



APPLICATION OF ADDITIVE MANUFACTURING / 3D PRINTING TECHNOLOGIES AND INVESTMENT CASTING FOR PROTOTYPE DEVELOPMENT OF POLYCRYSTALLINE DIAMOND COMPACT (PDC) DRILL BIT BODY

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ABSTRACT

This study is about the application of Additive Manufacturing (AM) technologies for the manufacturing of an improved design of Polycrystalline Diamond Compact drill bit body by using Thermojet three dimensional printing and investment casting. The aim of study is to investigate a faster and effective PDC drill bit manufacturing process without compromising the mechanical aspects of the fabricated model. The conventional fabrication processes could be lengthy and cost intensive for the development of a complex product. With the rapidly developing technologies, the aspiration of manufacturing rate is keep rising and will be higher in future for sure. To overcome these issues, AM is one of the tool between the manufacturing rate and high precision product. In the current study, a computer aided design (CAD) of PDC bit body model that was modified from a previous design was taken and sectioned into parts to optimize the three dimensional printing process. Wax patterns were created using AM in separate sections for minimizing the support structure. Then the drill bit body was casted using investment casting process. The end result was a PDC drill bit body fabricated with steel material.

Keywords: PDC drill bit body, additive manufacturing, 3d printing, investment casting.

INTRODUCTION

Additive manufacturing technologies are also known as Rapid Prototyping (RP), or commonly referred to as “3D printing (3DP)”. The manufacturing technology is different with traditional manufacturing method due to the technique of additive process. It is a manufacturing technique of producing a product with a manner of layer by layer deposition of material without any subtraction of bulk material. For the earlier stage, it has been invented to improve the industry performances. Since the technology have 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 has covered many fields in our daily life such as prototyping, biotechnology, fashion, architecture and automotive.

Advantages

The development of the AM technology has been forwarded into next era with a wide range of materials used by the machines, higher accuracy and reducing the relative cost of production. AM is a fabrication method with high potential to improve 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 economical for mass production with complex configuration and able to minimize the material waste produced [1]. The advance of technology is impressing

some designers and artists too since it is able to build up their desired ideas precisely with high levels of complexity. Furthermore, final product can be done without a large number of skilled craftsmen and longer periods of time [2].

Availability of materials

In the early stages of technology development, 3D printing is mainly focus on polymeric materials. Within some period of development, the technology start to involve metals, ceramic and composites as its printing materials. Those materials can be printed with one kind or a combination. A combination material powders (composite) have an advantage compared to single material chosen [3]. For rapid tooling, metal material powders are formed as a compound of two or more for the operation especially in sand casting [4]. 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.

Support material

In the rapid prototyping technology, some processes have two materials in the fabrication method, the actual build material and the support material [5]. The final products are generally prefer a lesser mass of the support material by using honeycomb shape or points supporting product surface only. The support materials are usually built on the overhang structure, hollow volume (porosity), subsurface and flanges determined by the AM machine. The native format for the AM systems are called



STereoLithography (STL) files. Some processes like Selective Laser Sintering (SLS) and powder based 3D printing does not need supports as the powder itself supports the overhanging structures of the part. A typical support structure with the build part is shown in Figure-1 with red color indicating the support structure.

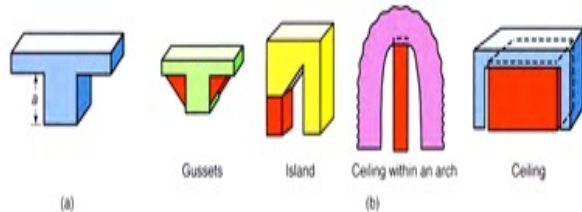


Figure-1. (a) A part with a protruding section which requires support material. (b) Common support structures used in rapid-prototyping machines. [6]

Material jetting (Thermojet printer)

Materials used in this 3D printing process are in their molten state or liquid form and ejected out from a different nozzles located on a print head. This process has multiple nozzle from which the molten material flows. After analyzing the format data, the nozzles will start to operate according to the build format. The material jetting out from the nozzles will form the model and the support material for the overhanging geometries and empty space inside the part. The nozzles will resume when the first layer is partially solidified. Thus, the process of the material jetting is also known as solidification of molten material [7].

Even though, there are a lots of RP technologies available these days, the general procedures are almost similar for all of them (Figure-2) which are designing, converting to STL files, pre-process, RP fabrication, and post process.

