COLLAPSIBILITY BEHAVIOUR OF ABS P400 AND PMMA USED AS SACRIFICIAL PATTERN IN DIRECT INVESTMENT CASTING PROCESS

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SPECIAL GRATITUDES TO:

MY BELOVED MOTHER,

Imilah @ Jamilah Binti Hasan @ Hassan

For her love, patience and support in my whole life

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ABSTRACT

The feasibility of the Investment Casting (IC) process has been choose to be vital route in producing the metal alloy products. However, less report regarding the feasibility of portable Additive Manufacturing (AM) machines to be employed in casting process. Sacrificial wax pattern in casting process has been substitute with the AM material due to its brittleness and higher cost for hard tooling. Due to this constrain, the quality of fabricated AM materials, collapsibility analysis and strain induce was investigated. The patterns were made using ABS P400 and PMMA materials by two different types of technique which are Fused Filament Fabrication (FFF) and Polyjet technique. There were three different types of internal structures which are hollow, square and hexagon patterns. The thermal properties of the materials were studied by thermogravimetry analyzer (TGA) and linear thermal expansion. The collapsibility screening was determined to investigate the behavior of the patterns underneath the expansion. Apparently, patterns made by Polyjet technique shows better accuracy compare to FFF technique. It shows that, the PMMA error lies between -2.2 % until -0.63 % compared to ABS which is -2.4 % until 1.2% for hollow, square and hexagon patterns respectively. The data of the surface roughness were varies whereas internal structures does not play significant role in improving the surface roughness. From the strain analysis, it can be suggested that hexagon internal structure yield less stress compare to square patterns. In terms of collapsibility, hollow and hexagon patterns yield most successful warping whereas it indicates the patterns able to collapse underneath the expansion. Moreover, PMMA material tends to gain higher strain compared to ABS material whereas this can be illustrated by the graph of linear expansion. Nevertheless, to overcome the cracking of ceramic shell due to higher thermal expansion, different build layer thickness was adopted to overcome the issue.

ABSTRAK

Kesesuaian proses tuangan deras (IC) dipilih sebagai satu kaedah untuk menghasilkan produk berasaskan logam. Tetapi, kurang laporan mengenai kesesuaian mesin serbaguna bahan pembuatan tambahan (AM) digunakan dalam proses tuangan deras. Acuan lilin telah ditukar ganti dengan AM kerana acuan lilin mempunyai sifat rapuh dan kos yang tinggi untuk acuannya. Disebakan oleh kekangan demikian, perkara yang telah dikaji adalah merangkumi kualiti bahan pembuatan tambahan (AM), analisis keruntuhan bahan dan juga daya terikan bahan. Corak bahan telah dibuat menggunakan bahan ABS P400 dan PMMA menggunakan dua teknik iaitu pembuatan filamen bersatu (FFF) dan juga teknik Polijet. Terdapat tiga jenis struktur dalaman iaitu berongga kosong, segi empat sama dan juga heksagon. Kajian haba bahan telah di kaji menggunakan Thermogravimetric Analysis (TGA) dan juga pengembahan haba selari. Keruntuhan bahan telah di kaji untuk mengetahui tindakbalas corak dibawah pengembahan bahan. Secara jitunya, corak yang diperbuat daripada bahan PMMA menampilkan ketepatan dimensi lebih baik berbanding teknik FFF. Seterusnya, ralat bahan PMMA terletak di antara -2.2% sehingga –0.63% manakala bahan ABS terletak di antara -2.4% sehingga 1.2% untuk berongga kosong, segi empat sama dan juga heksagon. Data untuk kekasaran permukaan pula adalah berbeza dimana bentuk struktur dalaman tidak memainkan peranan yang penting dalam meningkatkan kualiti permukaan bahan. Daripada analisis terikan, dilihat bahawa struktur bentuk heksagon menghasilkan daya tekanan yang kurang berbanding bentuk segi empat sama. Dalam aspek kerapuhan bahan pula, corak rongga kosong dan segi empat sama menghasilkan keledingan iaitu corak tersebut berjaya untuk menahan daya pengembahan. Tambahan pula, bahan PMMA mengalami daya terikan yang besar berbanding bahan ABS dimana ia dapat dilihat melalui graf pengembangan selari. Walaubagaimanapun, untuk mengatasi permasalahan keretakan seramik disebabkan faktor pengembangan haba yang tinggi, pelbagai lapisan ketebalan seramik telah digunakan.

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LIST OF SYMBOL AND ABBREVIATION

α	-	Type I error (α risk)
β	-	parameter
°C	-	Degree celcius
µm	-	Micrometer
K	-	kelvin
ΔL	-	Change length in speciment
ΔT	-	Temperature change during test
ΔX	-	Dimensional deviation
3DP		3D Printing
ABS		Acrylonitrile butadiene styrene
AM		Additive manufacturing
ASTM		American standard testing method
CAD		Computer aided design
CMM		Coordinate measuring machine
CTE		Coefficient thermal expansion
DIC		Direct investment casting
DA		Dimensional accuracies
FDM		Fused deposition modelling
FFF		Fused filament fabrication
IC		Investment casting
ISO		International standard organization
LM		Layer manufacturing
LT		Layer thickness
LOM		Laminated object manufacturing
MJM		Multijet modelling
MM		Model maker
PO		Part orientation

PMMA	Poly methyl methacrylate
Ra	Roughness accuracy
RP	Rapid prototyping
RM	Rapid manufacturing
RIC	Rapid investment casting
RT	Rapid tooling
Rv	Void ratio
SR	Surface roughness
SLA	Stereolithography
SLS	Selective laser sintering
STL	Stereolithography file
Tg	Glass transition temperature
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Research Background

Investment Casting (IC) is considered as a feasible method to substitute conventional manufacturing process regarding its advantages in producing near net shape of metal with economical of mass production. Conventional method of IC using traditional wax material as a sacrificial pattern has been preferred as the expendable material which can be reused after dewaxing process as well as reducing the materials cost. Despites its advantage in reducing the cost, there is a limitation in which producing the precision casting of metal whereas the wax material easily breaks and warps due to its brittleness properties. Thus, for requirement in precision thin wall casting which is need to be dipped into the slurry coating to develop deposition of ceramic shell molds, it is not recommended. In addition, using the wax as sacrificial pattern has encountered major problem such as slow processing development of new pattern mold in which results in expensive cost and longer total lead time process (Dickens *et al.*, 1995). Hence, it is not suitable for low volume casting production whereby longer lead time and high cost are the main concern factors. For instance, the high cost is determined by number of labours, price of refractory and binder materials as well as durable of mould fabrication. Elimination of hard tooling for wax pattern essentially needs justification in order to align with the low volume of production.

