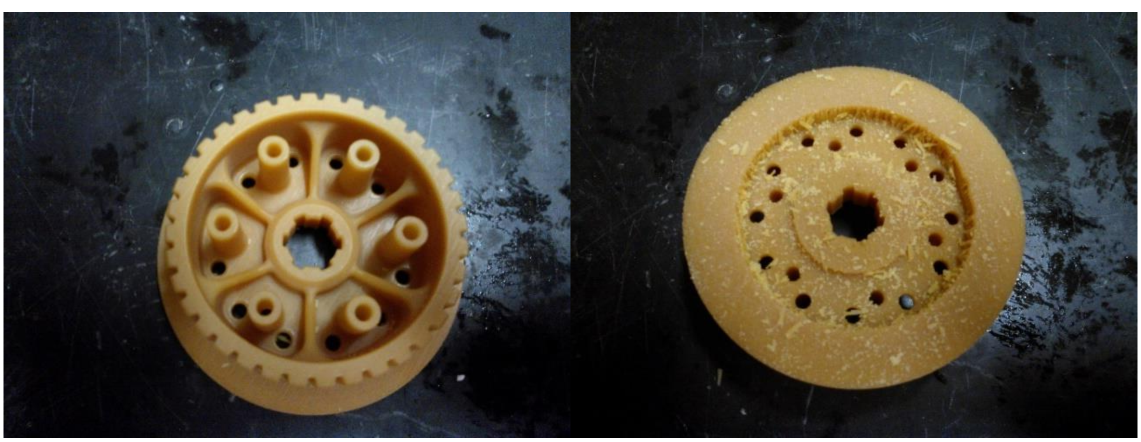


Figure 10 & Figure 11: Top view and bottom view of rapid prototyping product

2.8 Types of Rapid Prototyping Technology

RP technologies can be divided into those involving in material addition and material removal. From the material addition, it branch out for more details method, which are by liquid, discrete particles or solid sheets. In UTP, two printers that we have considered about for the project are under different categories. The unselected printer (Zprinter@450) is under the category of discrete particles, joining the particles with a bender. The reason of disqualified will be discuss in next section. In opposite, the selected printer (Thermojet) is under the category of liquid, solidification of molten material.

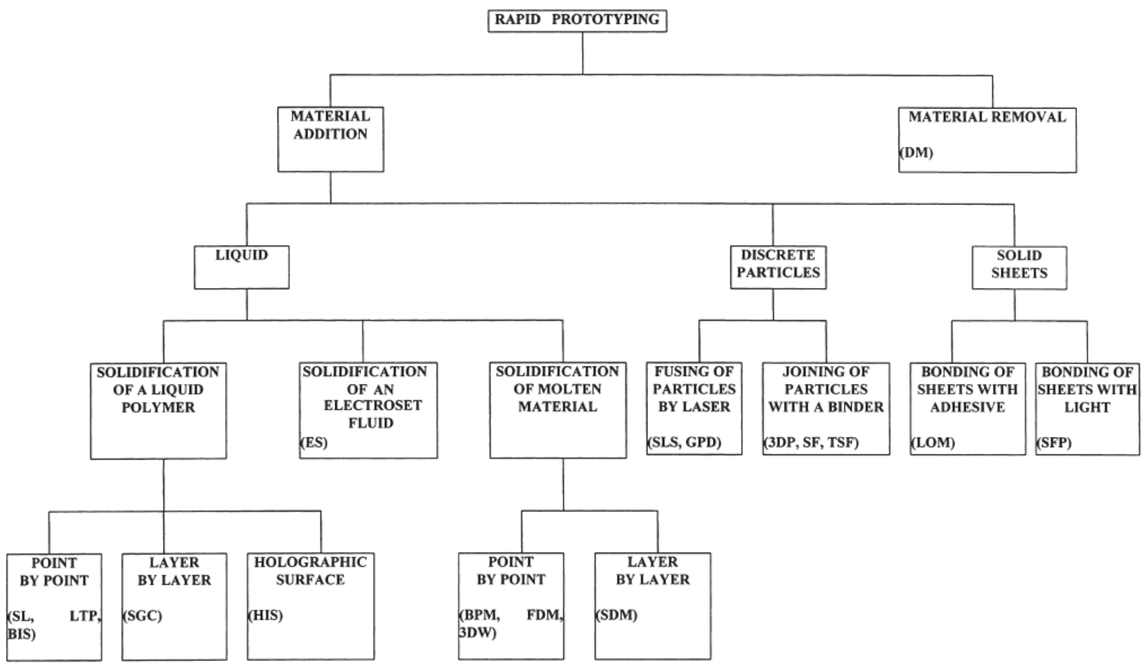


Figure 12: Classification of rapid prototyping methods (Pham & Gault, October, 1997)

2.8.1 Binder Jetting

Binder jetting technique is a RP method which using binder to group materials together into a desired model. First step of the operation is spraying the material powders into its coordinate accordingly. Once the materials is sprayed out, a roller will run through the surface of the materials and release binder to form a layer. With the same procedure, the layers will form and fused with the previous layer (Park, May 2014). Discussion about joining of particles with a binder also stated out in Pham and Gault (October, 1997). A layer of material powders applied on the surface of broad then selectively grouping by binder spray through a nozzle. However, in this study, it stated out the defects will form and the way to prevent water droplets or mist adding into the layer during the printing. Once the model is done, set the binder with a high temperature for few hours in order to fuse it. The remaining excess powder, acting as the support before, can be remove by water bath. Since no state interferences during the process, the strength of the model is improved and distortion is reduced.

According to Stucker (2012) & Pham and Gault (October, 1997), the advantages of binder jetting are short in time progress and able to perform without secondary support materials. It has the ability to build up a large parts quickly and relatively economic than other RP methods. A layer can be formed in a matter of seconds since volume parts are mostly built up with powder materials. For overhanging geometries, the surrounding powder involved are able to formed naturally and perform as support. Thus, no secondary support materials are necessary. The only disadvantage of this technology is producing a gritty surface finish molds and an operator for finishing is necessary.

There have a wide range of printing material that we can choose for the printing process in binder jetting (Park, May 2014). The materials can be ceramics, composites, glass or metal alloy powder. However, due to the printer that we have in UTP is Zprinter@450, material used is composite only, and it has been disqualified since the composite is unable to process IC. For investment casting, ZP 14 composite material is the only one that able to withstand the high temperature. Otherwise, the printer will not be consider anymore.

2.8.2 Specifications of Zprinter@450

(3D Systems, 2010)

Synonyms: Binder Jetting (BJ), Three Dimensional Printing (3DP), ProJet

Material class: Composite

Vendor	Material
3D Systems	Visijet PXL
3D Systems	ZP 130 powder
3D Systems	ZP 150 powder
3D Systems	ZP 14 powder

Characteristics: For comparison purpose.

Colour	Full colour/ Monochrome white
Resolution (x,y)	300 x 450 DPI
Maximal build envelope	203 x 254 x 203 mm^3
Minimum feature size	0.1 mm
Minimum layer thickness	0.09 mm
Typical tolerance	+/- 0.13 mm

General Application: Scale prototypes, green parts, molds and cores.

Figure 13: ZPrinter@450 in Block 16, UTP

2.8.3 Material Jetting

The different between material jetting machine and others printing machine is the number of nozzle operates when processing. It allows a simultaneous deposition of a range of materials. In other words, the desired model can be printed out from multiple of material with a range of properties and characteristics. Materials used in the printing process are in their molten state or liquid form. It will form the product accordingly with simultaneously jetting support materials (Park, May 2014). In Pham and Gault (October, 1997), it also stated out how the process of material jetting form a model. The materials involved are melted into molten state and ejected out from a different nozzle. It have multiple of nozzle with different molten materials. Within the analyzing of reading format data, the nozzles will start to operate simultaneously. The ejection of the nozzles will form the model and the support material for the overhanging geometries, empty space inside and size of porosity. After the first layer of droplets have deposited on the surface, the cooling process will be proceed with a blower or cooler. Those nozzles will only resume when the first layer is partially solidified. Thus, the process of the material jetting is also known as solidification of molten material.

According to Pham and Gault (October, 1997), the cooling rate of the molten materials used are different. Issue may happen like improper weld in parts. This is because when the droplets are solidified in shape, they are unable to merge with other droplets around. To overcome the problem, the material involved are ejected from the nozzle at a certain frequency which around 60 Hz. It is depend on the size of head nozzle. For the larger droplet which require the wider separations between, lower frequency will be carry out in the process. Parameters that have to be consider in the process are frequency of ejection from nozzle, size of head nozzle, cooling rate of materials involved. This process is similar to Stereolithography (SLA), support materials are attached on the product surfaces. Normally, those support materials are easily to be removed since the joint between are point by point only. However, in some cases, it filled inside a hollow part or the subsurface areas. For those cases, support material solution are required in order to clear out from the product.

2.8.4 Specifications of Thermojet

(3D Systems, 2000)

Synonyms: Material Jetting (MJ), Inkjet Printing, Multi-jet modeling

Material class: Wax

Vendor	Material
3D Systems	Visijet Dentcast
3D Systems	Visijet Hi-Cast
3D Systems	Visisjet ProWax

Characteristics: For comparison purpose.

Colour	Neutral, grey or black
Resolution (x,y)	300 x 400 DPI
Maximal build envelope	250 x 190 x 200 mm^3
Minimum feature size	0.1 mm
Minimum layer thickness	0.013 mm
Typical tolerance	+/- 0.025 mm

General Application: Scale prototypes, and casting patterns.

