DEVELOPMENT OF FUNCTIONAL PROTOTYPE OF STEEL PDC DRILL BIT BODY BY USING 3D PRINTING TECHNIQUE AND INVESTMENT CASTING

By

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Desertation submitted in partial fulfilments

of the requirements for the

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(Petroleum)

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Universiti Teknologi PETRONAS

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31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by:

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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.

Muhd Helmie Fiqri Bin Hairi

ABSTRACT

The project focuses on the fabrication of Polycrystalline Diamond Compact (PDC) drill bit prototype for industrial drilling testing to conform the previous study of the particular drill bit. The new designated drill bit had successfully shown an improvement rate of penetration through multi-layer formation by 58.33 % compared to the conventional drill bit based on Ansys simulation. Thus, further step is made to fabricate the design into functional prototype which can be used in industry drilling testing. Case history shows that almost all of the conventional PDC drill bit manufacturing contribute to a large number of waste materials, longer period of time, more motions and processes. The objective of this project is to investigate the application of new manufacturing ways to optimize the fabrication process of the new designated drill bit. An intensive study of manufacturing process and new technology was carried out and come out with the idea of rapid prototyping application (additive manufacturing) in the conventional PDC bit fabrication process. The project started with deciding on the rapid prototyping facilities available in UTP to make the sacrificial pattern of designated drill bit; in this case Thermojet 3D printer is chosen. The 3D CAD model of the PDC drill bit is sliced into 3 sections due to the oversize structure and redesign to have fittings before set for rapid prototyping. The Thermojet printer will build the part section in an additive manner (building layer by layer) and post processing job is needed once all the 3 sections (2 parts for the upper section, 1 part for the bottom section) are finished printed. All of the parts are then sent to the Prima Precision Sdn. Bhd. industry to accomplish the investment casting process. The methodology presented is the initial study of new manufacturing process for PDC drill bit body fabrication. The prototype formed through this methodology had successfully follow the initial design of the 3D CAD model. However, there are few area of improvements listed to help the future study on this topic. Throughout the project, the combination of rapid prototyping and investment casting of the PDC bit fabrication had resulted in lesser number of waste materials, period of time, motion and also processes.

ACKNOWLEDGEMENT

An endeavour over a period can be successful only with the advice and support of well-wishers. The author would like to take this opportunity to express his profound gratitude to Universiti Teknologi PETRONAS for providing the platform for the research project to be conducted.

The author also like to take this opportunity to express a deep sense of gratitude and regards to his supervisor, **Dr Khurram Altaf,** Senior Lecturer, Mechanical Engineering, Universiti Teknologi PETRONAS, for his cordial support, valuable information and exemplary guidance, which help the author in completing the final year project. The blessing, help and guidance given by hime time to time shall carry the author a long way in the journey of life on which the author about to embark.

The gratitude also goes to Rapid Prototyping Lab Technician, Mr. Zamil Khairuddin who always makes himself available to supervise the author in doing 3D printing processes and post processing job. The author obliged to the team members of Y-UTP for the valuable information provided by them in their respective fields. With their patience and openness they created an enjoyable environment. A big contribution and hard worked from them during project progress is very great indeed.

The author would like to thank Almighty, his parents, brother, sisters, and friends for their constant encouragement without which this report would not be possible

Thank you

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Abbreviations and Nomenclatures

3D	*Three Dimensional*
CAD	*Computer Aided Design*
PDC	*Polycrystalline Diamond Compact*
R&D	*Research and Development*
Y-UTP	*Yayasan Universiti Teknologi Petronas*
ANSYS	*Analysis System*
IC	*Investment Casting*
RP	*Rapid Prototyping*
STL	*Stereolithography Tessellation Language*

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Drill bit acts as one of the major role in the oil and gas discovery. It is used in drilling operation to drill a well aiming to find and developing new petroleum reserves. The successfulness of the operation depends mainly on the drill bit's performance. Due to the importance of it, a lot of researches and developments have been done on this particular equipment to further understanding of cutter/formation connection, cutter performance, bit dynamics and bottom hole assembly dynamics. It all started in the late 1980s, where the first modelling studies conducted by Sandia Laboratories that the analysis between the cutting elements of a PDC drill bit and the formation drilling has been widely investigated (Kerr,1988).

As the time passed by, variety of R&D projects have been developed adding a seemingly endless array of features to improve the bit's performance. However, case history found out that the subtractive manufacturing process practice by most of the conventional drill bit manufacturers commonly deal with a lot of waste materials and long period of time consumption. The complexities of the PDC drill bit body had also resulting in the huge amount of work and processes. Therefore, the author would like to propose the application of rapid prototyping (additive manufacturing) in the fabrication process which is believe to contribute a solution to the said problems.

In this project, the author will be working on the development of functional PDC drill bit body by using rapid prototyping application in the manufacturing processes. To be more specific, the author will be dealing with the Thermojet 3D printer under rapid prototyping technology. The author has to communicate with his supervisors, Dr. Khurram Altaf and also the production manager of Prima Precision Sdn. Bhd. to verify certain critical thinking in this project.

1.2 Problem Statement

Conventional manufacturing method of PDC drill bit body nowadays are working in the subtractive manners, where the built material is removed from the main part until it achieves the final form of the PDC drill bit body. This process is applied to the smaller and less complex structure of PDC drill bit body. For the larger and more complex structure, the initial production of mould is required in order to get the final form of the PDC drill bit body. Both of these methods undergo the same subtractive manners which contributes to the problem of having a large number of waste materials. Other than that, it is undeniable that most of the manufacturers use an advanced technology of machines to help shaping the PDC drill bit body until it reach the final accuracy model. In doing so, a lot of machines with different size of cutting elements is needed and number of process will also increases. Production period for a complex structure like the PDC drill bit body is counted by weeks. It is consider not economic if there is too much time loss in production, purchasing expensive tooling, and multiple works required to produce a scale model with the conventional manufacturing methods.

As a summary, the major problems faced through the conventional PDC drill bit body manufacturing practices are:

1. Large quantity of waste materials.
2. Long period of time consumption for production process.
3. Lot of works and processes needed.

1.3 Objective

The objective of this projects are:

1. To understand the parameters and function of rapid prototyping technology (specifically Thermojet 3D printer) in PDC drill bit body fabrication.
2. To develop a sacrificial wax pattern of PDC drill bit body with optimize RP computer system(part slicing) by using Thermojet 3D printer
3. To develop a functional PDC drill bit body made of steel by using sacrificial pattern formed through investment casting process.

1.4 Scope of Study

The scope of study based on the objectives can be simplified as follows:

1. Rapid prototyping system
2. CAD drawing
3. Fabrication of the sacrificial wax patterns by using Thermojet 3D printer
4. Fabrication of the functional prototype using investment casting method

CHAPTER 2

LITERATURE REVIEW

2.1 Development of PDC Drill Bits

The history of PDC drill bits started back in 1973 in which petroleum industry was introduced to the first development of drill bit that used synthetic diamonds as cutting elements (Kerr, 1988). Through this process, several design features that affect bit performance have become clear. The progress had lift up the PDC drill bits to the new level of main attraction between bit manufacturers in which fierce competition seemingly to take place in order to come out with the best bit that can improve the drilling performance. Since that, variety of new designs and types of bits becomes available in the market with each of it made with advance technology for certain types of application.

According to (Kerr, 1988), there are two type of PDC bit body material that are currently being used in the industry which are tungsten-carbide matrix and steel. There have not been any definite answer to which of the design is more efficient, but a few characteristics of each have become apparent. Among the differences are those matrixes bits are resistant to wear than steel. However structurally, steel bits are more resilient than matrix bits. An internal steel structure support is required for matrix bits.