Therefore, Additive Manufacturing (AM) has inspired many manufacture industries in providing variations of perspective in IC process. This technology benefits the designer to produce a 3D part directly from the Computer-Aided Design (CAD) data more frequently without additional lead time. The fabricated prototype patterns are used for evaluation assessment with the valuable impact of perception especially for tool making or early optimization of concept designs. The ability of producing smooth surface, better dimensional accuracy and complexity shape have taken AM technologies one step ahead from wax pattern. Henceforward, IC industry has taken these advantages of using AM technologies to produce the sacrificial pattern either by direct or indirect approaches.

Concurrently, there are several types of AM techniques that offer robustness in terms of patterns fabricated in which to be employed in IC process. Major techniques of AM such as Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Multijet Modeling (MJM) and Three Dimensional Printing (3D-Printer) have been explored its achievability in producing sacrificial patterns (Marwah *et al.*, 2012). Generally, utilization of AM parts in interchange of the conventional wax pattern has beneficial in substantial lead time, effective cost, excellence quality and turn into essential tool for fabricating new product design. Subsequently, implication of AM has speed up the lead times of production from virtual to physical prototyping. Regarding its proficiency to produce pattern, AM has a few potential issues that many researchers encountered since years ago. The issues regarding the quality of the pattern are shrinkage and wrapping which need a full consideration. In this case, early optimization of parameters should be implant in order to enhance the quality of the fabricated AM part (Sabau, 2007).

Nowadays, the advancement of Additive Manufacturing (AM) technology has develop a world most precise, cost-effective and portable AM machine such as portable 3D Printing which has same capability as full large scale high end AM machines. These machines works effectively in producing a full scale 3D prototype by depending on the types of materials used, commonly ABS and PLA. Most of the available portable 3D printer in market are based on the concept of Fused Deposition Modeling (FDM) which simply known as Fused Filament Fabrication (FFF) in which a process by a machine deposits a filament of a certain material on top or next to the same material, in order to create a joint by heat or adhesion. Moreover, another 3D technology which is capable of producing physical pattern which has precision dimension as well as smooth and transparent surface is Polyjet 3D Printer system. This system works on concept of similar to inkjet printing, but instead of jetting drops of ink onto paper, PolyJet 3D Printers jet layers of curable liquid photopolymer onto a build tray. Nevertheless, there are fewer reports regarding the quality of end product produce by portable 3D machines and the feasibility to be used as sacrificial pattern in IC process. Hence, in this study, it is essential to determine the competency of printed pattern by portable 3D machines to be used as sacrificial pattern in IC process.

On the other hand, occurrence of cracking of shell mold is major problem for non-wax materials such as Acrylonitrile Butadine Styrene (ABS) from FDM. Consequently, the reconstruction of internal pattern structures have been effectively and aggressively studies to solve the issue regarding the cracking of ceramic shell moulds (Norouzi *et al.*, 2009). Stresses induced by pattern expansion during burnout process are major problems resulting in shell cracking. In addition, most of researcher focused on different internal structure patterns especially on Stereolithography (SLA) process. Thus, less reports regarding the materials used by portable 3D printer based. Besides, the Coefficient of Thermal Expansion (CTE) is one of the major issue need to be fully understand and study in order to reduce the effects of shell cracking (Wang *et al.,* 2010). Furthermore, the glass transition temperature (Tg) also is comprehensive in determining the cracking of the ceramic shell molds and it is significant than CTE of plastic materials (Wang & Shih, 2010).

1.2 Problem statement

Conventional IC using wax as sacrificial pattern is favored to be a solid method in producing high precision casting metal. Nevertheless, conventional IC patterns made from wax have properties that limit its application in precision casting especially for parts with thin geometries. The parts usually tend to break or deform when handling or dipping in the refractory slurry (Wang *et al.,* 2010). Furthermore, it is not economical when producing small quantity parts of casting by using the injection moulding wax as a sacrificial pattern (Chua *et al.,* 2005). It is believed that the downside of conventional wax process essentially required die making for processing the patterns in which contributed to the higher cost and longer lead time and makes the method unsustainable.

Many studies have been conducted to substitute the conventional method by implanting the AM technology in IC process. However, most of the studies have circulated on the feasibility of the high-end AM machine such as FDM, SLA, SLS and MJM using different materials to substitute wax pattern as sacrificial pattern in IC process. There is less reports regarding the possibility of portable AM machine to fabricate as sacrificial pattern for IC process. In addition, there is also less report regarding the study of comparison between ABS P400 and PMMA based materials pattern fabricated by portable FFF technique and Poly Jetting technique respectively. The issue such as staircase effect is the main reason that affected the quality of pattern made by AM technique. This issue indirectly affect the quality of casting parts such as dimensional accuracy and surface roughness and need to be addressed continuously (Cheah *et al.*, 2005). Moreover, there is less report regarding the quality of part produce by portable AM machine in terms of dimensional accuracy and surface roughness that associated with IC process.

For the non-wax pattern applicable in IC process, it revealed that ceramic shell cracks due to excessive thermal expansions, incomplete collapsibility of pattern during burnout, residual ash and poor surface finish. Most of AM materials used for sacrificial pattern in IC process have CTE values larger than ceramic materials in which induce significant amount of stress on ceramic shell. In IC process, shell cracking occurs when the rupture temperature of the ceramic shell is lower than the glass transition temperature of the pattern material and internal web-link buckling temperature (Yao & Leu, 1999). The cracked occurs when the stress induced in the ceramic shell is greater than the Modulus of Rupture (MOR) of the pattern material. Due to this phenomenon, there are reports regarding the internal built structures for SL process and the hollow internal structure has been employed to decrease the stress and improve pattern drainage. However, research on the different inner structures patterns for portable FFF technique and portable Polyjet technique were still lacking.

1.3 Objectives of the Study

The objectives of this study are as follows:

a) To study the dimensional accuracy and surface roughness of ABS P400 and PMMA patterns made by portable AM machines that used in direct IC process.
b) To investigate the three different internal structures which are hollow, square and hexagon patterns collapsibility in IC process.
c) To analyse the rate of shell cracking during burnout process.