Figure 14: Thermojet in Block 16, UTP

CHAPTER 3
METHODOLOGY

3.1 Research Methodology

Understanding

Since the project title is provided by the supervisor, effort have to be there to make it clear about the related information such as additive manufacturing technology, structure support for rapid prototyping, PDC drill bits and 3D design software CATIA.

Research

Simple understanding is not enough for development of the project. Research and literature review are required for the details like PDC drill bit dimensions, the specifications of rapid prototyping machine Thermojet, material used, and casting methods.

3D Drawing

Rapid prototyping machine can only accept the 3D drawing format, STL. To adapt the requirement, utilize CAD drawing is important in the stage. After attend for some tutorials, we have to modify the PDC drill bits by using 3D design software CATIA.

Rapid Prototyping Product

By converting few of the complete 3D drawing from CATIA into the 3D drawing format, STL, it is able to print out now with Thermojet. However, it may consists some dimension errors and cause it unable to combine each other. If error happened, back to the previous stage.

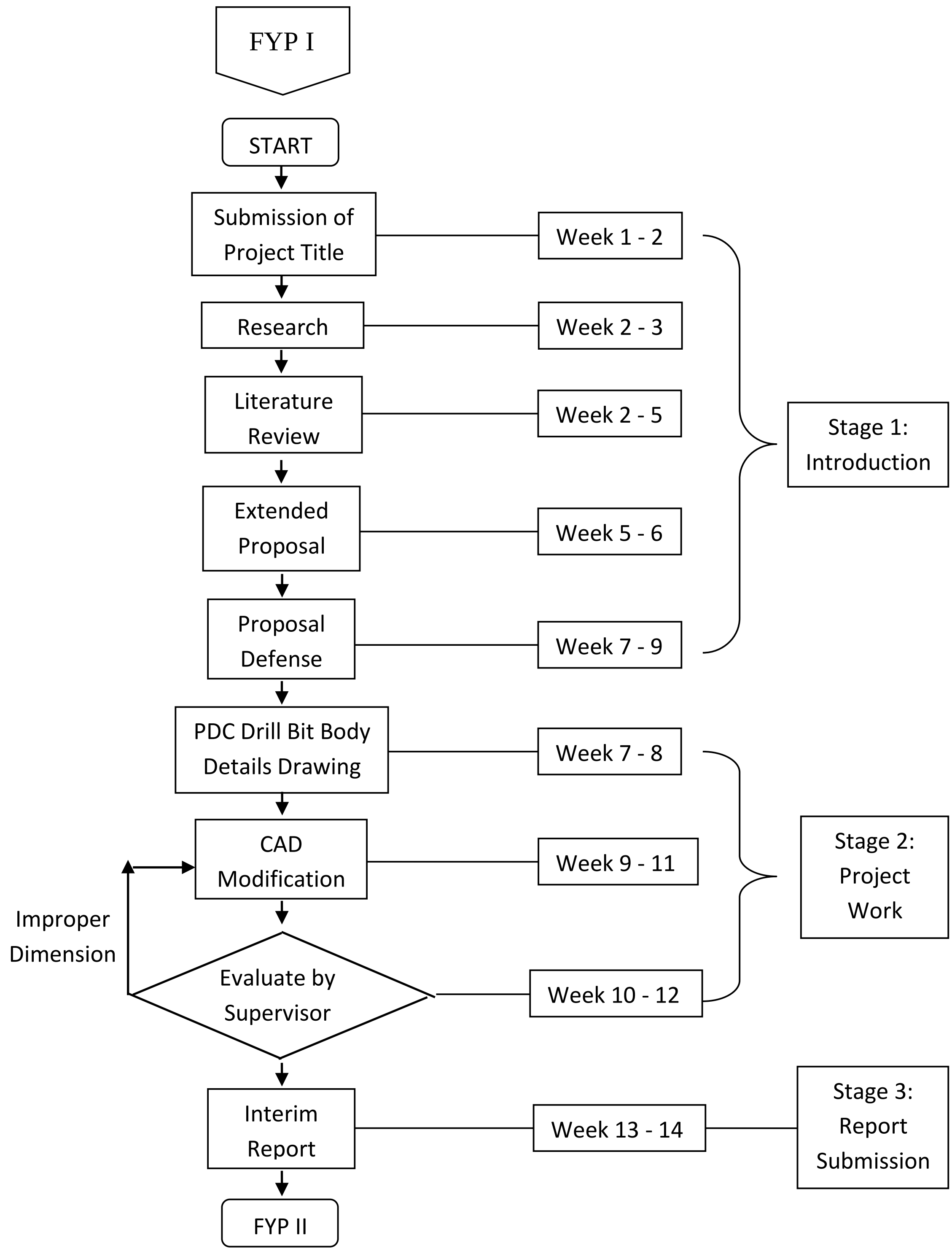
Investment Casting

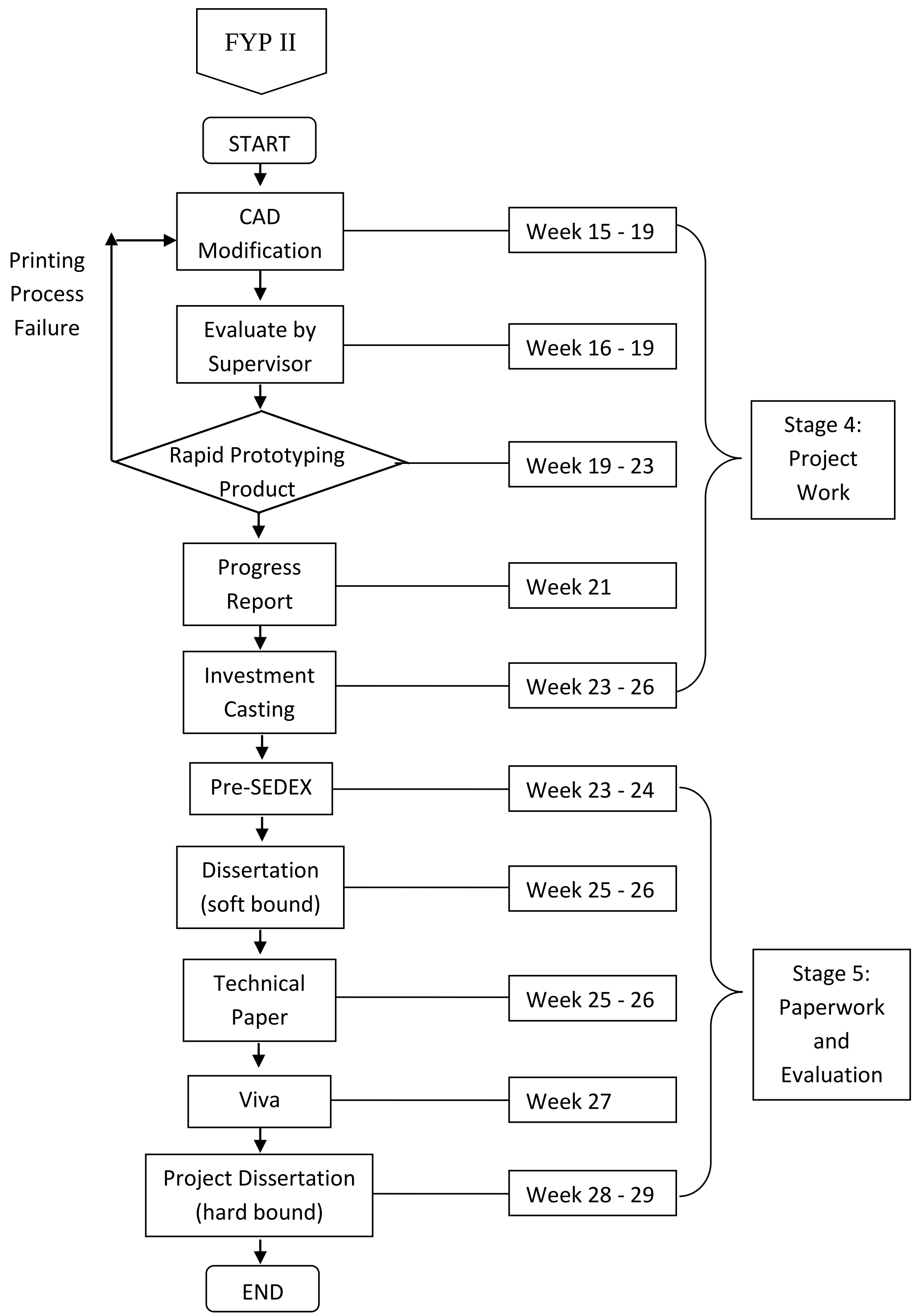
With the rapid prototyping products, it can be proceed to next manufacturing technique, investment casting. The model will sent to outsource since the technology is not available in UTP. A functional PDC drill bit can only formed by investment casting since it have to in metal form.

Dissertation

Records all the related information, calculation, specifications, data, PDC drill bit dimensions, 3D drawings into a report. Submit the reports to coordinate and examiner after evaluate by the supervisor.