Figure 1: *Steel-Body Bit and Matrix-Body Bit*

Source from Halliburton Drill Bits and Services

Now, steel and matrix drill bit are continuously progressing and their restrictions are regularly diminished. Steel bits are greatly being protected with materials that are more resistant to abrasion and erosion than matrix. Concurrently, the structural and wear properties of matrix are swiftly improving. The importance of steel bit is growing relative to matrix bits but both types have their place (Azar et. al, 2002). To be specific, the author will be working in the development of steel type PDC drill bit body.

In the early days, a basic process for manufacturing a drill bit is to machine the bit from a solid billet of steel into the desired final bit form (subtractive manner) (Symonds, 1999). The process improved as the use of investment casting took place, allowing substantial reduction in machining. Even though the procedure is quite complicated by additional of various steps, but the overall savings in time and cost are more than offset by the use of castings.

Figure 2: *Several structure and size of PDC bits that available.*

Nowadays, conventional manufacturing process of PDC drill bit are majorly enhance by the advancement of the technologies. As written by (Meister, 2001) the current practice of the PDC drill bit manufacturing can be classified into general steps. The bit bodies of metal particulate-based drill bits are fabricated in graphite moulds. The cavities of graphite moulds are typically machined with a five- or seven-axis machine tool. Fine features are then added to the cavity of a graphite mould by hand-held machines tools. Additional clay work may also be required to obtain the desired configuration of some features of the bit body. This type of method has actually benefitted a lot of PDC drill bit body manufacturers in getting the good accuracy in the final model.

However, the fabrication of such graphite moulds is typically very time consuming and expensive. Moreover, the use of graphite moulds is somewhat undesirable from an environmental and health standpoint, as the machining of such moulds typically generates large amounts of graphite and carbon dust.

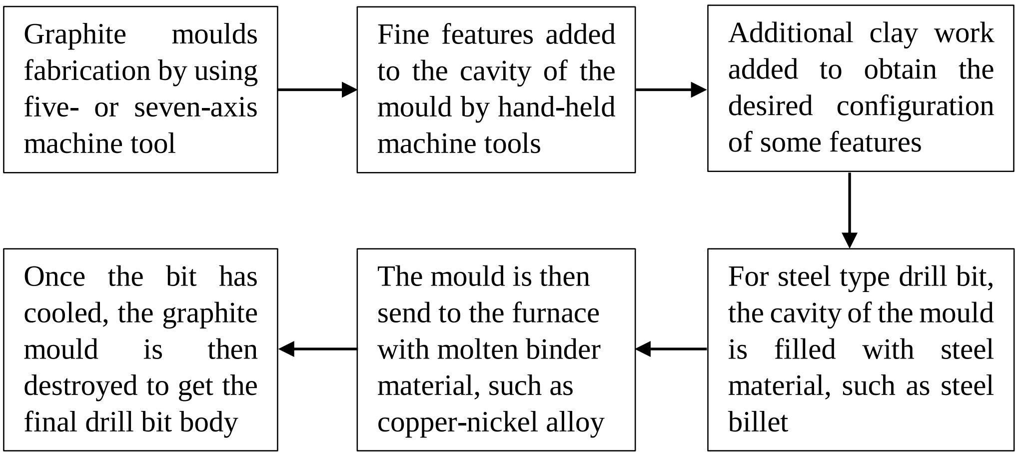


Figure 3*: Conventional Manufacturing Process of PDC Drill Bit Body*

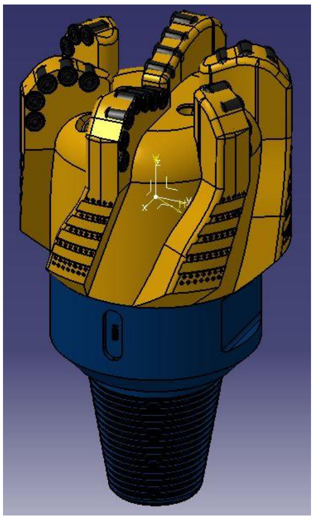
Therefore, further analysis on manufacturing processes has been conducted and the result found that latest technology of rapid prototyping which based on layer-by-layer manufacturing (additive manners) are not being used by the PDC drill bit body manufacturers. The author believe that with the application of this type of manufacturing process (using rapid prototyping), it could lead to the solution of the problem stated above. Therefore, throughout this project, the author will be working on application of the rapid prototyping manufacturing process in the development of steel type PDC drill bit body and emphasis on the solution that it bought for the said problems.

2.2 PDC Drill Bit Body Design

In this project, the author will use an improved design of PDC drill bit body which is the continuous work from the previous final year UTP student, Muhammad Hariz Bin Mohd Noor. Deeper study was conducted and about 9 drill bits has been designed focusing on changing few parameters which are bit profile, gauge design, back rack angle, and shape of the cutter. These parameters are chosen due to their big impact in improving the rate of penetration especially when undergo multi-layer formation. Other parameters are kept constant. All of the 9 designed drill bits and a conventional drill bit model are then run for ANSYS drilling simulation followed by a comparative study to select the best design with high rate of penetration for multi-layer formation. The simulation result shows that design 6 come out with the better average ROP which is 32.30 m/hr compare to the conventional model, 20.4 m/hr which is about 58.33 % better. Below is the features of design 6 drill bit:

***Table 1**: Input Features for Design 6 Model*

Parameter	Level 1	Level 2	Level 3
Bit Profile	Double-Cone	Parabolic	Concave
Shape of the Cutter	Beveled	Conical	Multidimensional
Back Rake Angle	0 degree	5 degree	20 degree
Gauge Design	Straight	Spiral	Spiral Track



Length: 25.0 cm

Width: 14.8 cm

No of Nozzle: 6

No of Blade: 6

No of Cutter's hole: 32

***Figure 4**: PDC Drill Bit Body Design Profile*

However, a simulation result alone does not enough to prove and quantify the effectiveness of the new designated drill bit as the real drilling operation may act differently. Therefore, an industrial approach is needed to convert the drill bit model into functional prototype, so that a more realistic testing can be prepared to achieve more realistic result. The proposed manufacturing process is the application of rapid prototyping to aid in the fabrication of the new designated PDC drill bit body.

2.3 Rapid Prototyping Technology

Rapid Prototyping Technology is a group of manufacturing processes that enable the direct physical realization of 3D computer models (Weineke-Toutaoui, 2003). This fast developing technology is able to convert the 3D computer data provided into a physical model with high degree of accuracy, allowing the user to save more on the cost and time-consuming machinery work. RP Technology is unlikely the conventional manufacturing processes (subtractive manner: removing material from raw block until the final shape of part is achieved), which the principles of work is builds up parts layer by layer or additive manner. There are various technologies in RP that can be divided by 3 categories; liquid, discrete particles, and solid sheets. Below is the classification of rapid prototyping methods according to (Phan & Gault, 1997).