1.4 Scope of the Study

The accomplishments of study based on several scopes such as:

a) The fabrication of three different internal structures such as hollow, square and hexagon patterns for ABS P400 material using portable FFF 3D printer (Odyssey X2) and PMMA material using Polyjet 3D printer desktop (Object 30 Pro).
b) The three different internal structures of fabricated AM parts were evaluated including dimensional accuracy and surface roughness.
c) By using TGA and DTA to determine the thermal properties.
d) Feasibility of strain gauge for detecting the strain induce on the patterns and the ceramic shell moulds.
e) Screening the patterns collapsibility behaviour during the burnout process using Protherm furnace ranging temperature in between 30 ℃ to 150 ℃.
f) The sacrificial patterns are based on the AM part shapes and size.

1.5 Significance of study

Enhancement of new application, invention and adaptation on an existing design tool will boost the improvement of quality production. Therefore, the study on the pattern development of AM application by implanting patterns as direct sacrificial pattern in IC is essential as it beneficial in elimination of hard tooling. Diversification of techniques in AM has been explored to minimize space thoroughly and able to generate diverse solutions in IC process. Intensification of AM technique currently pays attention to portable 3D Printer techniques which is currently economical. The fabrication of AM patterns in which requires high intricacy and low mass casting in IC is the key to significant reduction of total lead time and cost effective of manufacturing.

It is expected that the outcome of the study will be an abundant support to the IC manufacturer whereby 3D Printer technologies (portable FFF 3D printer and Polyjet 3D printer) are applied in production of pattern whereby it contributed to effective of metal casting parts. Therefore, direct IC routes by portable AM machines works efficiently whereby lower cost, fast fabrication of patterns as well as enhancement of quality products are the main criteria to be concerned.

1.6 Summary

This chapter presents the introduction of this study which is vital of implementing the AM method in the IC process. Besides, it also present the research background of this study whereas involved the conventional IC process, AM methods and relation of AM in IC process. Furthermore, it shortly discusses the vital problem about this study. In addition, the significant objectives and scopes of this study were mentioned in this chapter. In the end of this chapter, it discuss about the significant of this study towards community especially in demanding industries.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter particularizing few aspects such as potential of Investment Casting (IC) process, disadvantage of conventional IC process, Additive manufacturing (AM) process and the feasibility of pattern produce by AM process to be used as direct sacrificial pattern in IC process. At the end of this chapter, it be a summarization of different aspects regarding the related perspective views on this study.

Upon the modernization of the world of technology, AM has emerged the substantial contribution in manufacturing industry specifically in fabrication of prototypes pattern or significantly as end product. Due to the stresses in terms of high cost, longer lead time as well as larger quantity of materials usage, once again AM provides a significant solution regarding elimination of tooling and substitution of expandable wax pattern. This study concentrate on the feasibility of AM process in which produce a direct sacrificial pattern in IC process. Thus, a full review on viability of AM process and IC process discussed on this chapter.

2.2 Conventional Investment Casting

The advancement in the nature of the industry has driven the process to be named as lost wax process whereby the physical properties of wax itself can be shaped into anything. Since the early days of introduction of this technology, wax has been preferred as important material to be shaped according to desire end products.

The lost wax process is favored by the name of Investment Casting (IC) process whereas the process can produces high tolerance of casting, good dimensional stability as well as near net shape of end products for most metal which can be categorized as ferrous (commonly stainless steel, tool steel and carbon steel) to non-ferrous alloy (commonly aluminum, brass and copper) (Horton, 2008). IC is ideal for applications that have relatively low production quantities (10 to 10000 pieces) or rapidly changing the product designs. In addition, IC is the most familiar method of metal fabrication that has been used for several centuries.

Basically, IC process requires a sacrificial wax pattern in which have same geometrical shape, design and scale as the final metal cast part. In this casting technique, a pattern, usually made of wax, is utilized in forming the inside cavity of a refractory mould. The pattern is formed by injecting the molten wax into a permanent mould of the desired shape and there by cooling it until solidification. In the ceramic shell method, the pattern is gated to a wax sprue. Then the sprue pattern are invested with ceramic slurry which is then solidified forming a mould around the wax pattern. The wax pattern is then removed from the mould by melting or burning. The subsequent refractory shell is further hardened by heating and then filled with molten metal to produce the finished part (Bemblage & Karunakar, 2011).

The working efficiency of investment casting depends largely upon the quality of the disposable pattern since its surface and dimensional characteristics are transferred to the ceramic shell and also to the final casting. Wax is the most widely used pattern material but blends containing different types of waxes need to be modified in terms of their properties through the addition of some materials called additives and fillers (Bemblage & Karunakar, 2011). Nowadays, this technique rapidly used in producing high complexity geometry shape, high temperatures application as well as lightweight metals such as aircraft engine, turbine blade, medical instrument and so on (Vasconcelos *et al*., 2002). Figure 2.1 shows the flows of conventional IC process.