3.2 Key Milestone




FYP II
START
CAD Modification
Evaluate by Supervisor
Rapid Prototyping Product
Printing Process Failure
Progress Report
Investment Casting
Pre-SEDEX
Dissertation (soft bound)
Technical Paper
Viva
Project Dissertation (hard bound)
END
Week 15 - 19
Week 16 - 19
Week 19 - 23
Week 21
Week 23 - 26
Week 23 - 24
Week 25 - 26
Week 25 - 26
Week 27
Week 28 - 29
Stage 4: Project Work
Stage 5: Paperwork and Evaluation

3.3 Project Timeline (Gantt-Chart)

Tasks	Academic Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Introduction	■	■	■	■	■	■	■	■	■					
Submission of Project Title	■	■												
Research about Additive Manufacturing Technology		■	■											
Literature Review		■	■	■	■									
Drafting Proposal					■	■								
Finalize Proposal						●								
Proposal Defence								■	■					
2. Project Work							■	■	■	■	■			
Understand the PDC Drill Bit Details Drawing							■	■						
CATIA Design							■	■	■	■				
Evaluate CAD Drawing										■	■			
3. Report Submission											■	■	■	■
Data Analysis											■	■		
Drafting Interim Draft Report												■		
Submit Interim Draft Report													●	
Evaluate Interim Draft Report													■	
Submit Interim Report														●

● Suggested Milestone

■ Process

Tasks	Academic Week													
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
4. Project Work	■	■	■	■	■	■	■	■	■	■	■	■		
CAD Modification	■	■	■	■	■									
Evaluate CAD Drawing		■	■	■	■									
Rapid Prototyping Product					■	■	■	■	■					
Progress Report							●							
Investment Casting									■	■	■	■		
5. Paperwork & Evaluation									■	■	■	■	■	■
Pre-SEDEX									■	■				
Draft Final Report										■	■			
Project Dissertation (soft bound)											■	■		
Technical Paper											■	■		
Viva													●	
Project Dissertation (hard bound)														●

● Suggested Milestone

■ Process

3.4 PDC Drill Bit Body CAD Model

To achieve a more reality CAD drawing by using CATIA software, an actual PDC drill bit body was received by the team of research and been referencing in modelling. The figure 15 and figure 16 are the actual PDC drill bit body that we have received from PETRONAS. By the previous researcher, Muhammad Hariz Bin Mohd Noor, the CAD drawing was modelled out using CATIA software, and the figure 17 and figure 18 are top and isometric views of the model. At first, the model have been fabricated out by using Zprinter@450 with ceramic-based material. However, ceramic-based material is not sufficient for some real drilling simulation test. To make it one step forward into real drilling simulation test by another group, this model has been investigated and modified in this project and will be print out by using the Thermojet printer with wax material. This sacrificial wax pattern will undergo the next process which is investment casting for a functional prototype which is made of stainless steel. Before the model convert into STL file and start to print out by Thermojet, some of criteria have to be achieved to prevent printing failure and material waste.

1. Reduce the slope and curve sector or inner surfaces.
2. Magnify edge angle as possible.
3. Ensure the surfaces are smooth.
4. Measuring dimensions in metric.

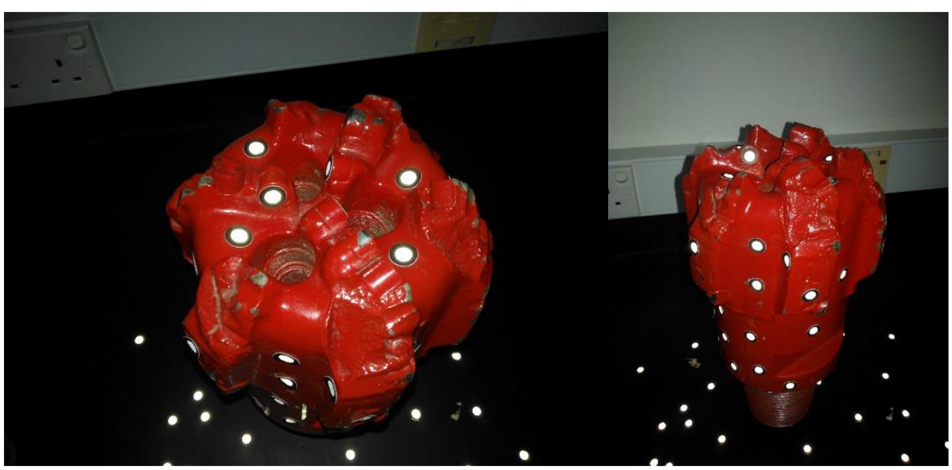


Figure 15 & Figure 16: Actual PDC drill bit body for referencing in CAD drawing

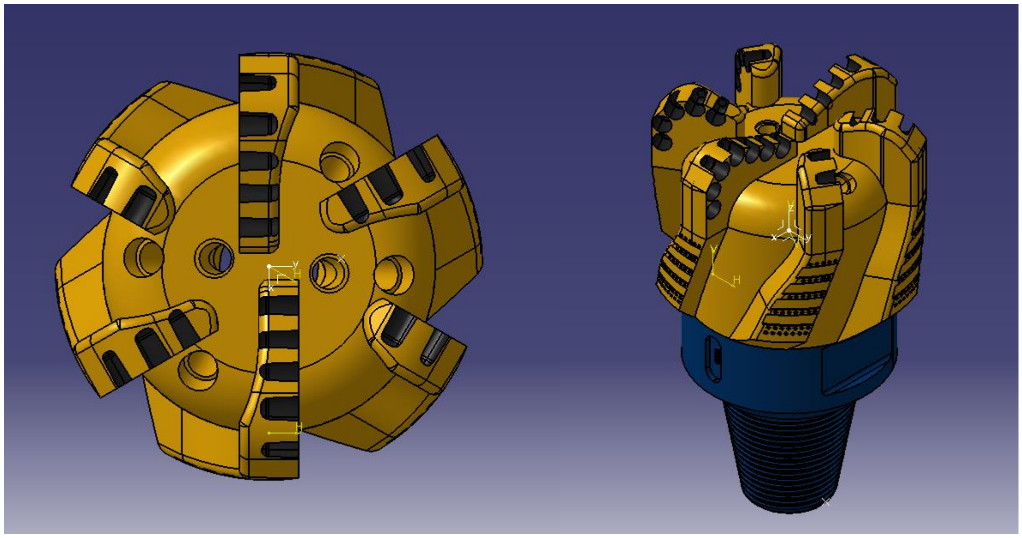


Figure 17 & Figure 18: Top view and isometric view of CATIA model

3.5 CAD Model Sectioning

It is a necessary to section or slice open the CAD model to expose all the hollow section and inner surface of the PDC drill bit body. The oversize of the model is also the reason that model is unable to direct printing out from the machine. The first two model are only sectioning without any modification. However, these methods are not sufficient to minimize the volume use in support material to build up the model.

Method 1: Separate the model at the middle and divided into two parts only.

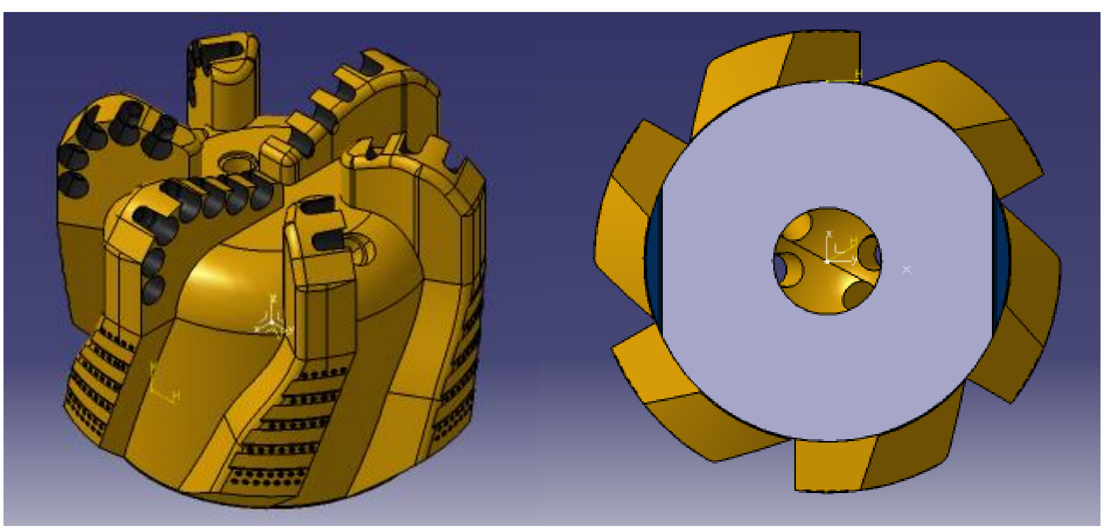


Figure 19 & Figure 20: Isometric view and bottom view of top section

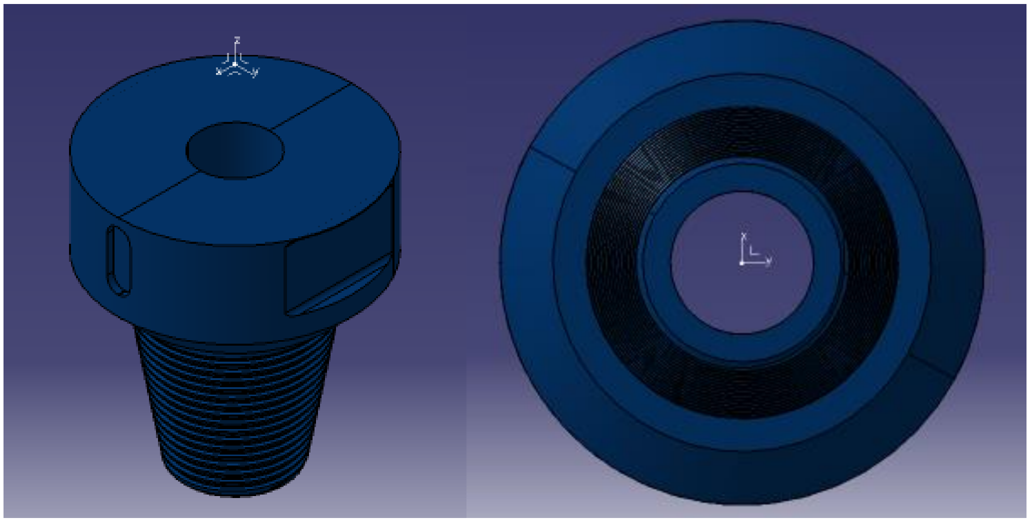


Figure 21 & Figure 22: Isometric view and bottom view of bottom section

This method is just divided the model into two section which is top and bottom part only as figure 19 and figure 21 shown above. It has been proposed to be print out by using Thermojet printer since the dimension of the divided part is small enough for the machine. However, the volume of support material is relatively higher than method 2 and the cleaning session will be harder. In opposite, it is easier to merge both of them together after printed out by using fastening for investment casting process later.

