PARAMETER OPTIMIZATION FOR PHOTO POLYMERIZATION OF MASK PROJECTION MICRO STEREOLITHOGRAPHY

KHAIRU BIN KAMARUDIN

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Faculty of Mechanical and Manufacturing Engineering
University Tun Hussein Onn Malaysia

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ABSTRACT

This study presents a research on 3D part fabrication from composition of photo initiator (Phenylbis(2,4,6-trimethylbenzoyl)), photo absorber (Sudan I) and 1, 6-Hexanediol polymer effect based on curing parameters. A DLP projector was used as energy light source which initiated the photo reactive polymer at three different light source distances with three different exposed time to evaluate photoreactive polymer solidification phenomena. The experiment results obtained shows that Sudan I composition, light intensity value and exposure time of the varied photo absorber give significant effect to mechanical properties such layer thickness, dimensional accuracy, surface roughness and hardness value. These works also prove that photo absorber composition solution gave a different mechanical properties effect for 3D microstructure fabrication.

ABSTRAK

Kajian ini adalah mengenai kesan percampuran bahan penyerap cahaya (Sudan I) berdasarkan parameter berkaitan dengan proses pengerasan dengan menggunakan projector jenis DLP sebagai sumber tenaga yang menyebabkan tindakbalas "photoreactive polymer". Bahan polimer asas ini terdiri daripada komposisi 1, 6-Hexanediol dicrylate dan Phenylbis (2,4,6-trimethylbenzoyl) phosphine oxide dengan tiga variasi campuran Sudan I bagi menghasil model 3D. Pengerasan "photoreactive polymer" akan menghasilkan model 3D dan seterusnya proses pengerasan yang berlaku akan dianalisis berdasarkan data-data yang berkaitan. Hasil ujikaji yang dijalankan menunjukkan bahawa masa dedahan kepada sumber cahaya memberikan kesan kepada nilai kekasaran permukaan, jumlah masa yang diperlukan untuk mengeraskan satu lapisan pada struktur 3D yang dihasilkan dan ketebalan setiap lapisan yang dihasilkan. Secara keseluruhannya ujikaji yang dijalankan menunjukkan kepelbagaian komposisi percampuran bahan-bahan akan memberikan ciri-ciri mekanikal yang berbeza ke atas penghasilan struktur mikro 3D yang dihasilkan.

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LIST OF SYMBOLS AND ABBREVIATIONS

ASTM	-	American Society for Testing and materials
FDM	-	Fused Deposition Modelling
STL	-	Stereolithography
3D	-	three dimensional
g	-	gram
s	-	second
mm	-	milimeter
µm	-	micrometer

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CHAPTER 1

INTRODUCTION

This report describes the design and development project for "Parameter Optimization for Photo Polymerization of Projection Micro Stereo Lithography". This chapter will explain the project background, problem statement, objectives, scope and project outline.

1.1 Research background

Since the introduction of the stereolithography (SLA) process as the first rapid prototyping (RP) process in 1988, several RP process which use different mechanism or materials have been introduced. Some of them such as laminated object manufacturing (LOM), selective laser sintering (SLS), fused deposition modelling (FDM) and 3D printing (3DP) have become commercially available. RP systems have been reviewed frequently from different perspectives.

RP open a new dimension to produce a product in manufacturing industry. RP has generated much interest the area of engineering and manufacturing as this technology, which has a unique layer by layer manufacturing method, enables time and costs saving associated with model making. Many type of product can be produced by RP in shorter time than using the conventional process. By the advancement of RP come in the industry more challenges comes from the manufacturers to improve the RP system and many study of RP was done until now.

However, this layer by layer manufacturing technique is not yet in widespread use especially in Malaysia, as it is still a relatively new technology. Known as new technology, this is very important to local manufacturer to produce their product with higher quality, better economic cost and shorter lead time. The user of RP enables the company from Malaysia to be more competitive with international company that will attract more investor to come to Malaysia as a technology hub.

1.2 Problems statement

RP technology is a new technology that was introduced about a decade ago. There are many different RP systems available commercially. However, the constraint that we are facing now is that the RP technology is not yet widespread uses among the toolmakers and the students especially in Malaysia. Currently, a few researchers, was looking for improvement involving process, cost, and the main power that is used to control the RP machine.

In this project, a portable 3D printing machine consist of a computer with power point images, optical lens, DLP projector, mirror, motorized translation elevator that control by Advance Positioning Technology (APT) software was used as the RP machine to produce product (3D object).

The DLP projector has been used as a replacement of laser source. Previous study has been done using LCD projector as a source to cure the polymer. The 3D fabrication using LCD projector was successful done but unfortunately the parameter is not yet optimize. The optical lens also will be added to make the projected image more sharp and precise. The parameter that needs to be optimized is curing time and material composition, surface roughness, dimensional accuracy, and optical parameter. In order to get the best quality product this parameter must be optimized.