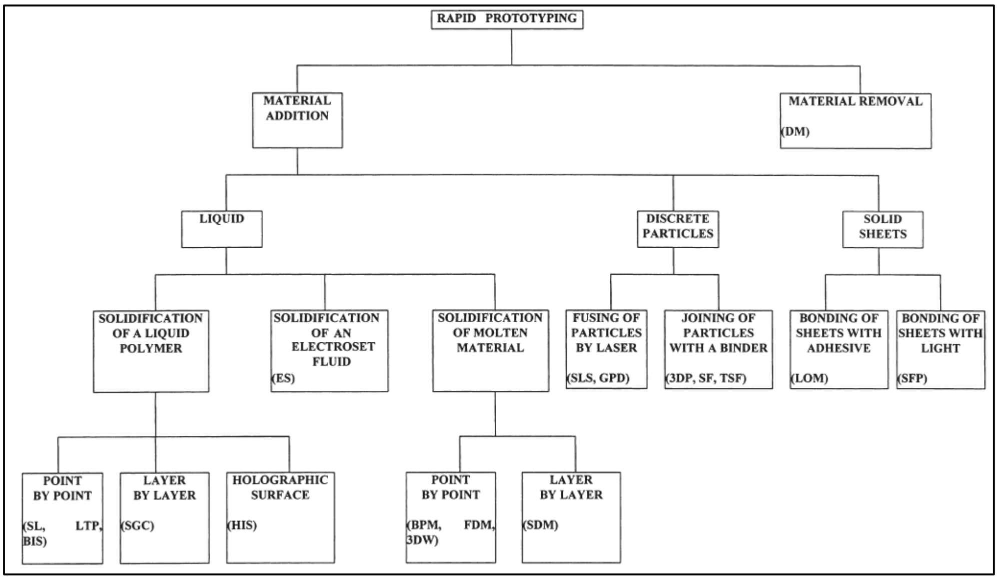


Figure 5: *Classification of rapid prototyping methods (Phan & Gault, 1997)*

In this project, the author will be working specifically with the rapid prototyping technology of Thermojet 3D printer which fall under the category of liquid, solidification of molten metal, and layer by layer section. Thermojet 3D printer is part of RP material jetting machine which produced wax products that can be used as sacrificial pattern in the investment casting (proposed manufacturing process).

Even though, there are a lot of RP technologies available, the general procedures are almost similar for all of them (Fig. 5) which are designing, converting to STL files, pre-process, RP fabrication, and post process.

Figure 6: *Typical RP process chain (Cheah et al., 2005)*

2.3.1 Material Jetting (Thermojet 3D Printer)

Thermojet 3D Printer can be classified as one of the many type of material jetting technology. The difference 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, 2014). In the research conducted by (Dickens et al., 1995), 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 analysing 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 (Phan & Gault,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 needed in order to clear out from the product.

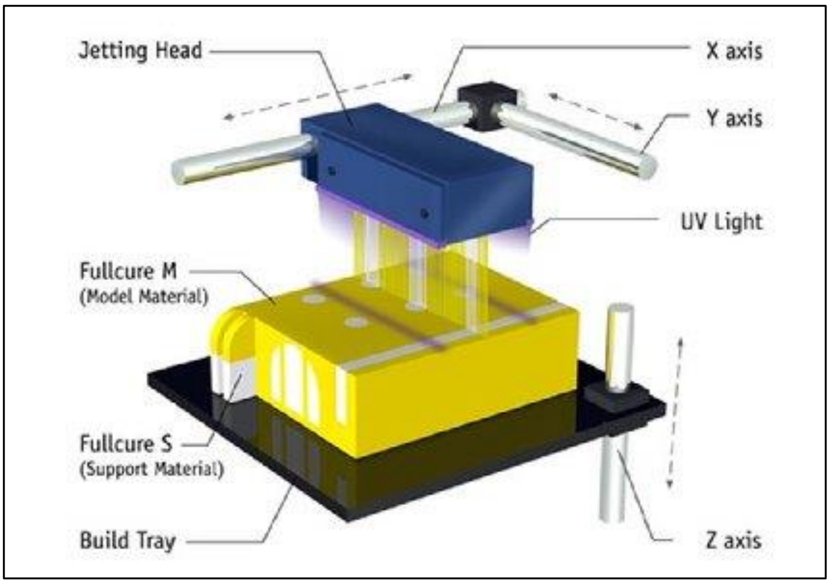


Figure 7*: Illustration of the Inner Part of Thermojet 3D Printer*

2.3.2 Thermojet 3D Printer Specifications

Table 2: *Thermojet Operational Specifications (Centric Associate, 2013)*

	X (Left/Right)	**Y (In/Out)**	**Z (Up/Down)**
Max Print Size	250	190	200
Resolution (DPI)	400	300	600
Resolution (mm)	0.064	0.085	0.042
Resolution (um)	64	85	42

The material used in the Thermojet printer is 3D Systems TJ88. This material is ideal to produce the wax patterns for investment casting as it leaves only 0.01% of ash following being burnt of the investment casting shell.

Table 3: *Material Properties Relating to Investment Casting*
(Centric Associate, 2013)

Properties	**Value**
Melt Temperature	Approx 85-95 °C
Softening Temperature	Approx 70°C
Density (g/cm^3) @140°C	0.846
Density (g/cm^3) @130°C	0.848
Density (g/cm^3) @ 23 °C	0.975
Volume shrinkage from 140°C to room temperature	12.9%
Linear shrinkage from 140°C to room temperature	N.A.
Ash content TJ88 Gray	0.00-0.01%

2.4 Investment Casting

According to (Cheah et al., 2005), investment casting (IC) or “lost-wax” casting, is a precision casting process whereby wax patterns are converted into solid parts following a multi-step processes. IC enables economically-production of dimensionally accurate components and is proven to be better in every aspect such as cost and time, as the process itself minimized the waste material and can be done in a short period of time. Besides, IC allows the production of intricate geometries and features from variety type of metals with a high precision and accuracy.

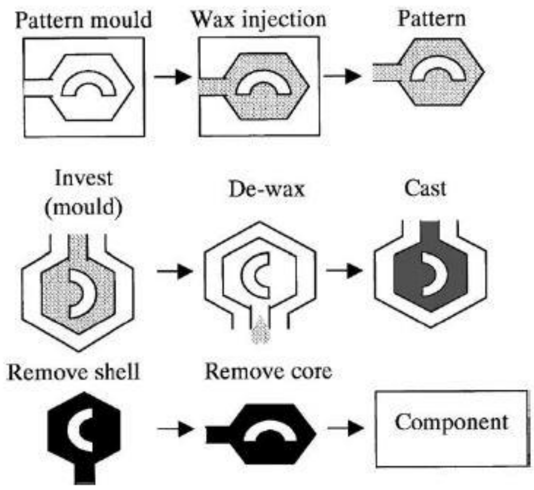


Figure 8: *General processes of the investment casting. (Jones & Yuan, 2003)*

Traditional IC comprises of block mould and shell mould which is a fundamental part of the whole process. The procedure chain for the ceramic shell process involves of the tooling, shell fabrication and casting stages (Cheah et al., 2005). Initially, a series of machining process is needed to design the mould for wax pattern from aluminium stocks. Once completed, it will be coated with release agent, assemble and injected with molten wax. The mould is then stripped to extract the patterns upon cooling. As it reached the shell fabrication stage, the patterns are attached to the wax sprue system to form cluster which is then used to repeatedly dip coated in silica or ceramic slurry followed by stucco application until it reached expected shell thickness and strength. As it dried, de-waxing process took place to reveal the inner cavities of the ceramic shell. For casting phase, molten metal is poured in the heated shells to form the castings. Once it hardened, the knockout process will took place to extract the complete model by cracking the shell. The castings are then cleanse and undergo finishing processes.

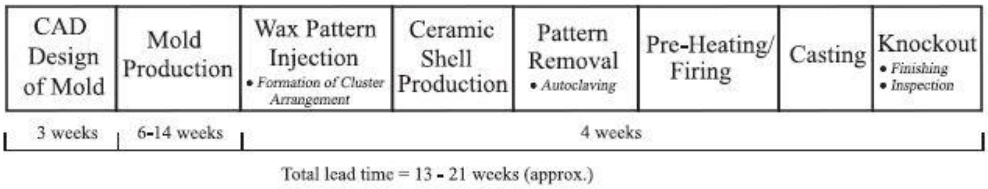


Figure 9: *Time allocation for investment casting process.*

(Cheah et. al, 2005)

However, even though IC has brought up the big advantage in numerous industries, the expensive costs and long lead-time (Fig. 9) in the mould production process condemned IC uneconomical for low-volume production. As the technology develop, some of the new inventions are identified to contribute in the improvements of the traditional IC steps especially in the mould production section. They are rapid prototyping technology (RP).