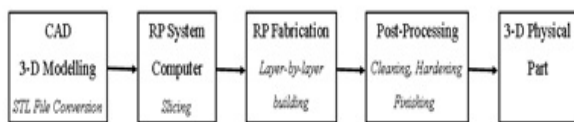


Figure-2. Typical RP process chain [8]

Traditional manufacturing of PDC drill bit body

Polycrystalline Diamond Compact (PDC) Drill bit acts as one of the major role in the oil and gas discovery. It was named after PDC due to first development of drill bit that used synthetic diamonds as cutting elements back in 1973 [9]. 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 [9].

Conventional manufacturing method of PDC drill bit body currently 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 mold 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.

The basic sequence to produce a steel bit pattern is machining multiple bulk metal into a desired form by using computer numerical control (CNC) machine. The pattern can be two or multiple pieces of moulds 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 pouring of molten steel. Break the shell mould from casting at the end of the cooling period, and proceed to substantial reduction in machining for the final bit formed. 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 [10].

The main objective for the current study is to fabricate a PDC drill body using Additive Manufacturing technology with the support of investment casting technique.

METHODOLOGY

CAD model modification

The 3D CAD model of PDC drill bit body was developed using solid modelling software shown in Figure-3(a). However, some of the modifications have to be done before proceeding to printing since its wall thickness needs to be reduced. The empty space inside was



increased and changed in shape accordingly to actual drill bit flow line in Figure-3(b). A groove joint was inserted on the top side and bottom side model to ease merge after investment casting.

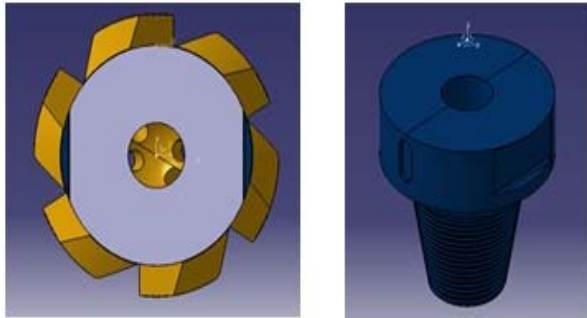


Figure-3(a). Original CAD models of PDC drill bit body, top and bottom sections.

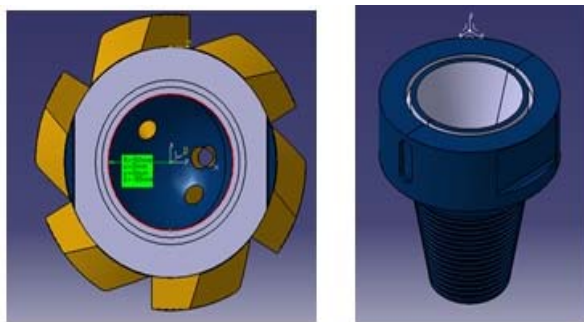


Figure-3(b). Modified CAD models of PDC drill bit body

It is necessary to section or slice open the CAD model for the top section to expose all the hollow section and inner surface of the PDC drill bit body to minimize the support material. Moreover, the original oversized model was difficult to 3D print as a single unit due to the machine printing limits. After some considerations, the model has divided into three parts and saved in different STL file format. Then, they were 3D printed out as Figure-4 below.

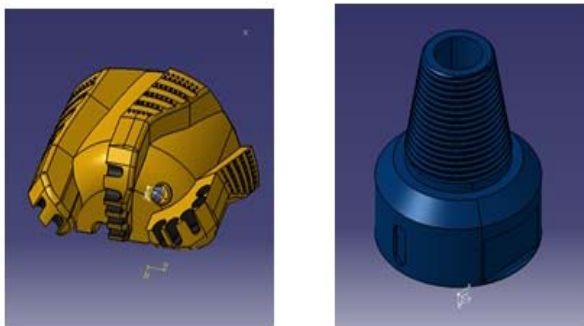


Figure-4. Division of model and 3D printing orientation

Post-processing

Post processing in the Thermojet 3D printing process is referred as the removing of the support structure. The PDC drill bit body wax pattern was divided into three parts and 3D printed individually. The process of removing support material was started from outer surface then inner surface by using hand tools. Those surfaces have to be cleaned out before undergo casting to ensure the closer dimension tolerances. Figure-5 shows the completed part with support structure and Figure-6 shows the part being separated from the build plate and removing the support structure in the post processing stage.