1.3 Background of study

Today, it is important to understand the concept of RP and their applications in recent technology. This study will show the operation of RP machine, especially 3D printing machine and the material that will be use for this project. The DLP projector will be use as source to initiate photoreactive polymer thats being used for this project to design the 3D object. The quality of the product will be verify and validate to ensure the quality. Printers capable of producing three-dimensional objects are becoming more common. Most of these printers are impractical for use because of the expense incurred in fabricating a print head that must be controlled in three dimensions. This research project propose a simpler solution to this problem that allows the emerging technology of three-dimensional printing to be examined and executed in a typical manner. By replacing the print head with a data projector that can develop two-dimensional layers of the objects simultaneously rather than sequentially, the need for expensive equipment is eliminated. A simple, cost-effective mechanical staging device can be constructed that allows for control of the third dimension of the object. This project to produce a product faster, in lower cost, higher quality and using simpler manufacturing process.

A photoreactive mixture of chemicals will polymerize when exposed to ultraviolet light, leaving nearby polymer unreacted. Using PowerPoint and a data projector, one can react different shapes by shining the light of the data projector into a beaker of the photoreactive polymer. PowerPoint allows black and white cross sections to be designed in a user friendly interface. Adding an ultraviolet absorber will prevent the light from penetrating into the polymer more than a fraction of a millimeter. By continually lowering the previous layer of hardened polymer into the beaker a three dimensional object can be made one cross-sectional layer at a time.

A form of three-dimensional printing called microstereolithography can be established using a UV sensitive monomer. Using a video projector with a UV output, they are able to create incredibly thin polymer layers (on the order of 400 nm) and build objects layer by layer. This activity uses the same principle but at a much larger scale.

This activity demonstrates the basic challenges of micro scale engineering and manufacturing. A regular video projector provides enough UV light to initiate a photochemical reaction by cleaving a molecule to form free radicals when white light is emitted. The free radicals will polymerize a monomer through an addition polymerization reaction. It will polymerize the solution, becoming solid, only where the white light is projected. It will remain an unreacted liquid elsewhere. The photosensitive monomer (1, 6 - Hexanediol Diacrylate or HDDA) works under the process of addition polymerization. The photoinitator (Irgacure 819) absorbs UV-wavelength photons and produces free radicals.

These free radicals react with the monomers (HDDA) to cause chain propagation, polymerizing the monomer. This chain propagation terminates when two chains react with each other. Successive layers are made by lowering the polymerized shape into a beaker of the solution. A thin layer of fresh solution flows over the top and light is again projected to solidify portions of the fresh layer. This will be repeated and a three dimensional object layer by layer will be created. The quality of the product will be verify and validate to ensure the quality by controlling the experiment parameter.

1.4 Objective of Study

The objectives of this study are;

i. To setup a system apparatus to initiate the photo polymerization of projection stereolithography experimental study.
ii. To validate formulation on concentration of Sudan I and Phenylbis effect for polymerization process.
iii. To optimize the parameters in order to get the best quality of product.

1.5 Research Scopes

The scopes of study are:-

i. To validate formulation on concentration of Sudan I and Phenylbis effect for polymerization.
ii. To utilize a sensitive monomer to fabricate three dimensional printing object called micro stereolithography by using DLP projector
iii. To optimize the optical parameter for polymerization process.

1.6 Organization of Thesis

The MP (Master's Project) study is organized to include five chapters. Chapter 1 is an introduction for this study which includes background, statement of problem, background study, objective of study and research scope. Chapter 2 is discussing about the literature review. Chapter 3 is discussing on method and procedures used in conducting the study in a well-developed research report. The research flow chart and planning of MP are shown in an Appendix A and Appendix B. In chapter 4, it finds out the result and discussion of the result obtained. For the last part, it is for the conclusion and recommendations are included in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

The aim of the literature review was to use past research and current knowledge and activity to provide direction for the research that gained through a lot of resources such as reference book, papers, journal, articles, conferences articles and documentations regarding applications and research work. This shows how the theory and the concept have been implemented in order to solve project problem. The theory understanding is crucial as guidance to start any project. The result of the project cannot be assessed if it's not compared to the theory.

2.1 Rapid Prototyping

The manufacturing companies of today are faced with the challenge of unpredictable, high frequency market changes in both local and international markets. These are results of shorter product development times, changes to existing products, fluctuations in product demand, and changes in processes and technology. To be successful, rapid time-to-market of new products is critical in the midst of highly competitive markets (Krar and Gill, 2003).

Rapid in other words, is quick or occurring with great speed. A prototype is the first or original example of something that been or will be copied or develop, it is a model or preliminary version (Sapuan, 1998). Rapid prototyping, consist of the stereo lithography (SLA), selective laser sintering (SLS), laminated object manufacturing (LOM), three dimensional printing (3DP), fused deposition modelling (FDM) and others. RP has the ability to rapidly produce accurate and tangible 3D models of products designed on a CAD system without the need for machining or tooling (Dimitrov et al, 2006).

There are three fundamental fabrication methods (Figure 2.1). Subtractive methods start with a solid block of build material larger than the final part. The desired shape is achieved by removal of material. Additive methods are the opposite of subtractive methods. Build material is added to the successive layers in order to build a part. Finally, formative methods use moulds or dies to form parts.