Method 2: Separate the model with coordinate and divided into six parts.

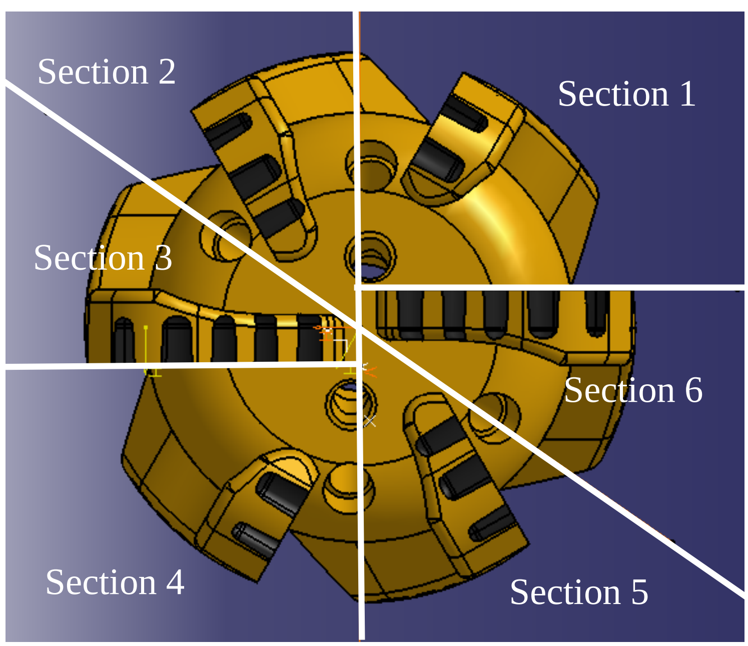


Figure 23: The division of model

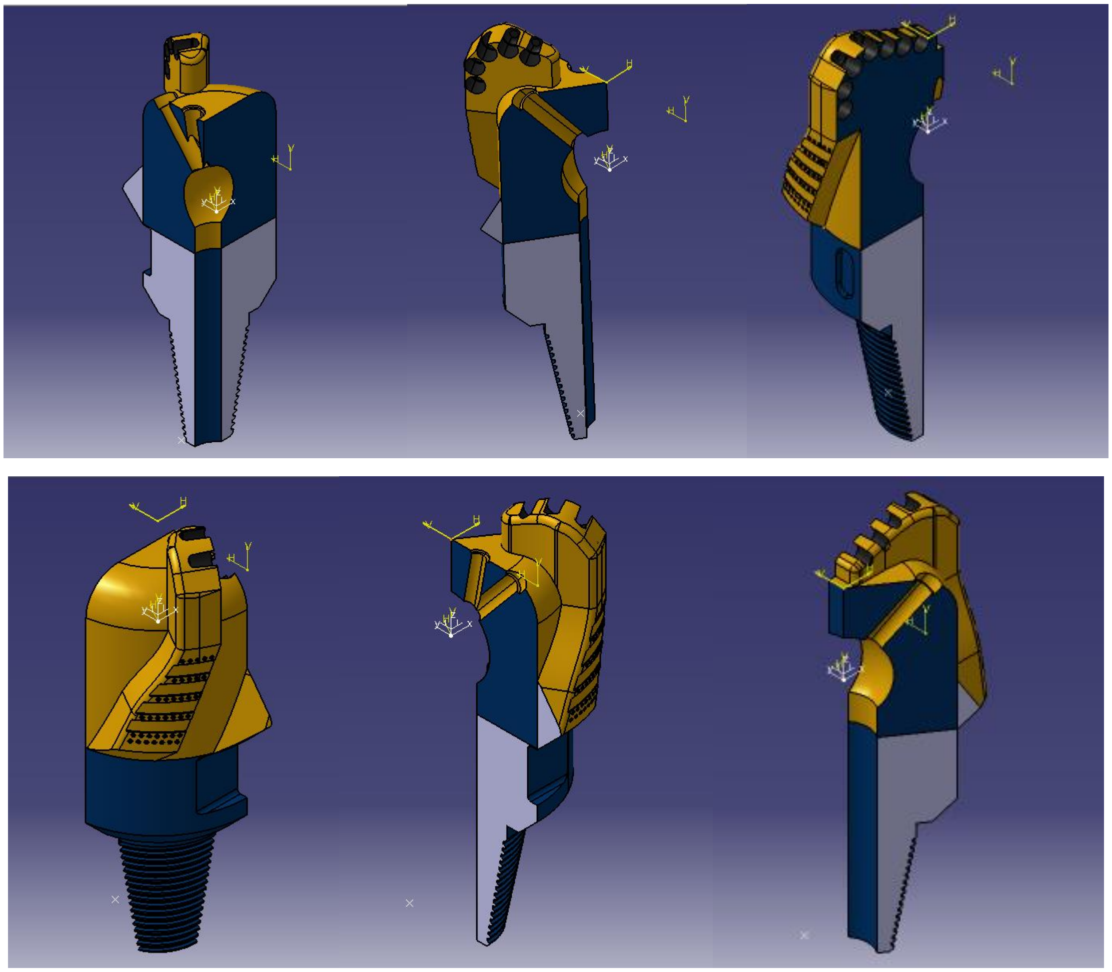


Figure 24: Isometric view of 6 sections

This method is relatively better in support material saving since all the hollow space are exposed and thus provided an easier way to achieve surface finishing product. These parts are recommended printing out horizontally from inner to outer surfaces since the inner surfaces is less curve and complex structure. However, this method is not easy in merging every single part into one. When six of them are merging each other just by fastening, it cannot be properly match. Tongue and groove joint are recommended for all them in order to merge into one and send for further process.

In short, this two methods are not good enough for the Thermojet printing. The CAD model for PDC drill bit body have to be modify into a less complexity model. Method 3 is the one which achieve less support material use and fit in printing dimension.

Method 3: Separate the model at the middle and divided into two parts within inner diameter modifications.

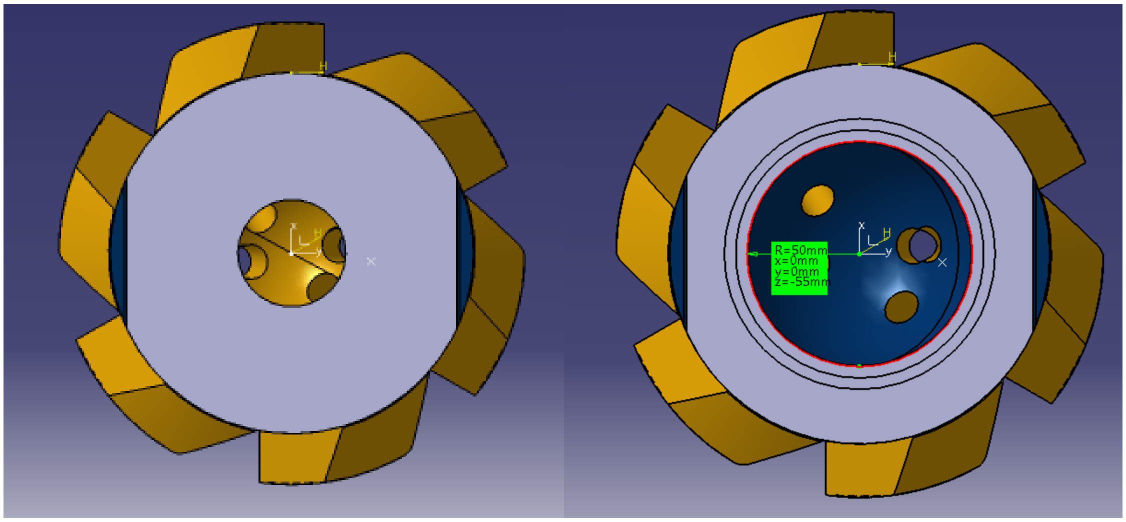


Figure 25: Bottom view of top section before and after modified

From the previous CAD model drawing, the PDC drill bit body top side was high in thickness. The empty space inside the part was an empty sphere with a radius of 37.5mm and the radius of the cylinder just below it and down to bottom part is 25mm. To reduce the wall thickness, the empty space inside has changed into round-head cylinder with radius of 50mm and 72mm length tall. Besides, the tongue and groove joint was insert on the top side and bottom side model to make sure them are easily merge to each other.