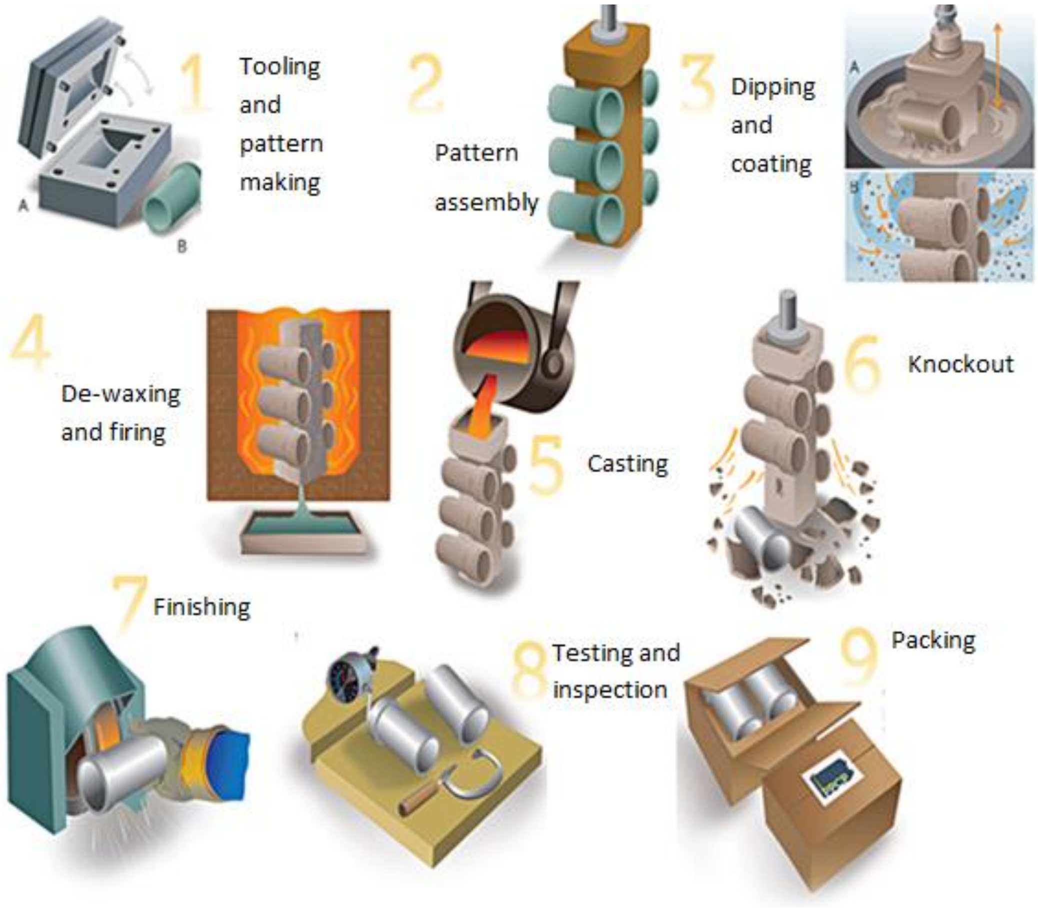

Figure 2.1: Overview of IC process (Tedds, 2013)

2.2.1 Constraints of Investment Casting Process

Despites its ability to produce an intricate design of metal part, IC suffer constrains in terms of cost and lead time. Conventional IC principally depending on the wax pattern for the fabrication of ceramic mold pattern, thus, there is necessity of tool for injecting the wax into desire shaped. In this case, the tooling for the injecting wax is the limitation of IC process due to the high cost of production and lead time as well as not effectively in changing the product designs. As mentioned by Ding (2004) there is about 70 % of total lead time when producing the initial tooling of new pattern depending on the complexity of the design shape. In addition, conventional IC process undergoes longer total lead time due to the fabrication of injection wax tooling approximately 13 - 21 weeks. However, the total lead time will increase if there is flawed on the pattern tools in terms of dimensional accuracy (Jacobs, 1995). Figure 2.2 shows the total lead time for IC process.

Conventional Investment Casting	CAD Design or mold	Mold fabrication	Wax pattern injection	Ceramic shell	Pattern removal	Pre-heating firing	Casting	Knockout ●Finishing
	3 weeks	6-14 weeks	4 weeks					

Total lead time = 13-21 weeks (approx.)

Figure 2.2: The total lead time of IC process

The application of IC with wax pattern has been favored by many manufactures as it provides good surface finish and near net shape of final metal products. Nevertheless, when making a hard tooling of wax pattern it involves with high cost fabrication as well as lead time process, thus, it is not efficient for a single or low volume production (Sivadasan & Singh, 2013). These perspectives are driven by two main factors such as requirement of hard tooling and longer lead time process for tooling itself. These factors affected the chain process of IC when a low volume of production is essential. In terms of fabricating the sacrificial patterns, the hard tooling for injection moulding process is needed to produce desired sacrificial wax pattern in which leading to cost justification. Besides, mould designer commonly face few problems when undertaking some adjustment on the hard tooling pattern such as precise dimension, alteration of designs and defects on design mould. Therefore, the total time for hard tooling significantly increase due to intricacy of designs as well as modification on the designs (Ferreira *et al*., 2006).

The needs of hard tooling in IC process must be eliminate without concerning the hard tooling cost and lead time process in order to fabricate low volume production effectively. Furthermore, low volume production suffers high tooling cost and expensive wax pattern moulding fabrication, thus it prefers for mass production (Cheah *et.al*., 2005). The inception of IC process without hard tooling has encouraged the application of AM technology to develop a low volume production whereby simultaneously applicable to the IC process. Furthermore, the substantial reduction in lead time and cost are associated with single or small quantity production. Consequently, it influences AM technology to be employed in IC process in terms of elimination of hard tooling.

2.3 Additive Manufacturing Technology

Additive manufacturing (AM) is a standardized term approved by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) (ASTM International, 2013). Early technique of Rapid Prototyping (RP) was developed in the 1980's for creating a prototypes parts in three dimensional view layer by layer using Computer-Aided Design (CAD) (Wong & Hernandez, 2012). The technology was created to ensure the designer have 3D visualization of their concept design. RP is one of the earlier Additive Manufacturing (AM) processes. Historically, AM technology was used to build conceptual prototypes referring to that process as RP, a term which is still often used as a synonym to AM. Those prototypes were meant to accelerate the development phase (time-to-market) of a product and under no circumstance are comparable to the end product regarding quality, material and durability (Thymianidis *et al.*, 2013). Scientific research was an important driver for AM technology development which boosted printer capabilities towards manufacturing functional prototypes leading inevitably to Rapid Manufacturing (RM). In addition, RM has evolved through AM due to technological advancements defined by Pal & Ravi (2007) as the manufacture of end-use products using AM techniques. As an impact of advancements in the field of AM in the past decade, this work distinguishes RM from AM due to the use of advanced printing techniques enabled by a range of sophisticated materials which facilitates manufacturing products with long term consistency for the entire product life (Levy *et al*., 2003).

In the beginning, prototypes provide benefits such as analysis the design concept, discovering the new design and accomplish performance to start the production (Das, 2004). Due to the shorter lead time of fabrication, AM benefits the designer to produce the virtual models of the CAD drawing into physical 3D model rapidly. In addition, the complexity and intricacy of early design concept can be built using this AM techniques.

Generally, most of the AM techniques work on the most basic concept which is the draft model design using CAD software. The model is slice from the 3D graphic model into 2D contours. This step follow by converting the CAD drawing file into the Stereolithography (STL) file whereas the STL file is common interface between CAD and AM system. Then the data must be altered to generate the commands to control the final stage of actual fabrication of the component. The final step is diverse between AM machines and depends on the basic deposition principle used in the AM machines (Sokovic & Kopac, 2006). Furthermore, it is essential to choose the appropriate building direction as it can change specifications of the object such as quality, cost and lead time.