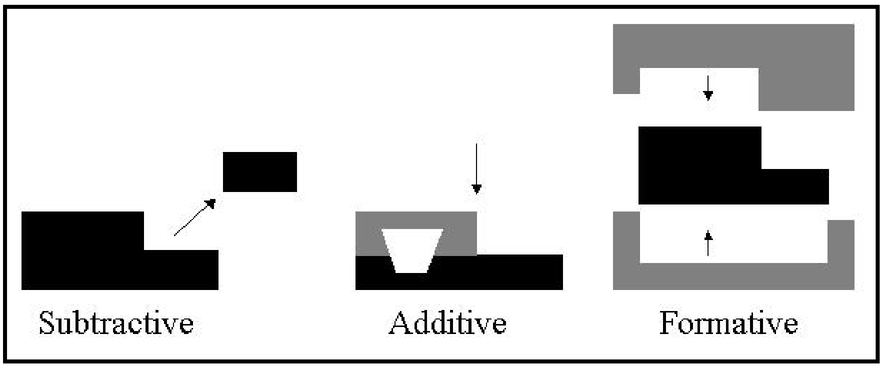

Figure 2.1: Three Fundamental Fabrication Methods (Chua et al, 2003).

Rapid prototyping can be divided into four main areas: input, method, material and applications. These are shown in the Rapid Prototyping Wheel in Figure 2.2 (Chua et al, 2003). Input - refers to the data format that represents a computer model. This is usually in the form of CAD files. It also includes the way a physical model is input transposed into digital form by reverse engineering technology, i.e. CMM (coordinate measuring machine). Method - refers to the way in which parts are created in the RP machine. This includes all the techniques that various machines employ. Material - encompasses all substances (solid, liquid or powder states) that are used in the creation of parts. Applications of RP are divided into three main industries. But there are always new application areas being found for RP.

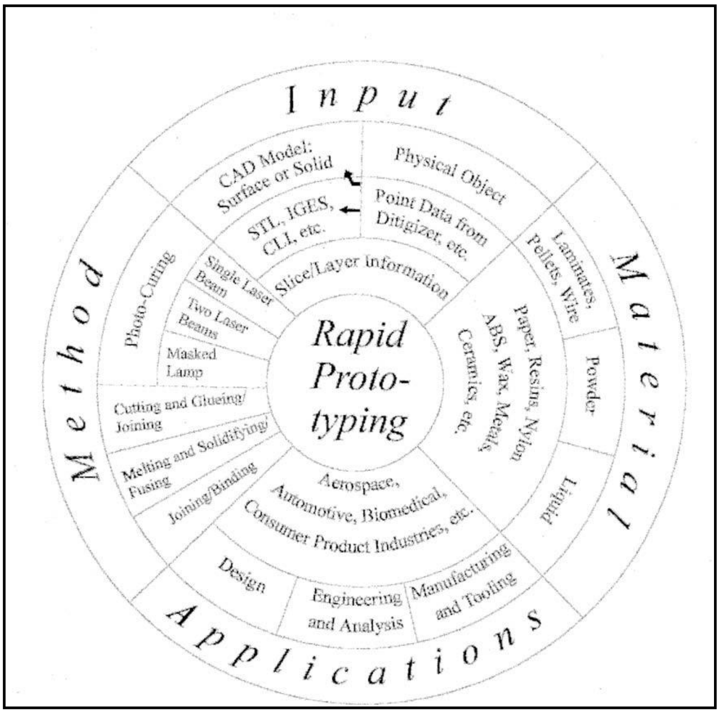

Figure 2.2: Rapid Prototyping Wheel (Chua et al, 2003).

2.1.1 Classification of Rapid Prototyping

Material a creation processes may be divided by the state of the prototype material before part formation, namely, liquid, powder or solid sheets. Liquid-based processes may entail the solidification of a resin on contact with a laser, the solidification of an electro setting fluid, or the melting and subsequent solidification of the prototype material. Processes using powders aggregate them either with a laser or by the selective application of binding agents (Chua and Leong, 1997). Figure 2.3 to shown classification which has been adapted to include new processes.