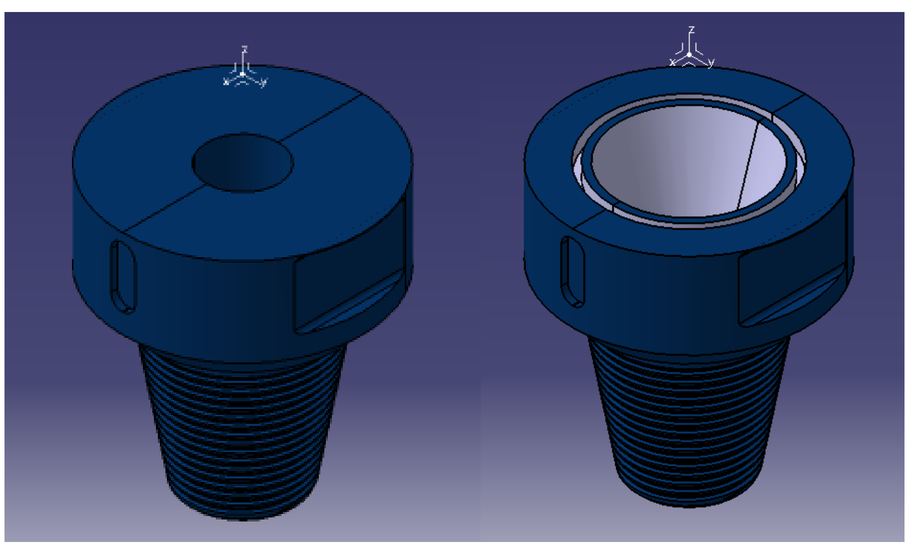


Figure 26: Isometric view of bottom section before and after modified

From the previous CAD model design, the PDC drill bit body bottom side is just a straight hole with 25mm radius from the surface till the end. To adapt the top side diameter after the modification done, it has been changed into a slope from 50mm radius top surface to the end surface with 25mm radius with a length of 80mm. It then extruded with a length of 80.5mm cylinder to ensure the same height with the previous design.

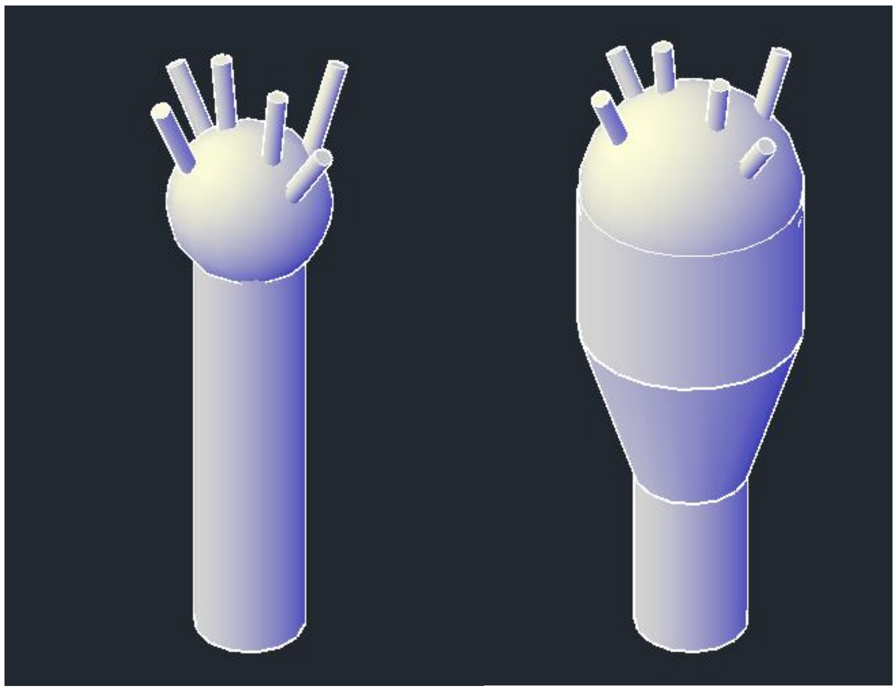


Figure 27: Isometric view of empty space inside the PDC drill bit body model

From the figure 27 above, we can observe that the empty space inside the PDC drill bit body model has increased after been modified. The sphere shape at the top part was changed into a round-head cylinder, and the bottom part was modified accordingly to the diameter of the top part and slightly decreasing into the same diameter as previous. The overhang of the sphere at the top part has reduced to become a cylinder. The “U” shape of the top side can be print out with much lesser support material included. With these modifications made, the model is easier to be manufacture out by using Thermojet printer.

3.6 Rapid Prototyping

After the modifications have been done, it is the time to decide whether it print out from inner or from outer for top section and whether upright or invert for bottom section. Although the volume of product is the same no matter how it print out, the volume of support material will not be the same with different printing directions. The printing orientations conduct an important role to minimize the support material usage. The model has divided into three parts and named as top1, top2 and bottom in STL files.

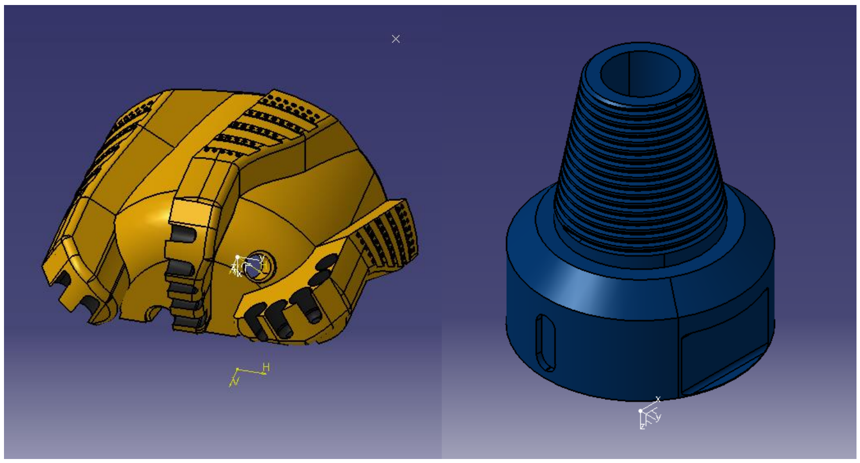


Figure 28: Rapid prototyping part orientations

As shown in figure 28, the top1 and top2 files (similar to each other) were printed out from inner surface to outer surface. The bottom file was printed out upside down. Those decisions are made after discussion with supervisor, Dr. Khurram Altaf.

Figure 29: Parts printed out with wax material

The figure 29 above are the top1 and bottom files printed out from Thermojet. Those product are still covered by support materials.

3.7 Post-processing

Although the PDC drill bit body has divided into parts and printing out individually, it have to merge into one to proceed the investment casting. However, before merging them together, removing support materials is the prerequisite stage. In the figure 30, it shown that the process of removing support material started from outer surface then inner surface by using mechanical hand tools. Those removed support materials will be disposal since it is made of wax and not recyclable.

Figure 30: Removing support material with mechanical hand tools

The figure 31 below are the view of inner surface and outer surface of top1 file product. Those surfaces have to be cleaned out before undergo the next stage to ensure the closer dimension tolerances. If the post-processing is not good enough, the end product of investment casting will be affected and surface finishing is harder to process.

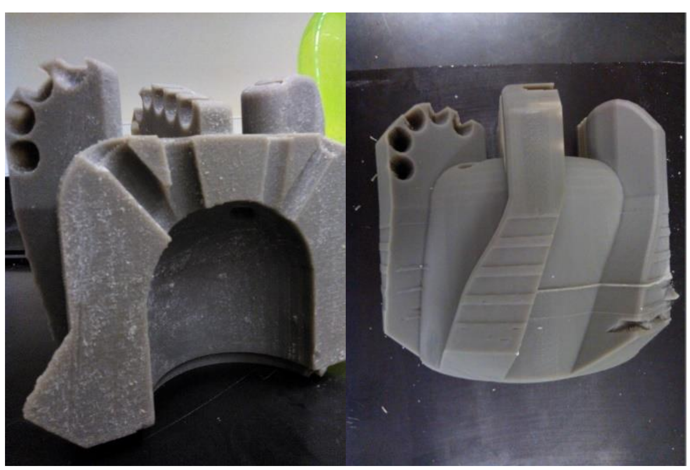


Figure 31: Top part wax product after removed support materials

3.8 Investment Casting

Investment casting (IC) is a precision casting process to convert a wax pattern into a solid part following a multi-step processes. Normally, a sacrificial wax pattern was made with machine and molds. However, in this project, it was made by Thermojet. The figure 32 below are the processes to convert wax material into a solid component.

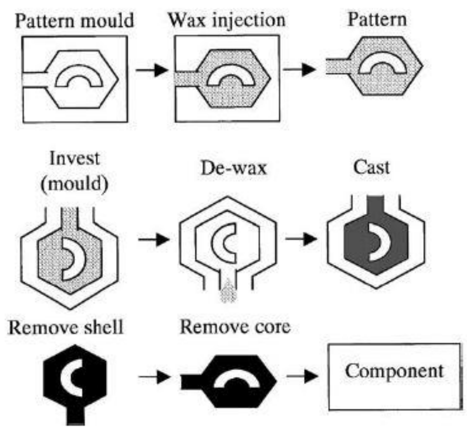


Figure 32: Basic principles of the investment casting process

In order to give reader to have a clear picture about investment casting, the processes are shown as table 1 below. Sequence of the processes is the same as the numbering.

Table 1: Investment casting process

1. Wax pattern 	2. Assembly 	3. Slurry Coating 	4. Stuccoing 
5. De-Waxing 	6. Shell Sintering 	7. Pouring 	8. Parting 

Since the investment casting technology is not available in Universiti Teknologi Petronas. To progress our sacrificial wax pattern into stainless steel product, we sent our product to Prima Precision Sdn. Bhd. They are not only provide investment casting services but also consultation about our product. Within the consideration of advices, we have chosen stainless steel SUS 304 for the investment casting in order to become a functional prototype with high yield and tensile strength.