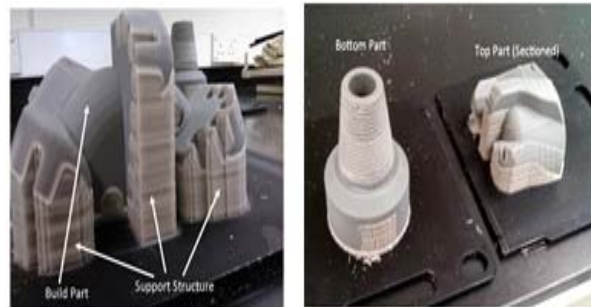


Figure-5. Part with support structure

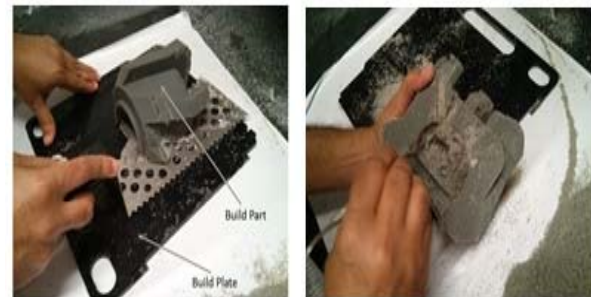


Figure-6. Part separation from build plate and support material removal in post processing

Investment casting

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 [8].

Investment casting (IC) converts a wax pattern into a solid metal part following a multi-step processes. Normally, a sacrificial wax pattern was made by wax injection moulding process. In the current study, the PDC drill bit body wax patterns were created with the Thermojet 3D printer. Available materials for casting have two main group, which are stainless steel and carbon steel. The material selected for the casting was Stainless Steel



304 as suggested by the foundry. The properties of different steel alloys are given in Table-1.

Table-1. Standard specification of steel alloys [11].

	Alloy	Strength (MPa)		Elongation (%)	Reduction Area (%)	Brinell Hardness
		Yield	Tensile			
Carbon Steel	42CRM O4	-	784	12	-	229 max
	S0C	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
	SNCM6 30	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 properties of TJ2000 are shown in Table-2 below.

Table-2. Thermojet material properties.

Properties	Temperature	Thermojet (TJ2000)
Melt temperature		70 – 75 °C
Softening temperature		55 °C
Density(g/cm ³)	at 140 °C	0.865
Density(g/cm ³)	at 110 °C	0.883
Density(g/cm ³)	at 23 °C	0.982
Volumetric shrinkage from 140°C to room temperature		11.7%
Linear shrinkage from 140°C to room temperature		2.3%

RESULT AND DISCUSSION

For the investment casting process, TJ2000 material was chosen due to its properties such as melt temperature, softening temperature, volume of shrinkage and ash content produced. It is a good material for investment casting since it only leaves 0.01% of ash following being burnt in 500°C during de-waxing process. The sacrificial wax pattern for PDC bit body in separate sections and in assembled form are shown in Figure-7(a) and (b).



Figure-7(a). Wax patterns for the top and bottom sections.



Figure-7(b). Assembled pattern.

The analysis of sacrificial wax pattern printed with Thermojet 3D printer and investment casted stainless steel prototype revealed some issues to discuss further for the next stages of study. The removal of support structure from the difficult to access features of the wax pattern was one of the issues. To overcome this particular issue, the pattern was sectioned into 3 parts to have access to the support structure for easy removal.

Results for the investment casted drill bit body

The end casted part was acceptable with some flaws such as porosity on top part and extra materials attached on cutter locations. Casting defect is one of the imperfections occurred during investment casting process. Other imperfection like porosity can be modified in order to make a better functional prototype in the next study. Porosity happened is because of small thickness for the different locations for the model. Thickness between outer surfaces and the drill bit cutter location is quite thin, which is not suitable for investment casting. For this case, the proposed minimum wall thickness of features should be 5mm. Within the thickness proposed, the sacrificial wax pattern is not easily broken off when removing the support material by mechanical hand tools. Besides, the ceramic drill bit cutters are 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. The final casted bit body is shown in Figure-8, before and after painting.



Figure 8. Investment casted PDC bit body

CONCLUSIONS AND RECOMENDATIONS

The current study has provided an analysis of Additive Manufacturing techniques and its application to manufacture a metal prototype of a PDC bit body. Some important conclusions and recommendations can be drawn as follows:

- Application of Additive Manufacturing and investment casting in the fabrication of PDC drill bit body could be a faster and effective technique. More study is required in this respect.
- Proper sectioning process for complex model is required to ensure the usability for investment casting. For a part with closed or difficult to reach features, its pattern should be sectioned in order for the part to be assessable for removing the support structure for a better pattern quality to be used in investment casting.
- Small holes and cavities of the wax pattern filled with ceramic-based material or tungsten carbide to provide a good stability of holes for investment casting. It is recommended that the next study on this topic should be focused on the combination of upper and bottom section of PDC drill bit body as a single part to be used in the investment casting process. Other types of AM technologies can also be considered to be used for fabrication like Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM).

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