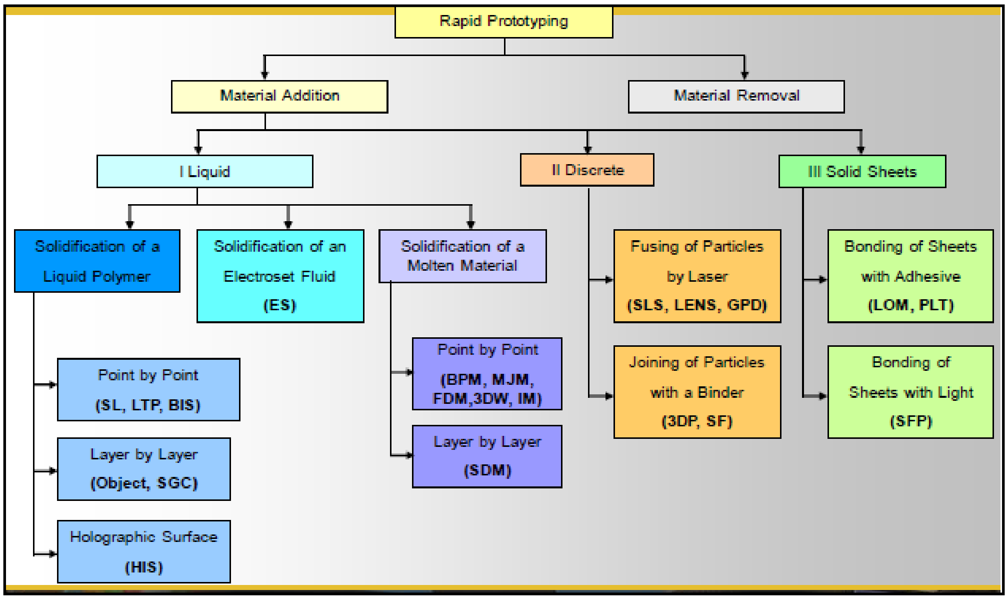

Figure 2.3: Classification of Rapid Prototyping Method (Chua and Leong, 1997).

2.1.2 Process Flow of Rapid Prototyping

Several RP techniques have been developed during the past decades. Some of the commercially available RP techniques are 3DP, SLA, LOM and FDM. From this, the basic steps for all current rapid prototyping techniques summarized as follows. Figure 2.4 shows a process flow of RP.

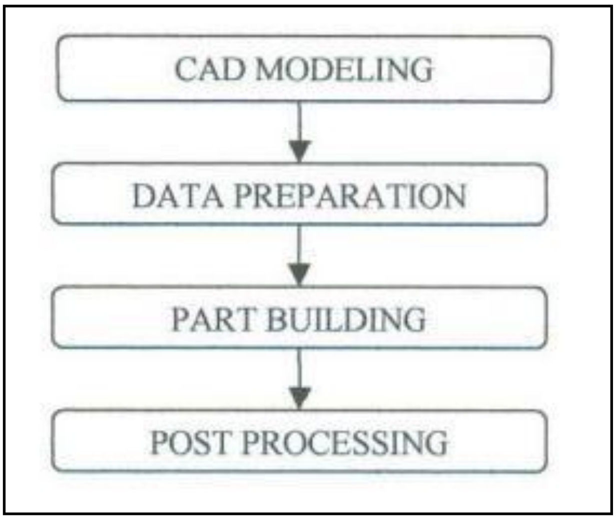

Figure 2.4: Process Flow of Rapid Prototyping

i. CAD Modeling

In RP process, the first step is the generation of 3D model or component on the CAD/CAM system. Create a 3D Cad solid model of the design. The object to be built is modeled using Computer-Aided Design (CAD) software package. This requirement ensures that all horizontal cross section are closed curves to create the solid objects.

ii. Data Preparation (Convert)

The second step is to translate and prepare the CAD file into the standard format of data. Models can create standard triangulation language (STL) files that are required for RP processes. The STL file connects the surface of the model in an array of triangles consists of the X, Y and Z coordinates of the three vertices of each surface triangle, as well as an index that describes the orientation of the surface normal. A large number of facets will accurately describe a curved surface but will require an extremely large file size.

iii. Pre-process

Different processes have various methods and timings to slice the file, some “slice on the fly”, that is they slice and then process the parts others such as SLA are sliced before manufacturing takes place, the following procedure is based on SLA.

iv. Part Building

The third step is the actual fabrication of the model using one of several RP techniques. The first layer of the physical model is created. The model is lowered by the next layer, and the process is repeated until completion of the model. This is the actual construction of the part. RP machines build one layer at a time from paper or powdered metal. Most machines are fairly autonomous, needing little human intervention.

v. Post processing

The final step in the RP process is the post-processing task. At this stage, the part are removed from the machine and post-processing operations take place, these may be to add extra strength to the part by filling process voids, finish the curing of a part or to hand finish the parts to the desired level. The level of post processing will depend greatly on the final usage of the parts produced , for example, metal tooling for injection moldings will require extensive finishing to eject the parts but a prototype part manufactured to see if will physically fit in space will require little or in post processing.

2.2 Stereolithography

The Stereolithography process begins with the definition of a CAD model of the desired object, followed by slicing of the three dimensional (3-D) model into a series of very closely spaced horizontal planes that represent the X-Y cross sections of the 3-D object, each with a slightly different Z-coordinate value. All the cross-sections are then translated into a numerical control code and merged together into a build file. This build file is used to control the ultraviolet (UV) light scanner and Z-axis translator. The desired polymer object is then “written” into the UV-curable resist, layer by layer, until the entire structure has been defined (Limaye, 2003).

The schematic of the Stereolithography machine is shown in Figure 2.5.