AM techniques are standard tools in the product design and manufacturing industries (Harun *et al.*, 2009). Moreover, AM become most essential tool for designer and shortening the required time to design the end product. This technology was employed in industrial applications to speed up the design and manufacturing process. Besides, AM approach is diverse from traditional manufacturing techniques (subtractive process) whereby, AM provides creating and object by adding materials layer by layer while in traditional ways the materials was removed by process of milling, turning, drilling, grinding and so on (Wang *et al*., 2010). Therefore, in terms of materials usage, AM has advantage in reducing the amount of materials to construct an object. In addition, AM significantly shortened the fabrication time of product as well as have flexibility in fabrication of intricacy shape whereby it is difficult to achieve using conventional manufacturing process (Relvas *et al.*, 2012).

Additionally, it has encouraged a substantial development in AM based tooling, whereas the hard tooling is eradicate. The steps begin with developing core and cavity using AM based processes starting from the CAD models whereby the tooling development time significantly reduced by 50% - 90 %. It is clearly that AM contributes to the potential in decreasing the cost production. Thus, AM process advancement capable to fabricate with a simpler set up and shortening the process build time. Consequently, AM techniques can be employed by direct approach, in which molds are fabricated in AM system, or indirect approach, in which master pattern is converted into a mold using a secondary process (Subburaj & Ravi, 2008). Rapid Tooling (RT) is considered a sub-category of RM; it aims only to create consistent tools which serve traditional manufacturing procedures (Karunakaran *et al.*, 2000). RT has been mostly used to create injection mould but recent developments enable RT technology to be used for casting, forging and other tooling processes (Levy et al., 2003). According to Wholers Report (2013), 16% of AM processes were used for direct part production (RM), 21% for functional prototypes (RP) and 23% for tooling and metal casting patterns (RT) from which approximately 56% and 9% of process preferences were direct metal and direct polymer tooling respectively.

As the term suggest, AM has variety of names regarding its capability in producing the prototype such as Free Form Fabrication (FFF), Layer Manufacturing (LM), 3D Printing and Rapid Prototyping (RP). Currently, AM process has attracted many manufactures and researchers to collaborate regarding its potential towards future. Moreover, over last decades, advancement in the technology of AM with the consumption of laser technology has empowered variety of metals to be used in production of parts directly (Yang *et al.*, 2009).

2.3.1 Classification of Additive Manufacturing

As demand in manufacturing process increase significantly, AM is a novel approach to solve the challenges faced by industries in terms of reduction total lead time as well as fabrication cost. The most common, and the most popular currently, is 3D Printing. AM is claimed to have triggered a third industrial revolution because the technology presents new and expanding technical, cost-effective and social impacts. Particularly, the increased accessibility to 3D printing capabilities has allowed mass customization to become more widespread in industries such as healthcare and consumer markets.

In this rapid growing industry, terminology evolves rapidly whereas the bunch of groups such as the mainstream press, the investment community, and the CAD industry recognized the technology as“3D printing” when referring to AM technology and the industry it represents. So although AM may be the official industry standard term, 3D printing has become the de facto industry standard.

Today, 3D printing accounts for only 28 % of the total manufacturing sector, but the market seems destined to explode (Wohlers, 2013). While the consumer market is expected to be the main driver of the sector growth, there is also room for innovation in the enterprise market. Most analysts expect that more companies, from large organizations to small and medium-sized enterprises (SMEs), begins to explore the technology and unravel new business cases.

Since the advent of mass production in the early 20th century, consumer's demands have been met by producing large numbers of goods in significantly less time than ever before. While production time and price decreased, it reduces parallel to the expense of customization. AM makes it possible to offer customers options to personalize the products and goods they are purchasing. There are seven different additive manufacturing processes, as defined by ASTM International. Table 2.1 summarizes the seven process classifications and technologies that comprise the 3D printer market with selected market participants.

Table 2.1: Classification of AM process (ASTM, 2012)

Classification	Technology	Materials	Developers
Binder Jetting	-3D Printing -Ink-jetting	Metal, Polymer, Ceramic	ExOne Voxejet 3D Systems
Direct Energy Deposition	-Direct Metal Depostion Laser Deposition -Electron Beam Direct Melting	Metal: powder and wire	DM3D Irepa Laser Sciaky Triumpf
Material Extrusion	-Fused Deposition Modeling	Polymer	Stratasys Delta Micro Factory 3D Systems
Material Jetting	-Polyjet -Ink-jetting -Thermojet	Photopolymer, wax	Stratasys LuXeXcel 3D Systems
Powder Bed Extrusion	-Direct Metal Laser Sintering -Selective Laser Sintering	Metal, Polymer, Ceramic	EOS 3D Systems Matsuura Machinery Phenix Systems
Sheet Lamination	-Ultrasonic Consolidation -Laminate Object Manufacturing	Hybrids, Metallic, Ceramic	Fabrisonic CAM-LEM
Vat Photopolymerisation	-Stereolithography -Digital Light Processing	Photopolymer, Ceramic	3D Systems Envision TEC DWS Srl

2.3.2 Potential Growth of Additive Manufacturing

A recent trend on AM technology has elevated concern of many manufactures to explore the advantages of this technique. Today, evolution of 3D printer has encouraged the technology to be employed in applications and industries as end product. This is acknowledge by giant manufacturer, Boeing in which uses Stratasys's 3D printers to make some components, and is constantly working on more ways to use the technology (Cotteleer, 2014). The airline company has even built an entire cabin using one of Stratasys's 3D printers. As a result of higher demands, Boeing has produced more than 20,000 3D-printed parts. It used those pieces in 10 different types of military and commercial airplanes, like the luxurious Dreamliner. The Dreamliner has about 30 3D-printed parts. Indeed, 3D printers helps to reduce the time between the design and manufacturing stages. It also a much more cost-efficient process. Figure 2.3 shows the application of AM systems in various sectors.