Table 2: Standard range of alloy

	Alloy	Yield	Tensile	Elongation	Reduction	Brinell
		Strength (MPa)		(%)	Area (%)	Hardness
Carbon Steel	42CRMO4	-	784	12	-	229 max
	50C	341	621	15	35	179
	S35C	272	497	18	40	143
	S45C	310	567	16	40	163
Stainless Steel	SCS 2	392	588	18	35	214 max
	SNCM630	785	883	17	50	311 max
	SUS 303	241	621	50	55	160
	SUS 304	241	586	55	65	150
	SUS 316	241	586	55	70	150
	SUS 440C	448	759	13	25	230

The figure 33 below shown that the end product of investment casting after we retrieve it within a week period. Some casting defects were found inside the drill bit cutter locations. To remove the steel depositions, manually surface finishing required. Overall, it considered acceptable.

Figure 33: The end product of investment casting

3.9 Surface Finishing

The stainless steel product was found out have some casting imperfection, mostly the outer surface of the drill bit body and the PDC drill bit cutter locations. It was happened due to the assembly tree in investment casting was not stable enough to support the heavy weight of sacrificial wax pattern. It made the stage three, slurry coating as mentioned above is not complete and formed some extra material on the spot.

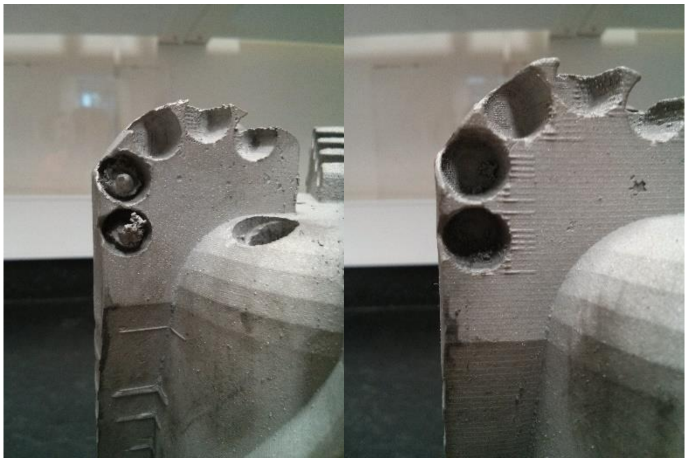


Figure 34: Comparison of PDC drill bit cutter locations

Surface finishing can be divided into two category which are removing or reshaping finishing and adding or altering fishing. Main reason of surface finishing in the project is to achieve better appearance and minimize surface friction. The sequence of methods we have involved on the stainless steel product are drilling, grinding, polishing and painting. Those methods are able to observe through figure 35 shown as below.

Figure 35: Sequence of surface finishing

CHAPTER 4
RESULTS AND DISCUSSION

In the section, I would like to discuss both products from 3D printing technology and investment casting. Both of them have some issues to discuss about for next stage of improvement.

4.1 Sacrificial Wax Pattern

The first product here is sacrificial wax pattern from 3D printer Thermojet by converted STL file from CATIA drawing. It printed out layer by layer accordingly to the CAD file. Theoretically, dimension of the printed product should be the same as the drawing. However, theory have not proven yet since we did not measure the overall dimension of the product before send for investment casting. The figure 36 and figure 37 can be observe that the pattern looks like and compare to previous ceramic product.

Figure 36: Top view of merged parts and ceramic product (non-functional prototype)

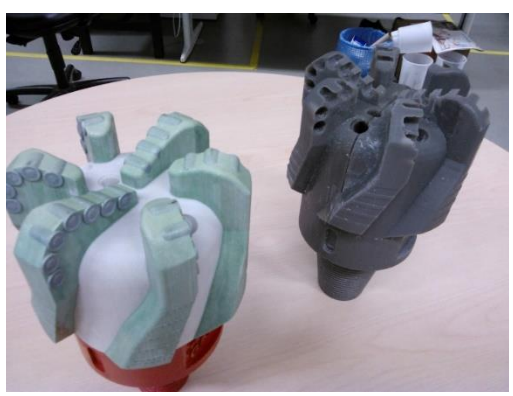


Figure 37: Comparison of size between two types of rapid prototyping product by isometric view

Not every wax material is suitable for investment casting. Between both of TJ88 and TJ2000 from 3D Systems industry, material chosen for the printing is TJ2000 due to its characteristics such as melt temperature, softening temperature, volume of shrinkage and ash content remain. It is an ideal material for investment casting since it only leaves 0.01% of ash following being burnt in 500 degree Celsius during stage 5 de-waxing process as mention above. To be specific, both of their properties are shown as table 3 below.

Table 3: Material properties

		ThermoJet 88 (TJ88)	ThermoJet 2000 (TJ2000)
Melt temperature		85 – 95 ℃	70 – 75 ℃
Softening temperature		70 ℃	55 ℃
Density(g/cubic cm)	@140 ℃	0.846	0.865
	@130 ℃	0.848	-
	@110 ℃	-	0.883
	@23 ℃	0.975	0.982
Volumetric shrinkage from 140 ℃ to room temperature		12.9%	11.7%
Linear shrinkage from 140 ℃ to room temperature		-	2.3%

From the table 3 above, we can know that printing material TJ2000 is easier soften than TJ88 with temperature. In opposite, material TJ2000 is less volumetric shrinkage from 140℃ to room temperature (27℃) compare to material TJ88. In this case, melt temperature and softening temperature are not in the consideration since according to geography of Malaysia, the highest temperature was on 9 April 1998, which is 40.1℃. The difference between highest environmental temperature in Malaysia and lowest softening temperature (TJ 2000) is around 15℃. With this data, we can confirmed that the sacrificial wax pattern is impossible to soften or melt in room temperature or weather temperature in Malaysia except extra heat applied. To ensure the sacrificial wax pattern is in perfect condition before send out for casting, we stored it into chiller with 18 ℃. However, the pattern can be easily broken if unintentionally force applied. The cutter location was damaged with the mechanical tool during post-processing for support material removing.

4.2 Casting Product/ Functional Prototype

With the available of sacrificial wax pattern, we sent and have the stainless steel casting product out from the service of Prima Precision Sdn. Bhd. in Perak. For further understanding about the investment casting process, we have a visit on industry for photo taking and records. The end products are ready in a week period and acceptable with some imperfections such as porosity on top part and extra materials attached on cutter locations. Three of them are merge into one by using fastening method, product of Araldite Rapid Steel Epoxy, which perfect for metallic work. The figure 39 is showing the product after merging three parts into one.

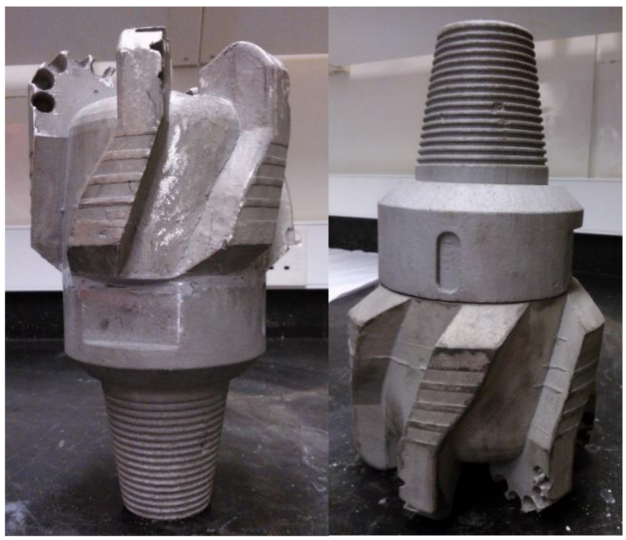


Figure 38: Upright and inverted front view of stainless steel drill bit body

Casting failure is one of the imperfections that is unable to discuss here since it is not affected due to the modification or improvement made. On the other hand, imperfection like porosity can be modified in order to make a better functional prototype in next research. Porosity happened is because of thickness on model. Thickness between outer surfaces and the drill bit cutter location is range as 0.133mm to 0.142mm as shown in figure 39, which is too thin or not sufficient for investment casting. For this case, the minimum thickness proposed is 5mm. Within the thickness proposed, the sacrificial wax pattern is not easily broke also when removing the support material by mechanical hand tools. Besides, the ceramic drill bit cutter is recommended to insert when producing the sacrificial wax pattern. It can be crack out to become a perfect drill bit cutter hole after investment casting. This method not only can provide a fit hole for cutter installation after but also reduce the risk of porosity.

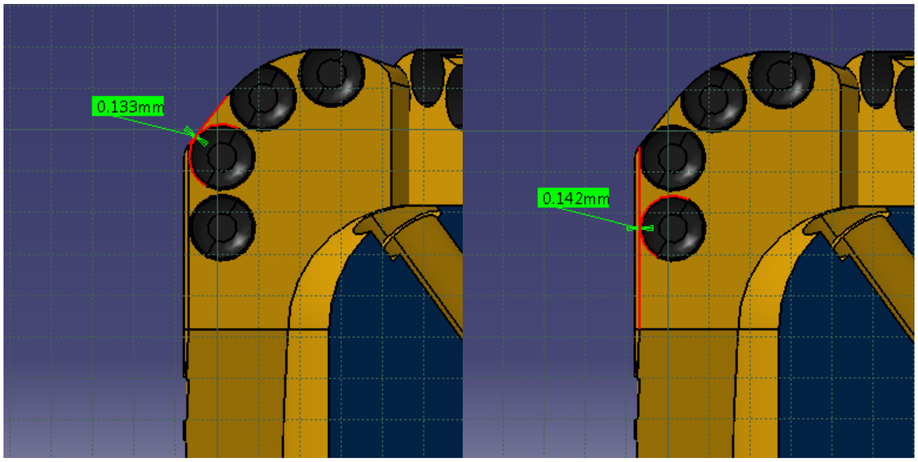


Figure 39: Thickness between outer surfaces and cutter locations

To provide a better appearance of final product, two color of paint was applied on the surfaces of stainless steel drill bit body or the functional prototype. In fact, both color are showing the boundary of printed product. As figure 40 shown below, the red paint is representing the top part where two parts have merged together with rapid steel epoxy, whereas black paint is the bottom part only. The functional prototype will be store in block 16 for further study.