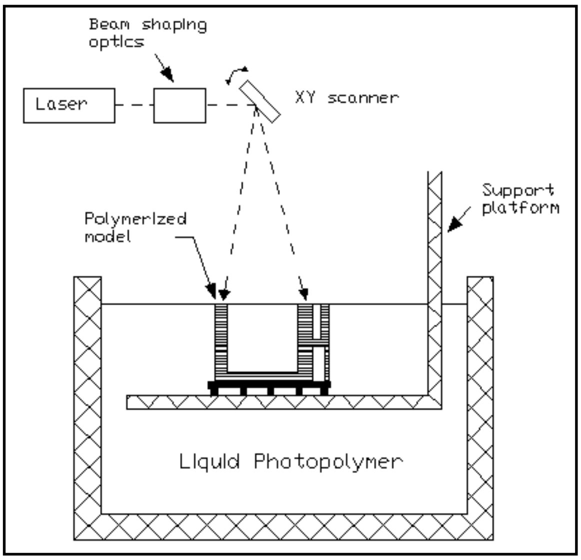

Figure 2.5: Schematic of a Stereolithography machine (Limaye, 2003).

The basic elements of a Stereolithography system are as follows:

- Laser Optics System
- Scanning System
- Elevator and Recoater
- Computer Control and Software

The laser optics system consists of the laser used to cure the resin and the beam shaping optics. The beam shaping optics is responsible for conditioning the laser beam and focusing it on the resin surface with the desired spot size. The scanning system consists of a set of galvanometric mirrors, which direct the laser beam so that the required cross-section is scanned (Limaye, 2003).

2.2.1 Micro-Stereolithography

When Stereolithography is used to fabricate micro-parts, it is called Micro Stereolithography. The principle of Micro Stereolithography is the same as Stereolithography, i.e. “Writing a cross section on a photopolymer surface by means of UV light”. However, the resolution required of a Micro-Stereolithography process is much finer.

Micro-Stereolithography systems developed so far can be divided into two categories:

- Scanning Micro Stereolithography Systems and
- Mask projection Micro Stereolithography Systems, or Integral Micro Stereolithography Systems

2.2.1.1 Scanning Micro Stereolithography Systems

It is believed that, in conventional Stereolithography, too many mobile optical elements lead to focusing errors and thereby, poor resolution. Also, the spot size doesn’t remain constant throughout the layer cross-section. As a result, lateral resolution is dependent upon the distance of a feature from the center of the vat. In scanning Micro Stereolithography, this drawback is eliminated by keeping the light beam focused onto a stationary tight spot and scanning the layer by moving the work piece under the spot. The principle of Scanning Micro-Stereolithography is shown in Figure 2.6.

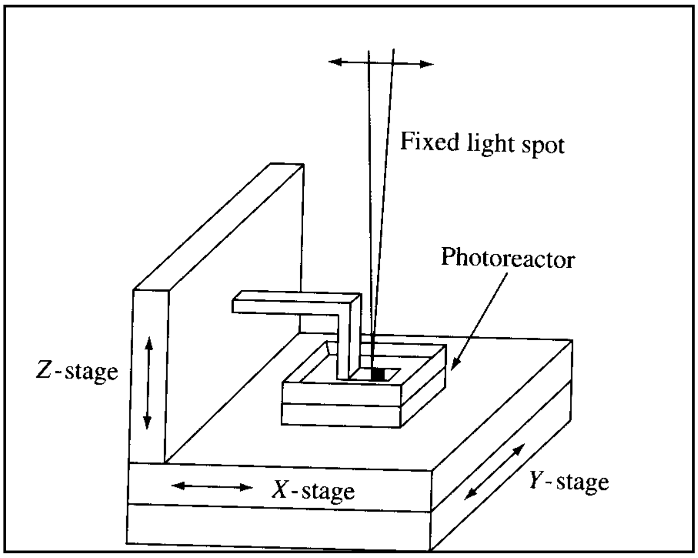

Figure 2.6: Principle of Scanning Micro-Stereolithography (Limaye, 2007).

2.2.1.2 Mask Projection Micro-Stereolithography

In Mask projection Micro Stereolithography, also called Integral Micro Stereolithography, a complete layer is polymerized in a single radiation. The principle of Mask projection Micro Stereolithography is shown in Figure 2.7.

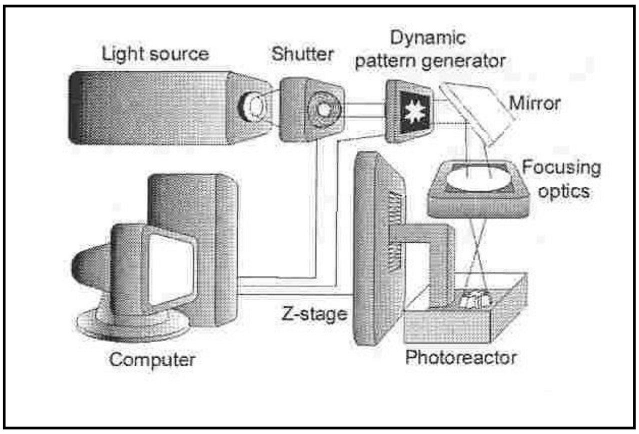

Figure 2.7: Schematic of a Mask projection Micro Stereolithography Apparatus (Bertsch et al, 2000)

Alonso (2010) mention that the concept of Projection Stereo lithography was introduced by Bertsch in 1997. Lithography was not a new concept, but Projection Stereo lithography transformed it from a slow serial process to an extremely rapid and effective parallel process. This technology employs a spatial light modulator, which is also known as a dynamic or digital mask. Light passes to the digital mask, which displays an image of the layer to be fabricated, and is either transmitted or reflected depending on the mask. A series of optical devices are then introduced to focus the image on the desired build plane. The light causes a polymerization reaction in the shape of the projected image, and stacks of these images produce three dimensional objects.