2.5 Application of Rapid Prototyping in Investment Casting for PDC Drill Bit Body Fabrication

Investment casting and rapid prototyping share the good potential for ideal marriage that their techniques fitted for complex parts especially in the mould and wax pattern production. Case history shows that, the first application of RP parts as sacrificial masters for IC was started back in 1989 with the use of block moulds (Greenbaum et al., 1993). The process was quite intricate as the study conducted is using the non-wax RP for IC where it is necessary to remove the wax runner system in order to embark on the next step. This problem is actually can be solved by steaming it in autoclave but the expansion of RP parts leads to the cracking of shell. There has therefore been a large amount of work undertaken by certain foundries to overcome these problems.

The research and development of combination between RP and IC has widely enhance day by day and today according to [1] almost all commercialised RP process (systems), selective later sintering (SLS), stereolithography (SL), fused deposition modelling (FDM), ink-jet plotting (MM II), 3D printing (3D-P), solid ground curing (SGC), multi-jet modelling (Actual) and laminated object manufacturing (LOM), can be employ to produced IC patterns. Some of the study are made using the new generation of RP technology with a better result compare to the conventional manufacturing process of PDC drill bit body. Table 5 presents an updated list of RP techniques, the building materials utilised and the final part characteristics.

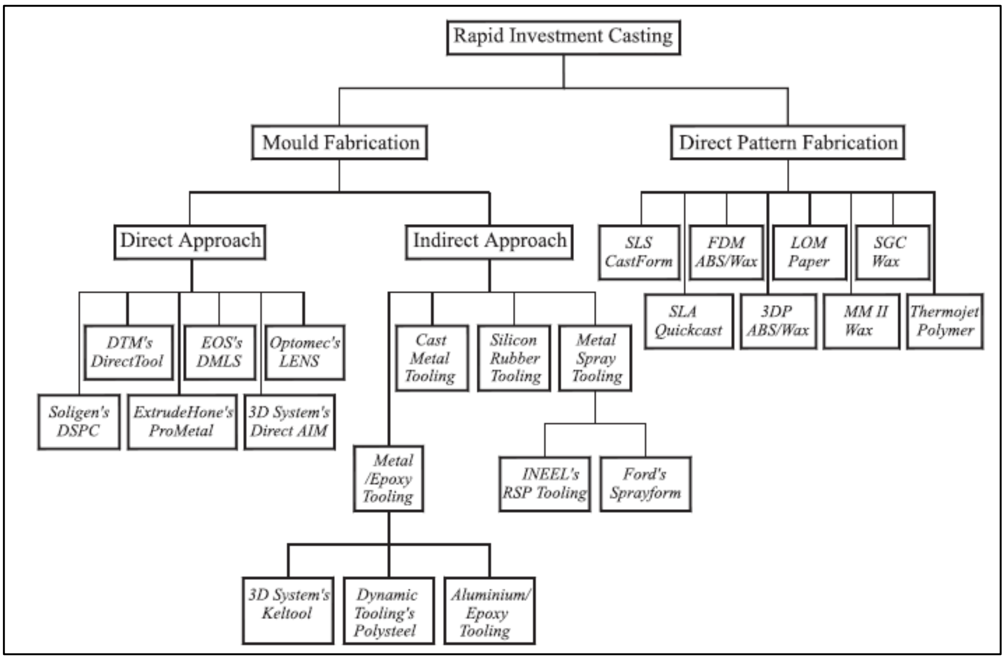


Figure 10: *Rapid Prototyping Techniques for Rapid Investment Casting (Cheah et al., 2005)*

Table 4: *List of Rapid Prototyping Techniques (Cheah et al., 2005)*

RP technique	Process	Build materials	Layer thickness (mm)	Surface roughness (μm) Ra (as processed)	Part accuracy (mm)	Residual ash (%)
SL	Photocuring	Epoxy	0.1	12.5	±0.05	N.A.
SLS	Sintering of powders	Polystyrene Polycarbonate	0.075	13	±0.25	< 0.02 N.A.
FDM	Melt extrusion	ABS Wax	0.05	12.5	±0.127	0.05 ≈ 0
LOM	Paper lamination	Paper	0.05	25	±0.25	N.A.
SGC	Photocuring	Epoxy	0.06	25	0.1%	N.A.
3DP	Ink-jet printing	Starch	0.1	N.A.	±0.020	1-2%
MM II	Ink-jet printing	Wax	0.013	N.A.	0.03%	≈ 0
Thermojet	Ink-Jet printing	Organic polymer	0.04	5.090	N.A.	N.A.

Another study conducted by (Meister, 2001) which using selective laser sintering (SLS) technology shows how the application of RP in IC of PDC drill bit body can provide a better solution to problem faced by conventional PDC drill bit manufacturing process. The method of fabricating a resilient model of the designated PDC drill bit body are based on layered manufacturing techniques. The resilient model may then be employed to cast one or more moulds from refractory material. The innovation help to reduce quite number of waste materials and can be completed in less period of time.

In this project, the author will continue the development by using Thermojet 3D Printer to develop the wax pattern of the designated PDC drill bit. This method reduced the number of process where, the mould fabrication is removed from the traditional IC process. The pattern will be then used to develop the final product made of carbon steel by using the following investment casting processes. According to (Cheah et al., 2005), the application of RP in IC has greatly shorten the time to get the final products from 13-21 weeks to as short as 4-5.5 weeks.

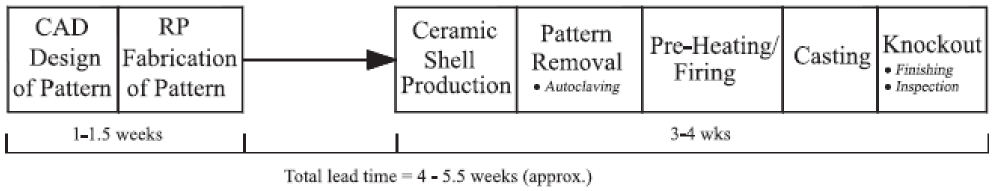


Figure 11*: Direct Rapid Prototyping Approach [1]*

2.6 Advantages of the application of Rapid Prototyping in Investment Casting

Besides reducing number of waste materials, lesser time consume for production, (Dickens et al., 1995) also lists several advantages in the application of RP in IC which are essential and covered every aspect that IC alone is lacking of. The main areas covered from using such technologies have been identified as listed below.

- The most obvious benefits are the savings resulting from the elimination of mould prototype (or low volume production) tooling. Conventionally, once a job is received, mould tooling is designed and produced in order for the prototype waxes to be injected. Depending on the complexity, these mould can cost between 1,000 and 50,000 Euro, and take from two to 16 weeks to procedure.
- As products are developed towards production, it is likely, if not certain, that there are changes to the design. Conventionally, each iteration requires more effort (and more costs) to modify tooling. By using rapid prototyping patterns for the development quantities,

there is no need to commit to tooling until the design has really been frozen. This is really important especially in the R&D process.

- Part of the investment caster's expertise is in the design and development of the gating and runner systems. Even skilled casters sometimes have problems because of poor gating – such as hot tearing, shrinkage or poor metallographic structure. By using rapid prototyping to produce trial patterns before the production tool has been ordered, the foundry can optimize these gating positions. They can then be incorporated into the production tool. Early patterns also allow the foundry to check on the "shellability" of the design – particularly features such as holes and slots.
- Early patterns also allow the foundry to evaluate different tree layouts – very important if the ultimate design is for high volume production and tree loading impacts the costs.
- By giving the toolmaker an accurate model of the wax which the tool is to produce, he/she can see more easily where he/she should split the tool, how many tool-parts are needed, where he/she may have wax feeding problems, wax- shrinkage etc.