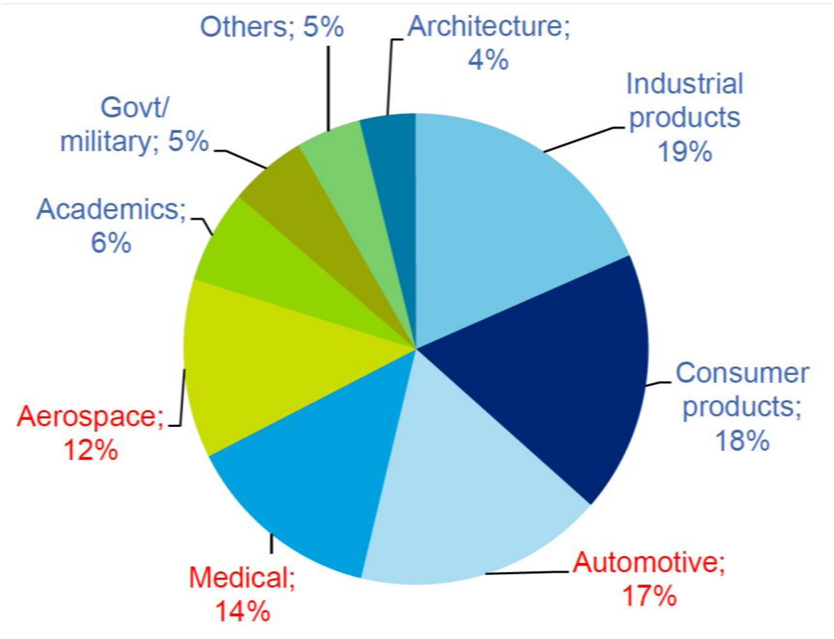

Figure 2.3: AM systems in various sectors in 2013 (Cotteleer, 2014)

As can be seen from Figure 2.3, major sectors are dominant by automotive, medical and aerospace which yields about 17 %, 14 % and 12 % respectively and currently leading about 43 % whereas this indicated the impact of AM systems in the industries. Therefore, regarding the AM potential in the industries, the usage will be increased significantly as a matter of time. Besides that, according to Cotteleer (2014), there is significant interest in AM systems distribution by applications whereas 29 % for functional parts, 20 % focusing on fit and assembly, 11 % for prototype tooling, 10 % for metal casting, 9 % for visual aids and models presentation and lastly 6 % goes to education research and tooling components. Recently, more companies typically spend extra time on production compare to prototyping. Figure 2.4 shows the AM systems deployment by applications in 2013.

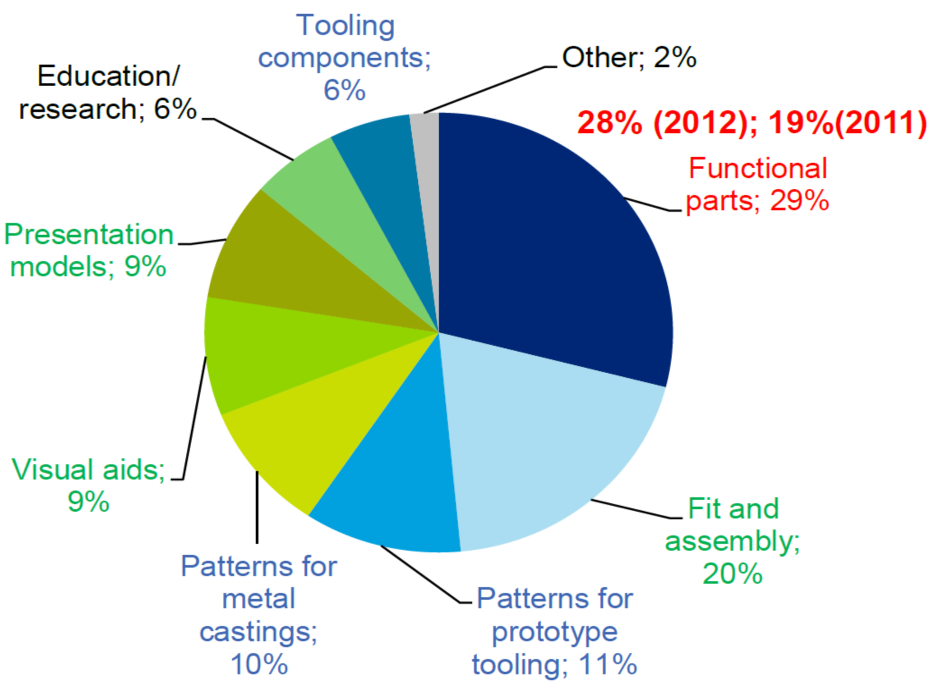

Figure 2.4: The AM systems deployment by applications in 2013 (Cotteleer, 2014)

2.3.3 Personal Desktop 3D Printer

Over the past six years, innovation in technology of AM relatively produces a new category of (AM) systems which is personal desktop 3D printers. Wohlers Associates defines personal desktop 3D printers as AM systems that sell under $5,000. The category includes RepRap and RepRap derivatives, MakerBot Industries, Delta Micro Factory Corp, Cube from 3D Systems and many others. Figure 2.5 shows the personal 3D Printer that available in the market.

Figure 2.5: Personal 3D printer by Makerbot industries

Mutually, these systems represent an interesting growth trends. The numbers represent the estimated number of systems sold each year. Growth averaged 70% each year from 2008 through 2011 and in 2012, the increase cooled significantly to an estimated 46.3% (Wohlers, 2013). One reason for the market is slowing due to the belief that the machines can be obtained or persuaded easily. Typically, most of the personal desktop 3D printer are being sold to do-it-yourselfers, hobbyists, young engineers, and engineering students. The market potential for personal desktop 3D printer is moving toward level of saturation and keeps on growing. Therefore, in this study, it briefly discuss the potential of portable or personal 3D Printer to be employed in metal casting end product. The market growth reports regarding the personal 3D printer from 2007 until 2012 are summarized in Figure 2.6.