The digital masks are the core technology that enables Projection Stereo lithography. Bertsch employed the first digital mask, a Liquid Crystal Display (LCD) in 1997. Researchers have a choice of devices to utilize as a dynamic mask, which include Liquid Crystal on Silicon (LCoS) chips, Digital Micro mirror Devices (DMD), or the standard LCD. These devices allow the manipulation of individual pixels. This provides the investigator with the ability to rapidly change the mask by sending a new digital image, rather than replacing a physical mask and painstakingly realigning the system as is standard in lithography. In 2003, PSL experienced a shift from being considered a rapid prototyping technology to being viewed as a manufacturing process. Xiawas able to produce a three-dimension microstructure directly under a MEMS device, described by Chen (Alonso, 2010).

Limaye (2003) summarized the Mask Projection Micro Stereolithography Systems have been presented in literature (Bertsch et al., 1997; Chatwin et al., 1998; Farsari et al., 1999; Chatwin et al., 1999; Monneret et al., 1999; Bertsch et al., 2000; Farsari et al., 2000; Monneret et al., 2001; Hadipoespito et al., 2003). Impressive results have been achieved by these researchers. The results are documents in Table 2.1.

Table 2.1: Results obtained using Mask projection Micro Stereolithography (Limaye, 2003)

Research Team	Light source	Mask	Component Size	Resolution	Reference
Bertsch	Laser 515 nm	LCD (Liquid Crystal Display)	1.3 x 1.3 x 10mm^3	5 x 5 x 5 µm	(Bertsch, Zissi, et al., 1997; Bertsch, Jezequel, et al., 1997)
Chatwin	Laser 351.1nm	SLM (Spatial Light Modulator)	Not reported	5 µm lateral resolution	(Chatwin et al, 1998; Farsari et al., 1999; Chatwin et al., 1999; Farsari et al., 2000)
Monneret	Broad Band Visible	LCD (Liquid Crystal Display)	Not reported	2 µm lateral resolution	(Monneret et al., 1999; Monneret et al., 2001)
Bertsch	Lamp (Visible)	DMD (Digital Micromirror Device)	6 x 8 x 15 mm^3	5 x 5 x 5 µm	(Bertsch et al., 1999)
Bertsch	Lamp (UV)	DMD (Digital Micromirror Device)	10.24 x 7.68 x 20 mm^3	10 x 10 x 10 µm	(Bertsch et al., 2000)
Hadipoespito	Lamp (UV)	DMD (Digital Micromirror Device)	Not reported	Not reported	(Hadipoespito et al., 2003)

The Function Structure abstracted from the above observation is shown in Figure 2.8.

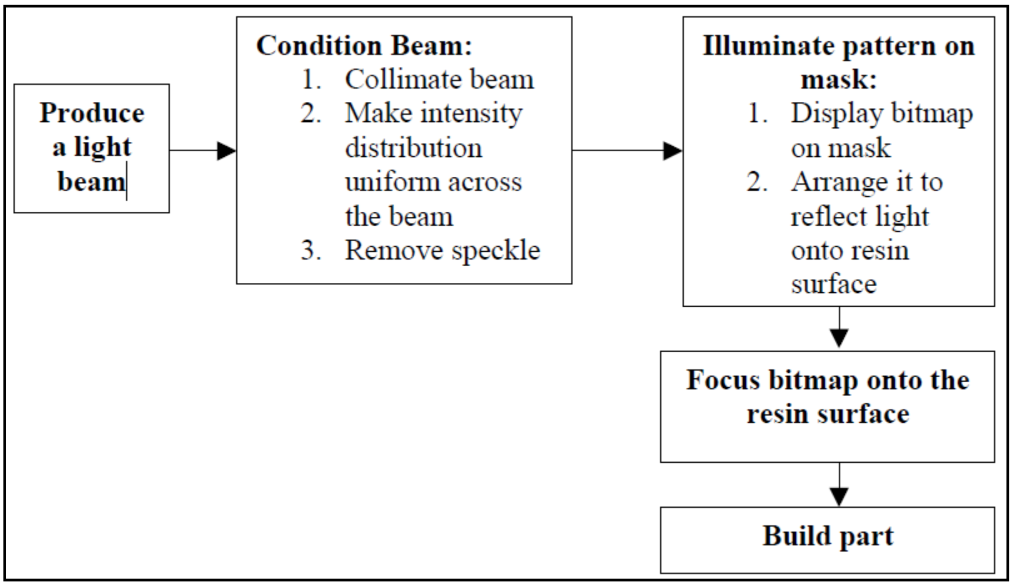

Figure 2.8: Abstracted function structure of any general mask projection micro-stereolithography system

2.3 Design of the MPSLA System

The optical schematic of a MPSLA system has been presented in Limaye (2004), as shown in Figure 2.9.