From the literature reviewed, the author believes that with the rapid prototyping (Thermojet 3D printing) of wax pattern parts for PDC drill bit body, it will enhance the current conventional manufacturing process. In this research, the author will try to execute all the methodology planned and come out with a result which can be a new reference for other researchers working on this area to continue improving the PDC drill bit body manufacturing progression.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Project Flow Chart

Figure 12 below illustrate the flow chart diagram for this project

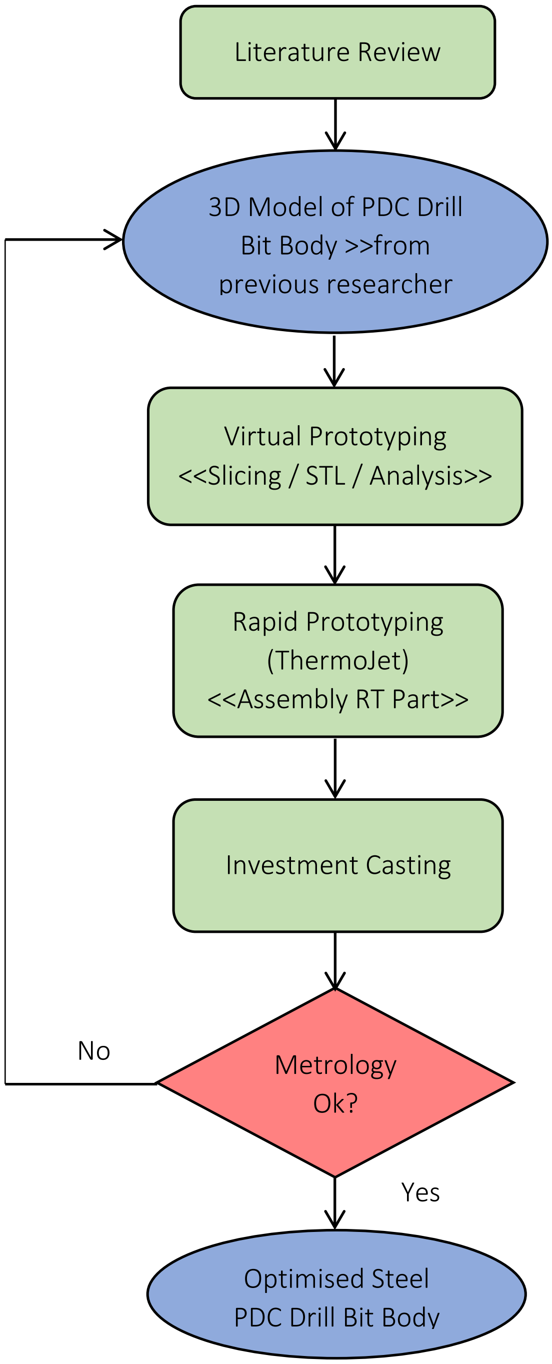


***Figure 12**: Project flow chart*

The project started with the preliminary research on existing studies on the topic from various articles. At this stage, the author takes some period of time to understand the rapid prototyping/tooling, manufacturing process and the mechanical aspect to be look in the research. The author undergoes several class of training on CATIA software for CAD drawing to apply virtual prototyping processes on the PDC drill bit body model. Cutting and building tools are recognized to redesign the model in order to achieve the target shape of sacrificial pattern part. The author had also learnt all the criteria that must be adhered in investment casting processes to have a final model of PDC drill bit body made of steel.

3.2 3D CAD Model of PDC Drill Bit Body

Previously, several improvements on the design features has been done on the conventional drill bits to improvise the rate of penetration especially when the drill bits facing formation interbedded with hard stringers. The drilling simulation between the new designated bit and the hard formation using ANSYS software has clearly shown an improvement in the ROP. The model itself has been fabricated with the aids of ZPrinter for physical visualization. However, the ceramic-based material used for the prototype is not suitable for the real drilling simulation test. Therefore in this project, the author will work with the Thermojet 3D printer to fabricate a sacrificial pattern of the designated drill bit before set for investment casting to get the functional prototype which is made in stainless steel. This project used 3D CAD model of PDC drill bit from previous UTP researcher, Muhammad Hariz Bin Mohd Noor and Thermojet 3D printer from Mechanical Department of Universiti Teknologi PETRONAS in order to generate the sacrificial wax pattern. Below is the figure of 3D CAD model of PDC drill bit and the fabricated prototype.

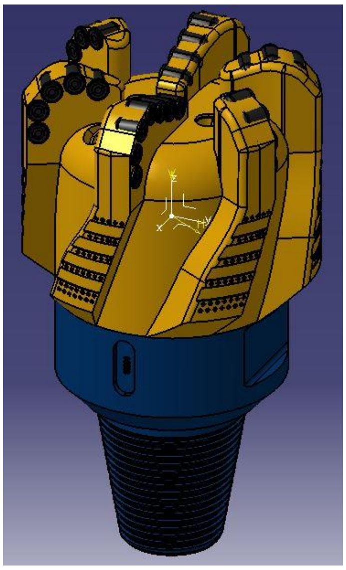


Figure 13: *3D CAD model of PDC drill bit*

Figure 14*: Ceramic-based Prototype of PDC drill bit*

3.3 Virtual Prototyping Analysis

A series of virtual prototyping analysis has been done on the 3D CAD model of PDC drill bit body before run for rapid tooling process. This including the criteria that must be adhered in 3D model design to achieved good RP progression in Thermojet 3D printer. Some of the criteria look is listed as below.

- Pattern accuracy achievability
- Pattern surface finish
- Contamination from pattern residues
- Stability and robustness to handling patterns
- Freedom from foundry defects, such as porosity and surface defects
- Compatibility with existing foundry practice
- Size of the patterns

Almost all of the criteria listed meet the expectation of the author except for specific size limitation of the Thermojet 3D printer.

3.3.1 Size of the Patterns

In this work, ThermoJet printer from 3D Systems, using the MJM technique is used to produce physical models of designated PDC drill bit model. This system uses a print head comprising 352 jets oriented in a linear array. The large number of jets allows fast and continuous material deposition at a resolution of 300 x 400 x 600 dpi (xyz), producing models with a maximum size of 250 x 190 x 200mm (xyz) and with a layer thickness of 0.042mm [12]. However according to the measurement of PDC drill bit body model in the CATIA software, it exceeds the maximum range of Thermojet system size which is 215 x 215 x 366 mm (xyz). Hence, few modifications (slicing, scaling, and printing techniques) need to be done in order to get the complete sacrificial pattern.

3.4 Support Structure

In the rapid prototyping technology, there have at least two materials are involved in the fabrication process, the production materials and the support materials. The final products are generally prefer a least mass of the support material by using honeycomb shape or points supporting product surface. The support materials were usually built between the surface of workbench and the surface of products, hollow volume, overhang structure, subsurface and flanges. Therefore, topological optimization is studied and be utilize during the rapid prototyping process with the aim to:

1. Minimize the support material, thus save cost of production
2. Ensure the support materials are able to be remove easily by chemical or physically

These can be achieved through rapid prototyping system (part slicing), and better positioning of the parts during the printing process.

3.5 3D CAD Model Slicing/Sectioning

The sectioning process is compulsory for this 3D model due to the complexity and oversize of the model. As represented from the model, the drill bit body consist of bit nozzle and hole through the model. Direct printing of this model will lead to the failure of getting the whole PDC drill bit's pattern due to the formation of support structure that will make the post finish job harder and some structure might not be able to be removed.

3.6 Part Design

As the model being sectioned for the printing process, the further step of the RP has to be consider in order to bring the sectioning part into combination after the printing processes is done. Modification on the combination design is based on the mechanical properties of the structure. Below is some of the design listed to be used:

- Thread
- Fitting

Further process such as the use of epoxy and brazing process are also consider after the main combination.

3.7 Conversion to STL model

Making the 3D prototypes with the RP machine involves the conversion of STL files of the parts in the machine's software. To produce the physical model of the part, the corresponding STL file is transformed by using CATIA software before set for ThermoJet printer client software, that enables to verify the STL file, auto-fix errors and determine the better position of the model on the working apparatus area, optimising both build space and time.