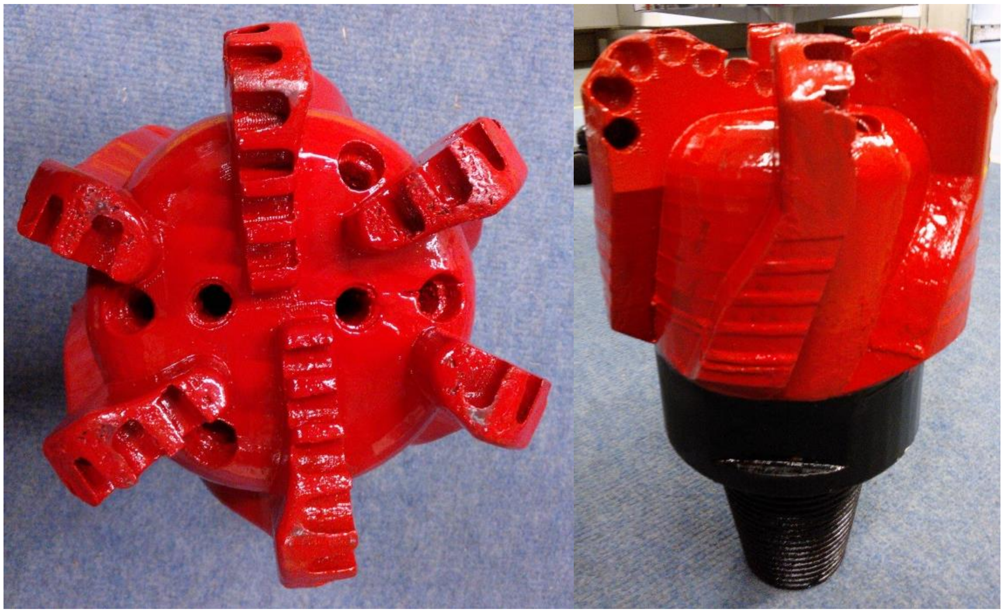


Figure 40: Views of end product after painted

CHAPTER 5
CONCLUSION AND RECOMMENDATION

The project is about 3D CAD drawing, rapid prototyping technique and investment casting technology. Within the project, student has the chance to discover Universiti Teknologi Petronas facilities regarding to additive manufacturing and further understanding its operation, requirements and materials. As a newcomer of the technology, study in theory and concept understanding are important. To fulfill both of them, literature review was wrote and related researches and supervisor were acknowledged in this dissertation.

Most of the mechanical engineering students are able to operate 3D CAD software such as Autocad, Catia and Solidwork. According to academic structure, we have the chance to learn and work with Autocad and Catia for two semester. However, normally students are able to construct a simple model but not a complex model like PDC drill bit body structure. To modify the model we have in project, further learning, practice and effort are necessary. It really helps in enhancing the CAD software skills.

There have variety of material are able to print out with 3D printer. To be specific, facilities here are able to produce in two type of material, they are ceramic and wax. For the previous research, ceramic prototype had printed out. It provides a good visual aid for presenter or exhibition but is unable to proceed to mechanical tests. In order to make the project one step forward from visual aid only, it requires to produce something have the metal properties. However, there are just only one metallic 3D printer in Malaysia and we are unable to utilize the facility. After some researches done, the combination of wax pattern and investment casting had decided to conduct in the project.

From all type of steel, the consideration for investment casting is important for a functional prototype. It can affect the performance after such as mechanical hardness test. Amongst stainless steel and carbon steel, we have chosen stainless steel for the process with some reasons and also the consultation from experience industry. Besides, students are able to run out from texts and have a chance to explore the industrial operation with permission. The experience is precious especially for a mechanical engineering student.

For manufacturing technologies, dimensional tolerance is conducting an important role in fabrication. It is nearly impossible to make a product zero error or without any deviation from the drawing. A tolerance is the ability or willingness to tolerate some variation of a specified quantity. In this project of steel fabrication, additive manufacturing is under manufacturing technologies and should involve in tolerance measurement. For the further research, dimensional tolerance should be measure in every steps of sequence.

This project is differ with other research study which related to computer simulation. The study is more towards industry demands. It is not only provided the bridge between university and industrial areas, connect to each other and helps in solving problems but also created a triple win situation for student, university and industry. For student, we have the chance to explore related manufacturing industry and learn about industrial management system, operation sequences and services provided. It make student clear about the actual working life out of university.

Besides, university have its benefit. The facilities in university are provided for student understanding but not in high standard for production. Those equipment is consider not complete to produce a functional prototype that able to run mechanical tests. With the aid from industry, the product is able to reach higher level of accuracy and more capable. The functional prototype can be only done by cooperation with industry. Nevertheless, industry can gain their knowledge about the new technology nowadays such as additive manufacturing. All three party have their own benefit within this project.

University Teknologi Petronas should have more project connected both university and industry. It helps student explore more from outside and understand the demands of industry, for example: time, investment and craftsman. By solving the industrial problem, it not only help to rise up university reputation but also will provide a better chance for student been employed by those related industry.