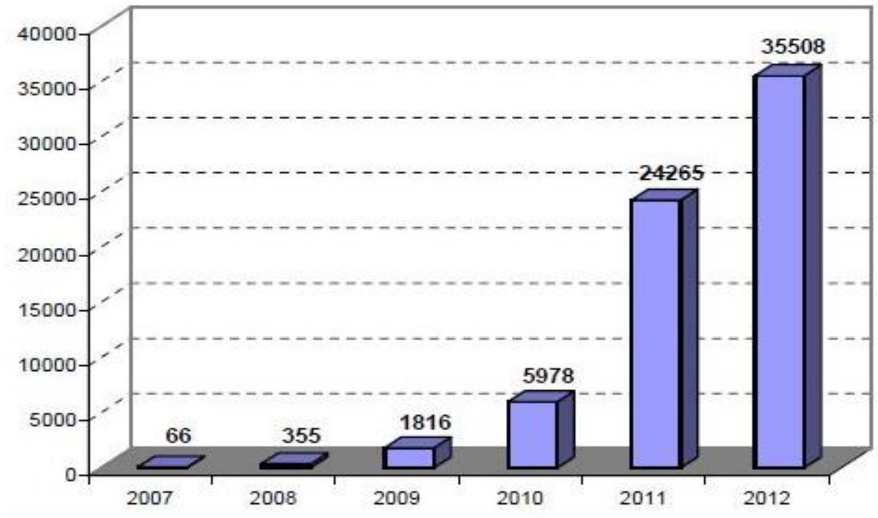

Figure 2.6: Market growth of personal 3D printer (Wohlers, 2013)

Generally, prototyping are important in application of 3D printing as research and development (R&D) project and part of product improvement. According to Cotteleer, (2014) most of the revenue generated by the 3D printing sector come from commercial users, as printer makers experience continued price pressure and 3D printers become more affordable. In the past, few giant companies such as 3M and Ford had participated in 3D printers and explore new product lifecycles or commercial models concept. For instances such as 3M company which has used AM to conduct research on health problems while Ford has used it to build prototype and components of the car. Regarding the 3D printer affordable prices, smaller companies are progressively joining in the exploration of applications. Some are even purchasing 3D printers to explore new business opportunities and productivities.

Every upcoming year the world of technology is introducing uptrend innovations in the field of 3D printing. As stated by Canalys (2014) who is working under global technology market analyst firm deems that the recent exponential development and enthusiasm around 3D printing made the market one of the most promising markets for the years to come. Indeed, the commodity prices are decreasing, resulting of much cheaper prices for 3D printers, which allow a significantly higher demand. On the other hand, the evolution of the technology is giving the opportunity to produce at a much faster pace a much bigger amount of products. Canalys, (2014) predicts the global 3D printing market will grow from $2.5B in 2013 to $16.2B by 2018, attaining a growth average of 45.7% in the forecast period. Figure 2.7 shows the comparison of forecasts and relative market growth by 3D printers, services and materials.

Global 3D printing market

Estimates and forecast of market value to 2018, in USD

Category	2013 estimates	2014 forecast	2018 forecast	CAGR (2013 - 2018)
Total	**$2.5b**	**$3.8b**	**$16.2b**	**45.7%**
3D printers	$0.7b	$1.3b	$5.4b	50.1%
Services and materials	$1.8b	$2.5b	$10.8b	43.8%

Source: Canalys estimates and forecast, © Canalys 2014

Figure 2.7: Global 3D printing market estimates and forecast (Canalys, 2014)

Nevertheless, when matching between personal 3D printers with high end 3D printers that commonly used in the industrial, there are difference between both systems. Firstly is regarding its cost, whereby personal desktop 3D printer is cheaper rather than high end 3D printer. Thus, personal desktop 3D printer has less capability due to the inexpensive and compactible size. The printer is capable on printing the small 3D objects, usually up to the size of A5. However, a new invention model has a large scale of platform measuring up to 210mm (X) x 210mm (Y) x 240mm (Z). Besides that, other important different is regarding its printing quality resolution. Most of the personal desktop 3D printer capable to print the 3D objects up to 100 microns in contrast the high end 3D printer has much higher resolution. Referring this situation, the quality of 3D objects made by personal desktop 3D printer is lower compare to high end 3D printer. Therefore, many companies have taken huge efforts improving the quality of low end 3D printer. Days by days, improvement has affected the consumption of personal desktop 3D printer to be engaged in industrial applications as a matter of fact that, it is economical in terms of cost.

2.4 Fused Filament Fabrication Technique

Nowadays, rapid growth on AM technology has spread simultaneously over the world, hence providing personal, compact and affordable desktop 3D printer for consumer usage. Commonly called by the name of Fused Deposition Modeling (FDM) in which a trademark by Stratasys. Besides that, it also may be called as Fused Filament Fabrication (FFF) or extrusion based system. Extrusion based desktop 3D printers are getting widely popular due to increasing visibility of the printers, but still industrial usage is dominant. The early industrial FDM machines are made by giant professional companies which are Stratasys and 3D Systems. Frequently, there are varieties of desktop 3D printer in market which made either by small or huge company.

As a matter of fact that most of the available desktop 3D printer process at the present time are based on the extrusion filament process in which inheritance by high end FDM machines. This process is most common and recognizable in the 3D printer process. The most common materials for entry level FFF are Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA). Besides that, other materials also are available such as flex and conductive ABS in which comes with variety of colours. The process begins with directly feed the polymer material into the extruder which is in the form of filament. The extruder uses a torque and a pinch system to feed and retract the precise amount of filament. Then, the filament passes through extruder and flows directly to the heater block whereas this block will heat the filament according to significant temperature. The semi molten filament is forced out through the heated nozzle at a small diameter. Next, the small filament diameter deposited at the top bed platform forming the layer upon layer in the XYZ. This process is continuing whereby the molten polymer deposited layer upon layer until full solid prototype complete. In addition, a supports are built along the way providing overhanging geometry materials to withstand the building process. However, with only one nozzle working, it is challenging to provide efficiency supports. Thus, as the system has advanced to integrate dual extrusion head nozzle, the issue become less important. With the improvement in dual extrusion, a combination of colours can be made significantly thus providing a colourful end product. Figure 2.8 shows the schematic flows of FFF process for 3D printer.