3.8 Investment Casting

The author established a network with Prima Precision Sdn. Bhd. industry to aid in the next process of the proposed manufacturing methodology which is investment casting. The sectioning wax pattern parts are given in two parts (upper and bottom section) to be casted into carbon steel with a grade type of 304. The material chose is based on its ability to withstand great amount of strength which is about 525 (Mpa) min and hardness up to 95 HRB. Besides that, it exhibits excellent resistance to a wide range of atmospheric, chemical, textile, and petroleum industry exposure. The methodology process of the combination between RP and IC started with the pattern fabrication from RP and followed by the sequence of IC process as explained in the literature review.

3.9 Tools and Equipment

Tools and equipment used in this project are CATIA V20 software, ThermoJet 3D printer and investment casting.

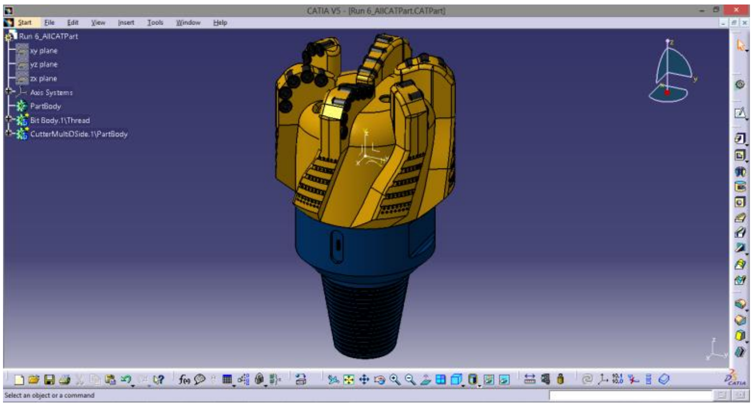


Figure 15: *CAD drawing in CATIA V20 software*

Figure 16: *Thermojet 3D Printer*

3.10 Gantt Chart and Key Milestone

Table 5: *Gantt chart for FYP 1 and FYP 2*

FYP 1

No	Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review														
2	Preliminary Research Work														
3	CATIA Training														
4	Virtual Prototyping														
5	Analysis of STL file														1

FYP 2

No	Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review														
2	RP of drill bit's patterns														
3	Patterns assembly					2									
2	Investment Casting										3				
3	Post process												4		

Process

Suggested Milestone

Table 6*: Key Milestone*

1	Key Milestone 1: Ready for rapid prototyping process of drill bit's patterns.
2	Key Milestone 2: Completed the sacrificial pattern for investment casting.
3	Key Milestone 3: Completed investment casting of the prototype.
4	Key Milestone 4: Fabrication of functional prototype completed

CHAPTER 4

RESULT AND DISCUSSION

The output parameter for this project is the final structure of steel PDC drill bit body prototype manufactured through the application of rapid prototyping in the investment casting. The manufacturing methodology used is actually quite different compare to the conventional process where most of the processes are working with principle of subtractive manners. Rapid prototyping on the other hand, is a layer-by-layer (additive) manufacturing process.

In this project, the master pattern of the PDC drill bit body is initially fabricated by using Thermojet 3D printer which help to save a lot of time. Proper analysis on sectioning method was conducted and the best method with less time consumption and ease of combination is preferred. After the combination process, the pattern is then set for investment casting and the final result is analysed. Below is the result of wax pattern and final steel prototype of the designated PDC drill bit body.

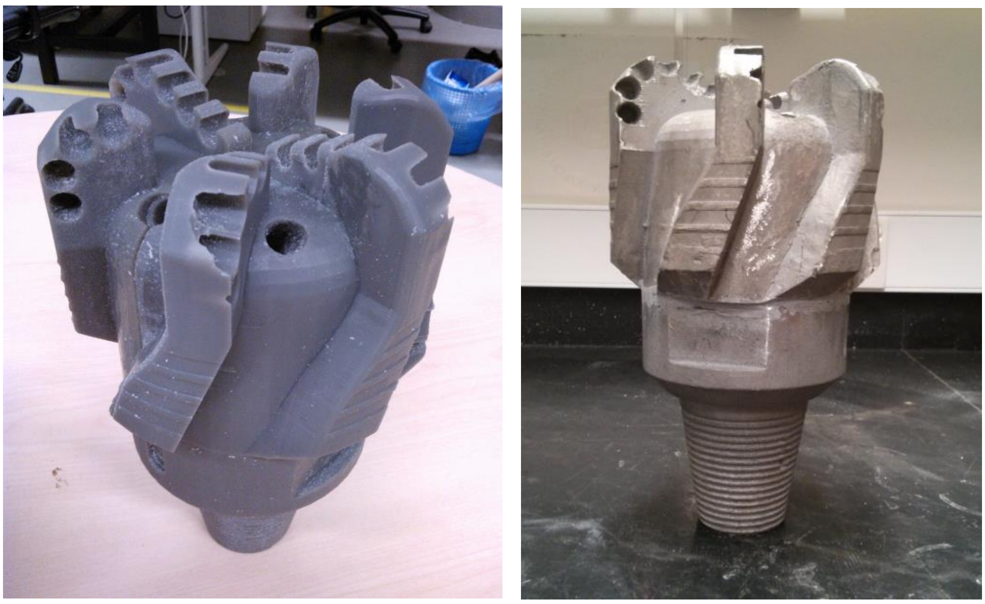


Figure 17: *Wax Pattern and Final Steel Prototype of PDC Drill Bit Body*

4.1 Discussion

4.1.1 3D Model Part Sectioning

Due to the complexity and oversize of the structure, the author had work on some sectioning of the model. The author use the Boolean operation (remove) function in the CATIA software to section the part into 2 methods of sectioning in order to fully utilize the size of the bit body.

Different orientation and angle of sectioning is fundamental to get the most flat surface structure from the whole model in order to minimize the volume of support structure formed during the RP process. Below is the 6 sections (Method 1) and 3 Sections (Method 2) formed from CATIA software.

Method 1: Separate the model with coordinate and divided into 6 parts.

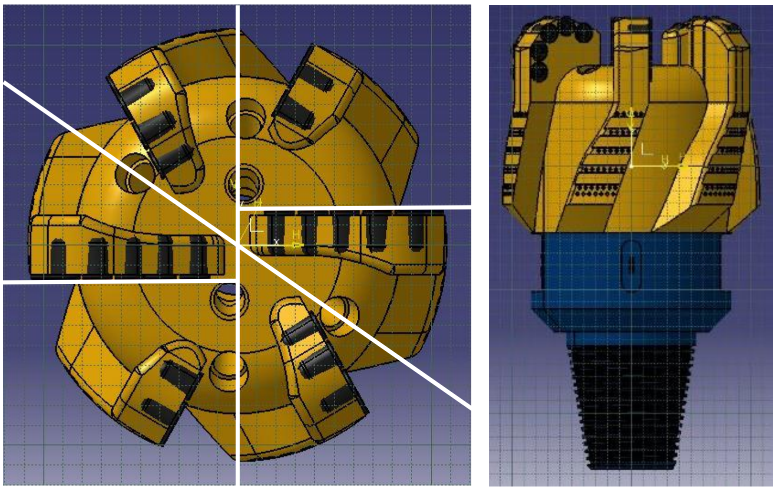


Figure 18: *Representation of sectioning part of 3D CAD PDC drill bit model in X-Y and Y-Z*