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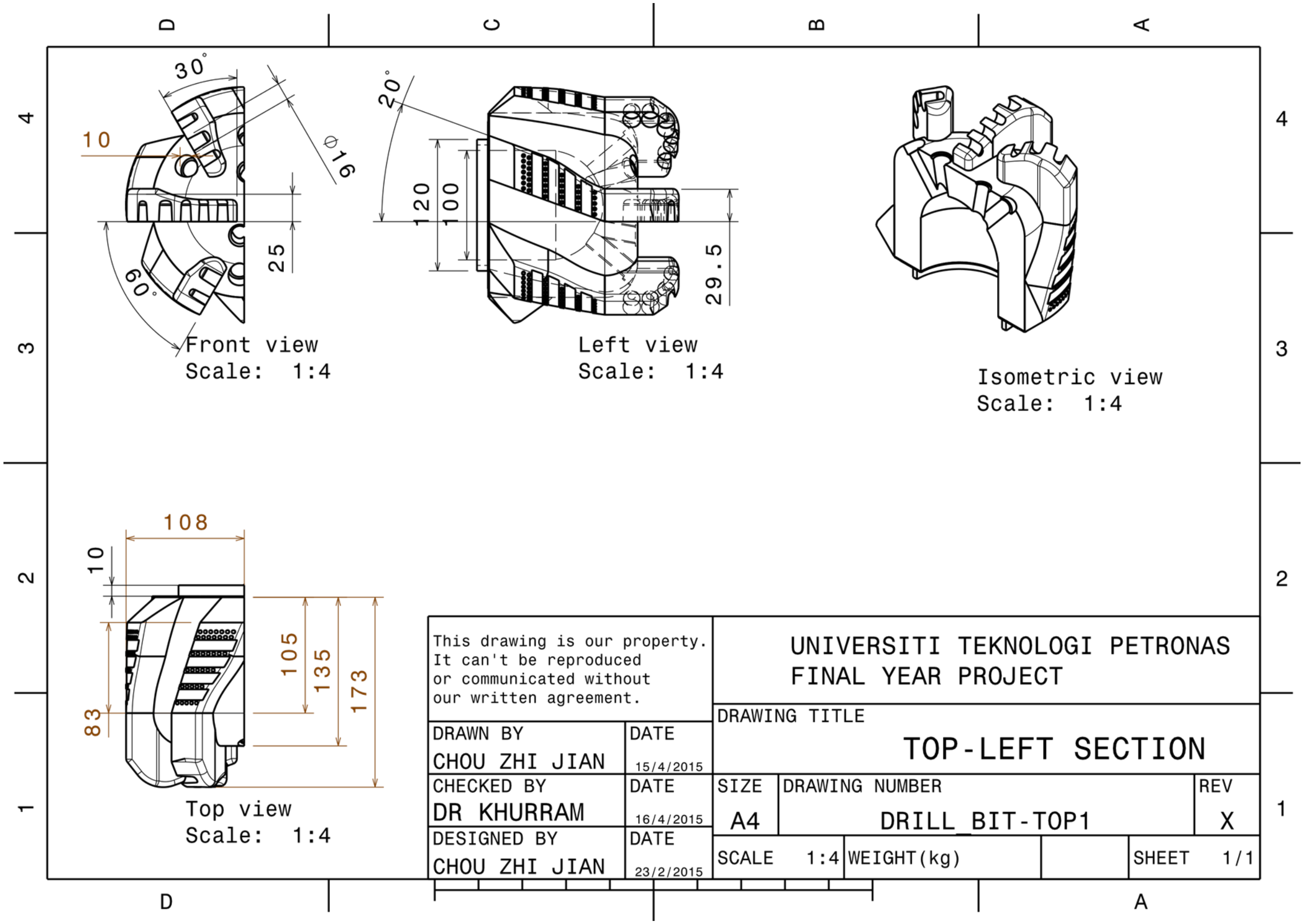
APPENDICE A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30°
10
Ø16
25
60°
Left view
Scale: 1:4
20°
120
100
29.5
Isometric view
Scale: 1:4
Top view
Scale: 1:4
108
10
83
105
135
173
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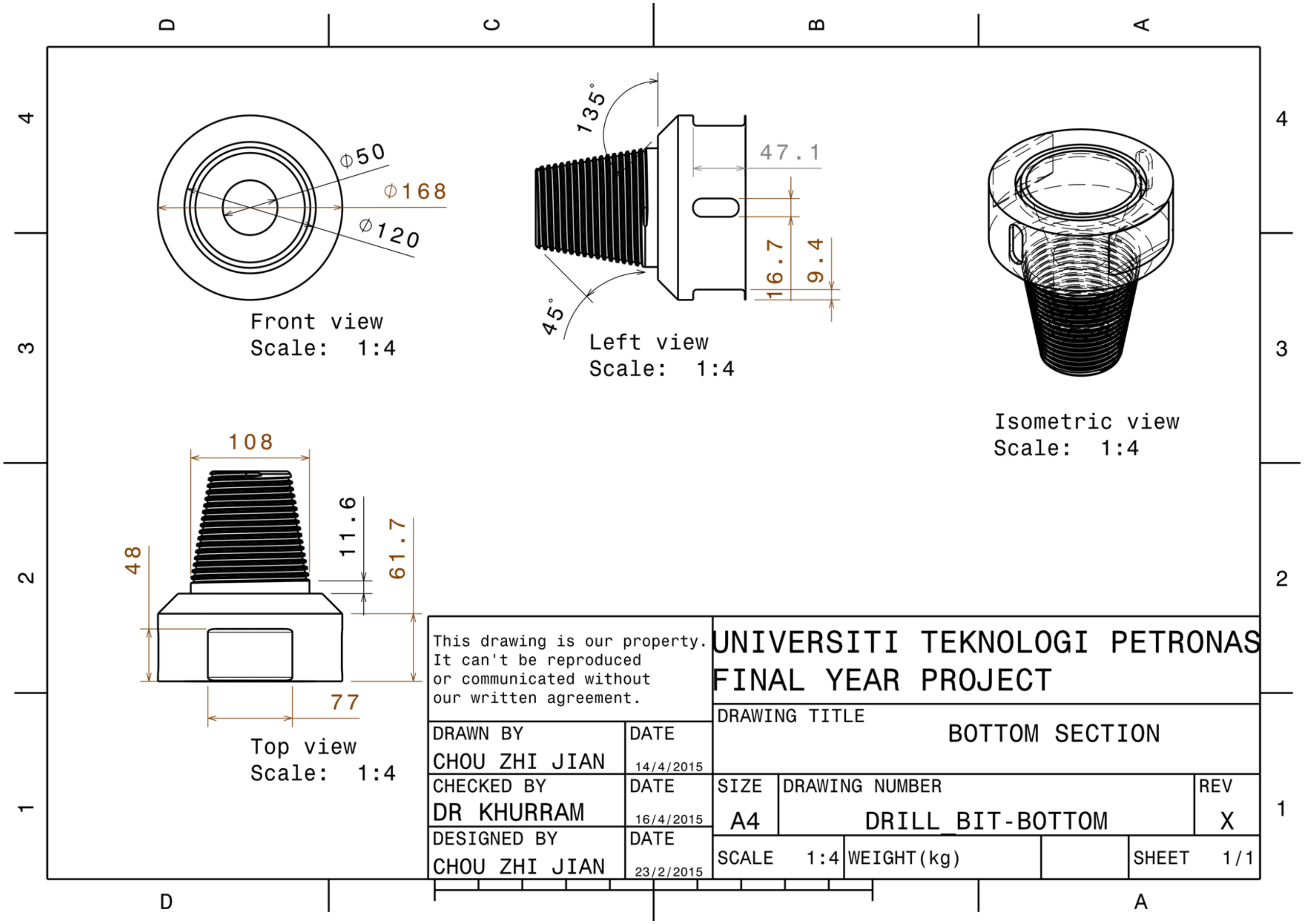
UNIVERSITI TEKNOLOGI PETRONAS
FINAL YEAR PROJECT
DRAWING TITLE
TOP-LEFT SECTION
DRAWN BY
CHOU ZHI JIAN
DATE
15/4/2015
CHECKED BY
DR KHURRAM
DATE
16/4/2015
DESIGNED BY
CHOU ZHI JIAN
DATE
23/2/2015
SIZE
A4
DRAWING NUMBER
DRILL_BIT-TOP1
REV
X
SCALE 1:4
WEIGHT(kg)
SHEET 1/1

APPENDICE B


Φ50
Φ168
Φ120
Front view
Scale: 1:4
135°
47.1
16.7
9.4
45°
Left view
Scale: 1:4
Isometric view
Scale: 1:4
108
48
11.6
61.7
77
Top view
Scale: 1:4
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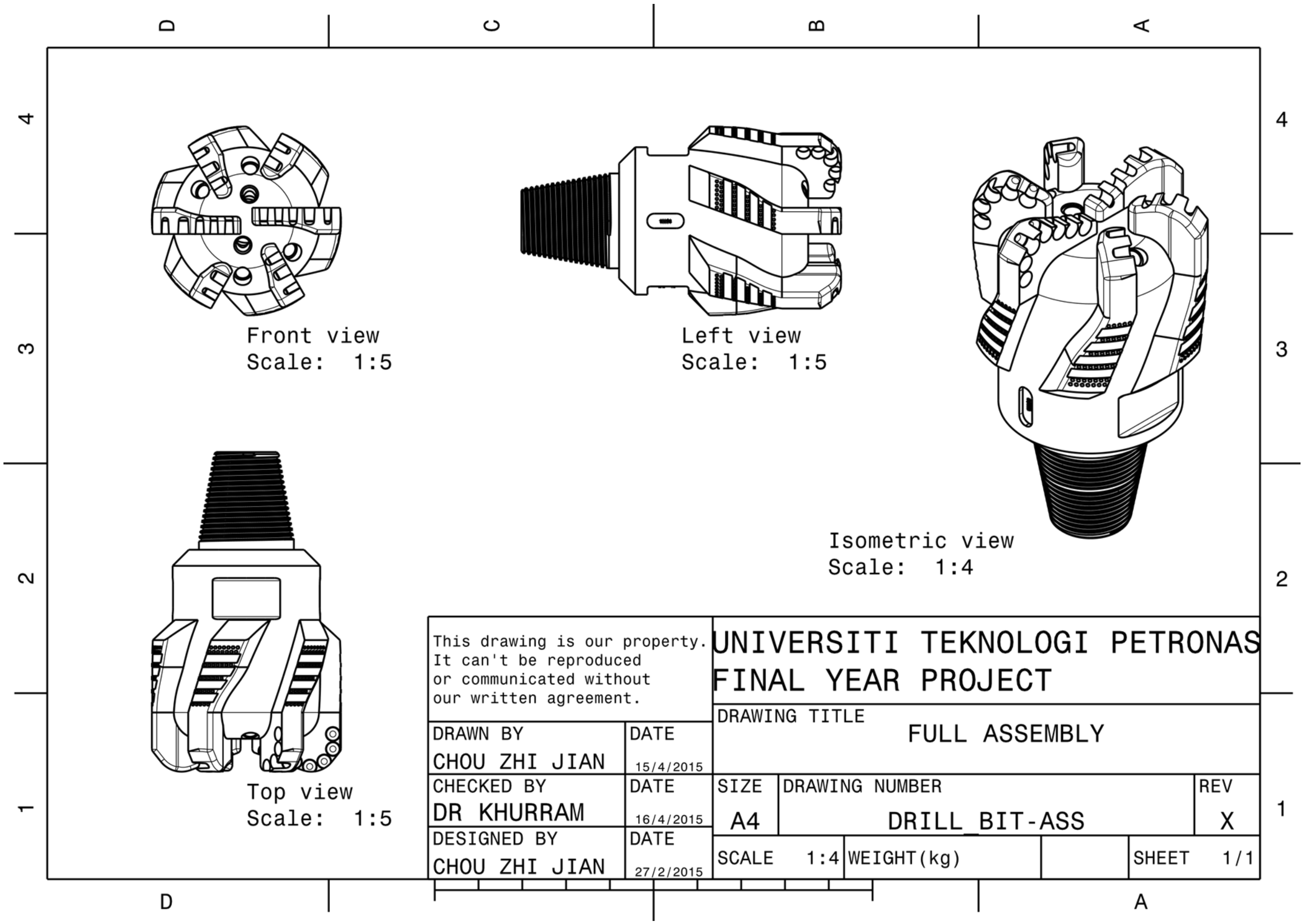
DATE
23/2/2015
DRAWING TITLE
BOTTOM SECTION
SIZE
A4
DRAWING NUMBER
DRILL_BIT-BOTTOM
REV
X
SCALE 1:4
WEIGHT(kg)
SHEET 1/1

APPENDICE C


Front view
Scale: 1:5
Left view
Scale: 1:5
Isometric view
Scale: 1:4
Top view
Scale: 1:5
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DRAWING TITLE
FULL ASSEMBLY
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CHOU ZHI JIAN
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15/4/2015
CHECKED BY
DR KHURRAM
DATE
16/4/2015
DESIGNED BY
CHOU ZHI JIAN
DATE
27/2/2015
SIZE
A4
DRAWING NUMBER
DRILL_BIT-ASS
REV
X
SCALE 1:4
WEIGHT(kg)
SHEET 1/1
D
C
B
A
4
3
2
1