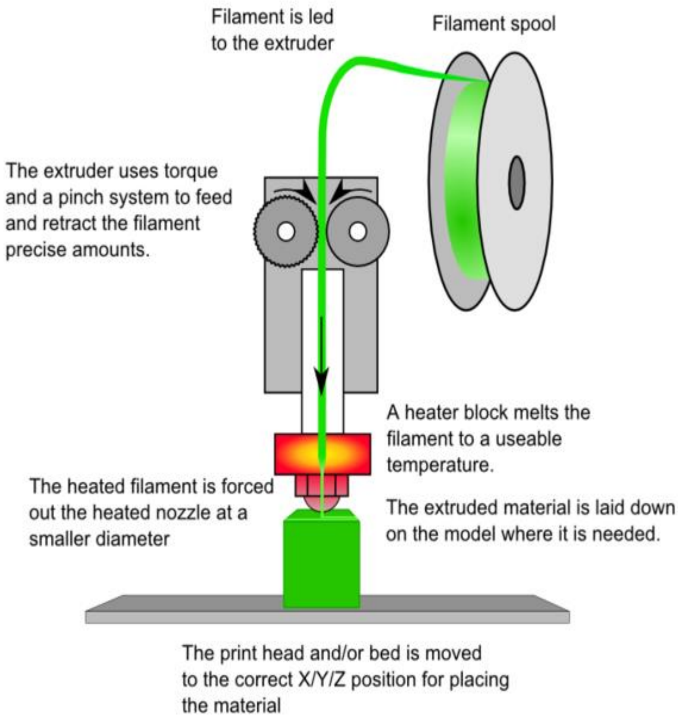

Figure 2.8: Schematic of Fused Filament Fabrication (3D PRINTING, 2014)

2.4.1 Material Characteristic for Fused Filament Fabrication Process

Generally, most common filament materials that used in FFF process are ABS and PLA. However, this literature of material for FFF process covered the ABS material only. ABS polymer is synthesized from three combination of monomers linkage such as acrylonitrile, butadiene and styrene. The basic molecules on ABS material are based on carbon, hydrogen and nitrogen. The compositions of ABS have an average composition of 27% acrylonitrile, 25% butadiene and 63% styrene (Shahir, 2010). In addition, monomer Acrylonitrile mainly offers heat stability as well as chemical resistance, while monomer butadiene provides impact strength and robustness and lastly the monomer styrene delivers equilibrium of clearness, stiffness, easily processing (Shahir, 2010). The combinations of these three components provide the good characteristics and the properties of the plastics. Those properties are controlled by molecular structures as well as monomers. Figure 2.9 shows the chemical bonding linkage of ABS structure.

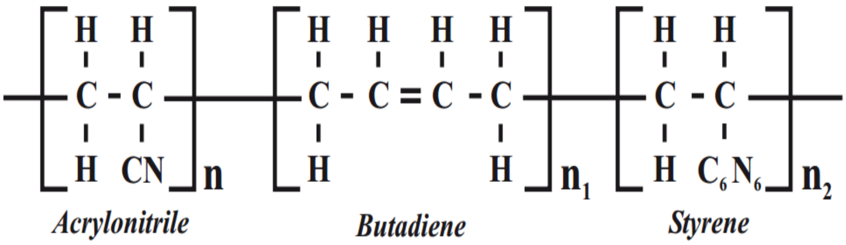

Figure 2.9: Chemical structure of ABS polymer (Wilks, 2001)

Additives may be added to the ABS composition such as stabilizers, colorants and lubricants, thus it will produce very complex ABS structure as well as provides excellent flexibility in the design. The impact of durability in ABS structure has made it well known and being commercialize into variety of products. Most of the major products are based on pipe line systems, appliances, automotive parts, consumer electronics, refrigerators, power tool applications and toys. ABS can be divided into two major groups such as injection molding and extrusion grades. The injection molding ABS grade has significantly low melt viscosity which is the major difference between these grades (Wilks, 2001). While the corresponding classes of grades can be divided into the impact strength and surface gloss. Besides that, there are also some specialties ABS grades in which are high heat, plating, clear, flame retardant, and structural foam grades. Basically the ABS material is in the form of filament whenever the material needs to be consumed in AM process. There are varieties of ABS filament diameters measured from 1.75mm up to 3.0mm. Figure 2.10 shows the varieties of ABS P400 filament in the market.

Figure 2.10: ABS P400 filament (3D PRINTING, 2014)

2.4.2 Properties of ABS Material

Essentially, ABS is widely used in components of plastics due to the fact that ABS has high chemical resistance, flexibility and stiffness thermoplastic polymer. In addition, ABS is exceptional choice for conceptual design prototype. Over the years, ABS has been embedded in AM process due to its precision, strength and repeatability properties. ABS is classified as thermoplastic materials that capable to fabricate complexity as well as thin layer of 3D objects. Today, there are lots of manufactures that produce ABS filament. Kindly, most of the ABS materials filament produce have different thermal and mechanical properties. This is due to the percentages of composition to be added into the filament. In addition, this is the "recipe" that most of the manufactures kept it as secret. Thus, not much company providing the thermal and mechanical properties of the ABS filament. It is important to fully understand the thermal and mechanical properties of material in order to fabricate the 3D prototype. Furthermore, the thermal and mechanical properties are guidelines as it enable the user specifically to manufacture a full concept 3D object without failure. Table 2.2 shows the thermal and mechanical properties of ABS P400 material by Stratasys.

Table 2.2: Thermal and Mechanical properties of ABS P400 (Stratasys, 2011)

Thermal and Mechanical Properties	**Value**
Tensile Strength	22 MPa
Tensile Modulus	1627 MPa
Flexural Strength	41 MPa
Flexural Modulus	1834 MPa
Glass Transition Temperature, T_g	104°c
Coefficient of Thermal Expansion, CTE	10.08×10^{-5}

2.5 Jetting Technique

This technique may be called as Polyjet, Thermojet and Muljet Modeling (MJM). Evolution in AM technology has emerged giant company to explore new process to adapt in desktop 3D printer. Hence, collaboration of two giant companies such as Objet and Stratasys has formed a new company consisting of market value worth $3 billion whereby the pattern of desktop 3D Polyjet system is taken by Stratasys. Today, there are variabilities of Polyjet desktop 3D printer based on Polyjet technology such as Object 24, Object 30, Object 30 Pro and Object 30 Prime.

The Polyjet desktop 3D printer is based on PolyJet technology system. In contrast, the indirect 3D printer processes is different concept whereby, jetting the binder into a bed of building material. Therefore there is absent of powder bed in the Polyjet desktop 3D printer process. Besides that, the Polyjet systems are differs from Stereolithography (SLA) systems whereas the materials come in the form of cartridge (no vat of liquid photopolymer).

In this case, the concept is similar to ink jet document printing whereas it has capability to print diagram onto paper. However, instead of jetting the drops of ink on paper, Polyjet desktop 3D printer jet layers of liquid photopolymer onto a build tray and cure them with UV light. Layer upon layer is created in order to fabricate 3D prototype. Post processing is eliminate due to the end material can be handle and used directly. However, the 3D printer also offers a gel-like support material particularly designed to sustain overhangs and intricate geometries. The support material can be removed using Waterjet. Moreover, this technique is versatile due to

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