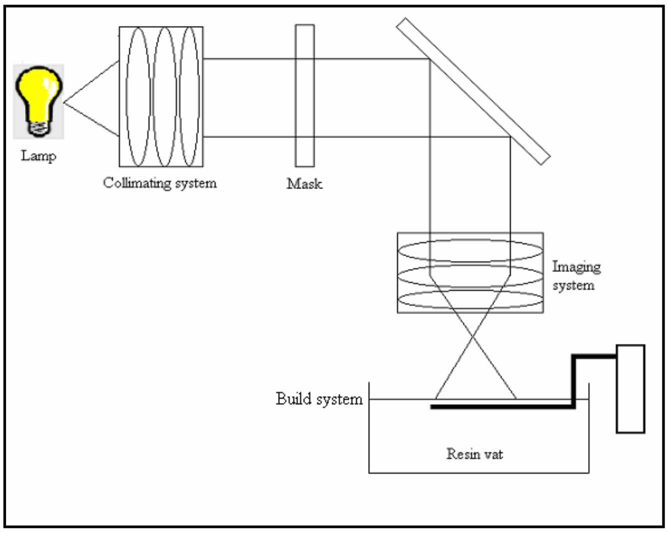

Figure 2.9: Optical structure to embody

For the focusing lens, Limaye (2004) compute the focal length of the lens:

The final system is as shown in Figure 2.10 and the description of every component is presented in Table 2.2 (Limaye, 2007).

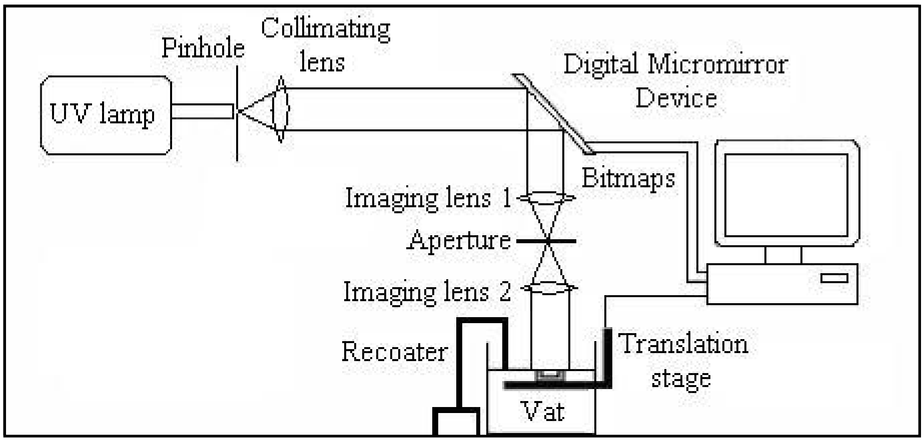

Figure 2.10: Optical schematic of the MPSLA system realized as a part of this research (Limaye, 2007).

Table 2.2: Specifications of the components used in the MPSLA system (Limaye, 2007).

Component	Description	Model/Manufacturer
Broadband UV lamp	Broadband Mercury vapor lamp. Peak at 365nm. 3000mW at 365nm.	ADAC System Cure Spot 50/ DymaxCorporation
Aperture 1	Adjusted to 4mm diameter	Thorlabs
Collimating lens	Fused silica Plano convex lens Effective focal length = 40mm Diameter = 25.4mm Radius of surface 1 = 18.4mm Radius of surface 2 = infinity (plane) Lens thickness = 7.1mm	Thorlabs Catalog # LA4306-UV
DMD	1024 X 768 array of micromirrors Dimension of micromirror = 12.65µm square. Spacing between mirrors = 1µm	Texas Instruments. Distributed by Prodsys Inc.
Imaging Lens 1 and Imaging Lens 2	Fused silica Plano convex lens Effective focal length = 40mm Diameter = 25.4mm Radius of surface 1 = 35.7mm Radius of surface 2 = 35.7mm Lens thickness = 6.7mm	Thorlabs Catalog # LB4030
Aperture 2	Adjusted to 1.5mm diameter	Thorlabs Catalog # SM05D5
Translation stage	XYZ translation stage; 100nm resolution	Applied Scientific Instruments Model # MS2000
Photopolymer resin	Ec, Dp to be found experimentally	DSM SOMOS 10120

2.4 Optical Terms, Practical Considerations and Implementation

This section will review the depth of focus, depth of field, power for a lens and optical lens configuration.

2.4.1 Depth of Focus and Depth of Field

Zyzalo (2008) mention that the depth of focus is often confused with depth of field. Depth of focus is the amount of image defocus which corresponds to being out of focus by one-quarter of a wavelength. This means that the optical path difference (OPD) between the real wavefront leaving the exit pupil at is outer periphery and a reference wavefront centred normal to the image plane is one-quarter of a wavelength of light.