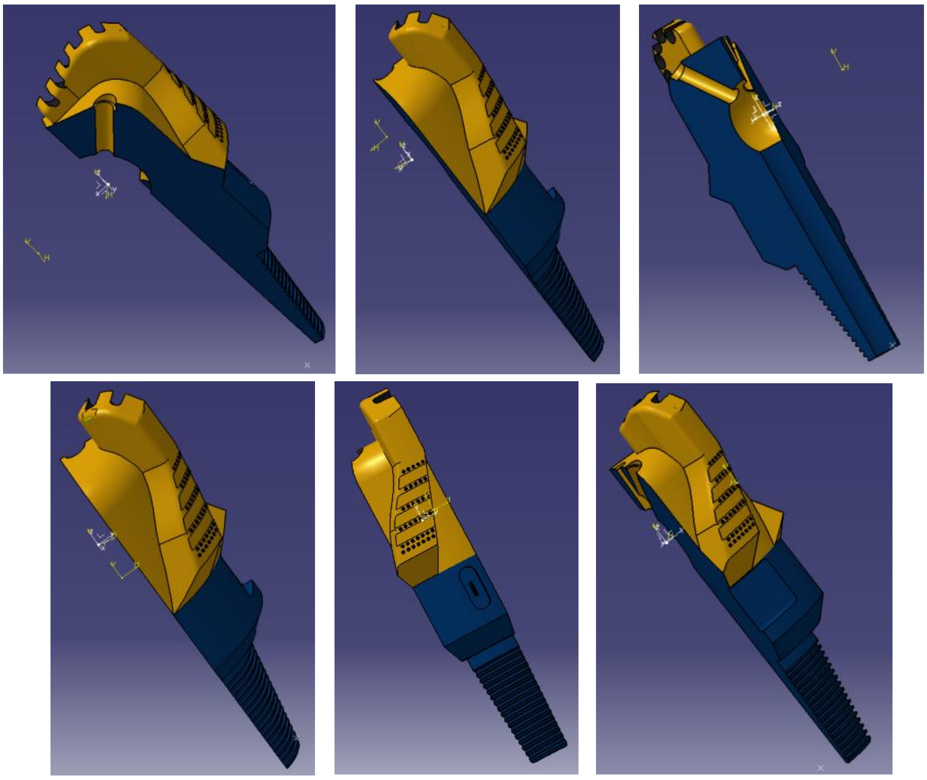


Figure 19*: 6 Parts of PDC Drill Bit Body*

Method 2: Separate the model at the middle and divided into 3 parts

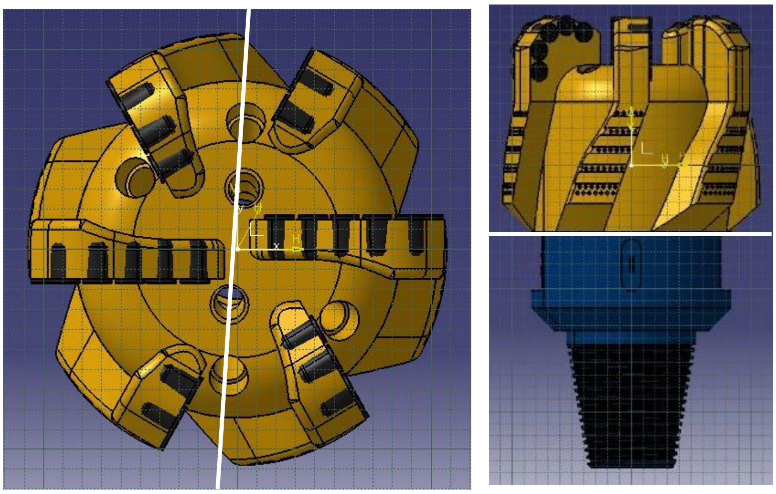


Figure 20: *Representation of sectioning part of 3D CAD PDC drill bit model in X-Y and Y-Z*

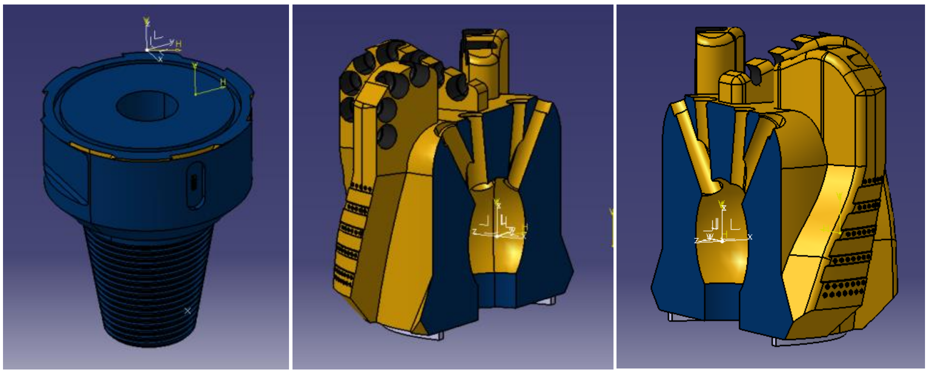


Figure 21: *3 Parts of PDC Drill Bit Body*

Thorough analysis has been done to select the best sectioning method for RP. The area concern are the waste materials, number of parts, cumulative period time for printing, parts combinations and also the needs of scaling. Based on the comparison tabulated below, method 2 is preferable as it contributes more advantages compare to the method 1.

Table 7: *Comparison Study between Method 1 and Method 2*

	Method 1	**Method 2**
Scale	Scale down to 70%	Do not need scaling
No of Parts	6	3
Cumulative Period of printing time	42 hours	21 hours
Parts Combination	Harder to combine due to larger no of parts and scale defects	Easy to combine due to less no of parts
Support Structure	Less	More

4.1.2 Modification on Part Model

The final discussion of the design modification conclude to use the fitting design for combination part. A circular groove for fitting with a thickness value of 5.5 mm and radius of 90 mm is made on the bottom part of the model. For the upper section part, a circular fitting with same value of thickness and radius is embodied to sectioning parts. The tolerance is assumed to be around 0.5 mm.

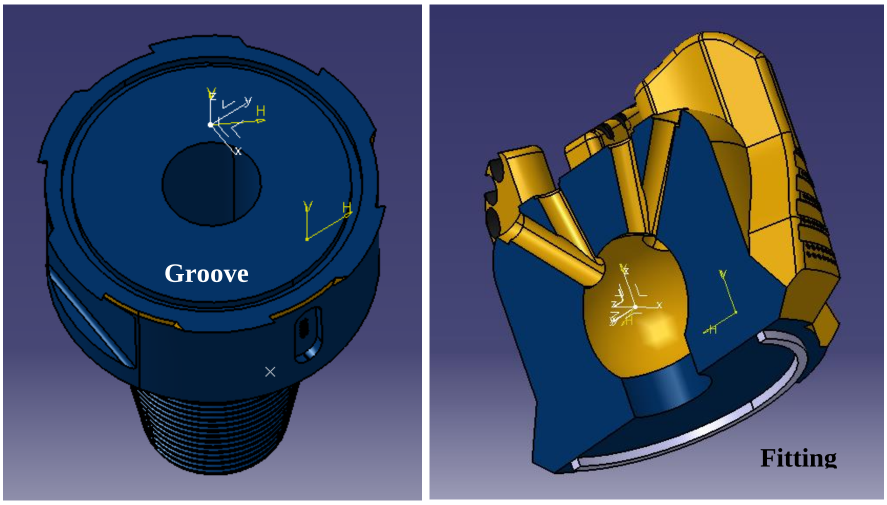


Figure 22: *Representation of Groove and Fitting of the Sectioning Parts*

4.2 Results for Application of Rapid Prototyping in Investment Casting of PDC Drill Bit Body

Observations from before and after the investment casting is analysed based on different criteria which are:

- Accuracy of the castings
- Surface finished of the castings
- Foundry defects , such as porosity and surface defects

4.2.1 Accuracy of the Castings

The steel prototype is measured on its x – y axis, diameter of the nozzle, PDC cutter hole and the liquid flow line and compare with the initial CAD model of the PDC drill bit body.

Table 8: Difference of Measurement between CAD Model and Casting Model

Parameters	CAD Model (mm)	Casting Model (mm)	Difference (mm)
Length (x-axis)	250.5	250.0	0.5
Width (y-axis)	148.0	147.0	1.0
Diameter of nozzle	20.0	19.8	0.2
Diameter of liquid flow line	50.0	50.0	0.0

From the comparison results, the accuracy tolerance of the castings from Thermojet sacrificial pattern vary within 0-1.0 mm. This project was not intended to be the final say concerning the accuracy of the systems available. It should be considered as another piece of information in assessing the processes.

4.2.2 Surface finished of the castings

The surface finished of the casting varied less than the wax pattern model. The surface followed exactly as the printed wax pattern especially on the regular surface of PDC drill bit body. However, the surface finished of complex part which is near to the holes and cavities (PDC cutter and nozzle nole), the surface finished is a little bit rough compare to regular/flat part. This can be assumed that the coating process had the difficulty to cover the complex part typically during the first and second layer of coating. Regardless of that, the problem can be solved by the post processing job which include sand blasting to softer the surface.

4.2.3 Foundry Defects

As observed from the final result of the prototype, two out of 32 PDC cutter hole faced a major defect where there is the formation of excessive steel material attached to the holes. Assumptions are made that there is a leakage/shell cracking occurred inside the holes probably during the stuccoing process or probably during sending through the furnace. These holes are considered as critical part and harder for investment casting due to the thin wall of the holes. The problem of this matter has been rise up and further discussion has been made with the expert in the investment casting of Prima Precision Sdn. Bhd.

Figure 23*: PDC Cutter Hole Defect*

Referring to the said problems, the suggested solution is filling the PDC cutter's hole of wax pattern model with a ceramic billet before send to the investment casting processes. This is because the ceramic material will be embodied to the ceramic slurry coating and make a good shell mould after the de-waxing process. This method has been practiced by quite some times to provide a good quality of holes, pores, and cavity inside the metal casting. Below is the illustration on how the ceramic billet positioned.

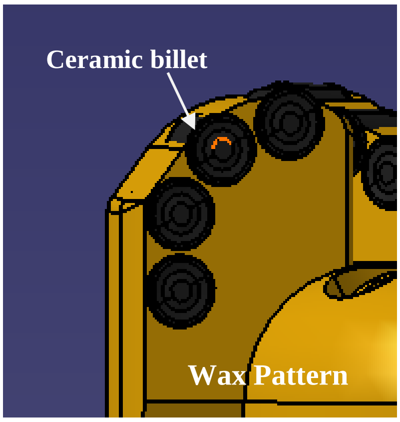


Figure 24*: Application of Ceramic Billet to Wax Pattern*

4.3 Significant Improvements

The ability of rapid prototyping (Thermojet 3D printer) in creating the wax pattern of PDC drill bit body in a short period of time and high degree of accuracy has contributed to the better and faster way of PDC drill bit manufacturing especially under research and development progress. Further improvement is the reducing time of production due to the elimination of long process mould fabrication production (estimated from 6-14 weeks). Besides that, the technologies used are lesser and better for small scale production especially for R&D project like this. The comparison between conventional method and the new method is tabulated as below.

Table 9: *Comparison between Conventional and New Method of PDC Drill Bit Body Manufacturing*

Conventional Method	Application of RP in IC
Requires expensive CNC machines for tooling purpose.	Requires Thermojet 3D Printer for tooling purpose. Cost is lower than CNC machine.
Long period of time consumption for production process especially for mould fabrication production (estimated from 6-14 weeks)	Less time consumption for production process. Rapid Prototyping (1 week) and Investment Casting (2-3 Week)
Large number of waste materials produced	Low number of waste materials produced
Larger cost	Cost-savvy

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Summary of Project

This project has provided a literature review associated with the development of PDC drill bit manufacturing. Some important conclusions are as follows:

1. Application of rapid prototyping and investment casting in the fabrication of PDC drill bit body is much faster, cheaper and effective compare to the conventional method.
2. The virtual prototyping analysis must be adhered in order to get the final structure PDC drill bit body.
3. Proper sectioning process for complex model is required to ensure the usability for investment casting. For closed part, it must be cut open in order to do the investment casting.
4. Holes and cavities of the wax pattern must be covered or filled with ceramic-based material or tungsten carbine to provide a good holes protection for investment casting.

5.2 Future Work

It is recommended that the next study on this topic, to focus on the combination of upper and bottom section of PDC drill bit body as the investment casting process required to be an open structure. More extensive method of accuracy testing like the use of Special Electron Microscope (SEM) may also be used to get a better and details result. Besides that, other type of RP technologies can also be considered to be used as another application of RP technologies in IC for better manufacturing process.

References

Azar, M., Beaton, T., Ford, R., Kembaiyan, K., Mensa-Wilmot, G., Oldham, T., & Rideout, W. (2002). Introduction to PDC Bits. Houston Smith International Inc.

Carvalho Ferreira, J., et al. (2006). "Integration of VP/RP/RT/RE/RM for rapid product and process development." Rapid Prototyping Journal 12(1): 18-25.

Centric Associate (2013). Rapid Thermojet Wax Patterns and Moulds for Investment Casting. Retrieved from http://www.centric-associates.co.uk/thermojet-wax-patterns.html

Chantrill, A., Private Communication from 3D Systems Inc. Ltd, 1995.

Cheah, C., et al. (2005). "Rapid prototyping and tooling techniques: a review of applications for rapid investment casting." The International Journal of Advanced Manufacturing Technology **25**(3-4): 308-320.

Chua, C.K., Leong, K.F. and Lim, C.S. (2003), Rapid Prototyping – Principles and Applications, 2nd ed., World Scientific Publishing Co. Pte. Ltd, Singapore.

Clayton, R., et al. (2005). New Bit Design Cutter Technology Extend PDC Applications to Hard Rock Drilling. SPE/IADC Drilling Conference, Society of Petroleum Engineers.

Dickens, P., et al. (1995). "Conversion of RP models to investment castings." Rapid Prototyping Journal **1**(4): 4-11.

Ferreira, J. C., et al. (2006). "Rapid tooling aided by reverse engineering to manufacture EDM electrodes." The International Journal of Advanced Manufacturing Technology 34(11-12): 1133-1143.

Greenbaum, P. et al., "Direct investment casting of rapid prototype parts", in Dickens, P. M. (Ed.), Proceedings of the 2nd European Conference on Rapid Prototyping and Manufacturing, University of Nottingham, Nottingham, 15-16 July 1993,pp.77-94

Jones, S. and C. Yuan (2003). "Advances in shell moulding for investment casting." Journal of Materials Processing Technology **135**(2): 258-265.

Kerr, C. J. (1988). "PDC drill bit design and field application evolution." Journal of petroleum technology **40**(03): 327-332.

Meister, M. (2001). U.S. Patent No. 6,200,514. Washington, DC: U.S. Patent and Trademark Office.

Park, R. (May 2014). The Free Beginner's Guide *3D Printing Basics.*

Pham, D. T., & Gault, R. S. (October, 1997). A comparison of rapid prototyping technologies. *International Journal of Machine Tools & Manufacture, 38*(1998), 1257 - 1287.

Smith, R. H. (1996). U.S. Patent No. 5,544,550. Washington, DC: U.S. Patent and Trademark Office.

Southland, S. G. (2002). U.S. Patent No. 6,353,771. Washington, DC: U.S. Patent and Trademark Office.

Symonds, D. H. (1999). Production process for casting steel-bodied bits, Google Patents.

Wieneke-Toutaoui, B. M. and H. W. Gerber (2003). "Rapid Prototyping Technology– New potentials for offshore and abyssal engineering." Proc. 13th ISOPE, Honolulu **1**: 27-32.