According Fischer & Tadic-Galeb (2000), depth of field is a term more commonly used in photography to relate how acceptable an image looks to the eye. If a camera is focused at a given distance, how much further or closer from the camera than this distance will objects be in acceptable focus.

Depth of field, to a great extent, is controlled by the f-number of a lens. In an ideal lens design, the f-number is the limiting factor in system resolution. Common machine-vision optics integrates an adjustable iris into the design, allowing the user to adjust for varying light levels and to control the depth of field. Increasing the size of the aperture decreases the depth of field, but will often increase the resolution of the lens. Decreasing the size of the aperture increases the depth of field, but decreases the effective diffraction limit of the lens. This degrades overall system performance (Fales, 2003).

2.4.2 Power of a Lens

Optical designers will sometimes refer to a lens by its power. The power of a lens or optical system is the reciprocal of its effective focal length. Usually, focal lengths are expressed in millimetres or centimetres. However, the unit of measure is dioptres where the focal length is given in meters (Smith, 2000). Dioptres are more commonly used in optometry to specify the power of lenses in eyewear.

2.4.3 Optical Lens Configurations

Design forms and system configurations are discussed by (Fischer & Tadic-Galeb, 2000). A configuration includes the number of elements, relative optical power and the distribution of the elements within the system. The differences between several lens configurations are compared with regard to system specifications. The major factors influencing these specifications include field of view, performance requirements, f-number, packaging requirements and spectral range. Figure 2.11 shows diagrams of the lens types and configurations that are discussed in this section.

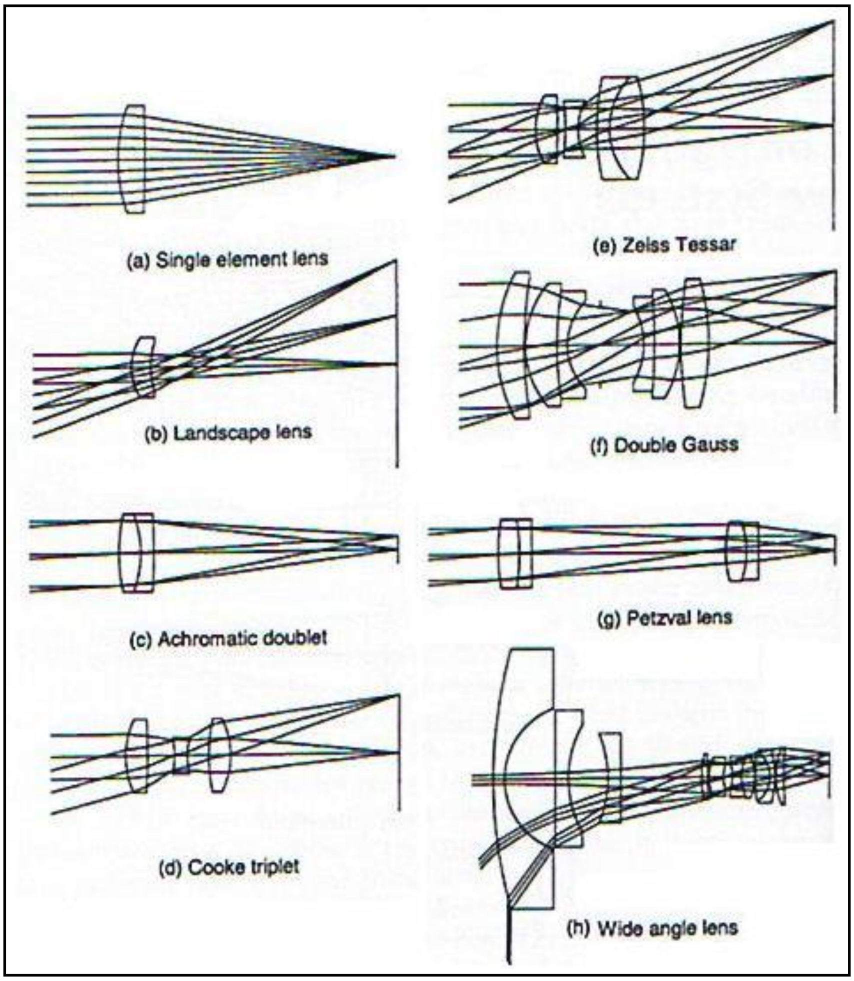

Figure 2.11: Lens configurations (Fischer et al, 2000)

2.5 Material Selection

Materials selection is a task normally carried out by design and materials engineers. The aim of materials selection as the identification of materials, which after appropriate manufacturing operations, will have the dimensions, shape and properties necessary for the product or component to demonstrate its required function at the lowest cost. For the purpose of material selection, thousands of data would be needed to characterize all the grades of materials. Many selection systems are available to help design engineers to choose the most suitable materials. At the most basic level, design engineers could use tables of material properties in data books. However, data sheets are incomplete and once published, they are difficult to update. How information about engineering materials, can be divided into two main categories. Data is defined as the results of measurements, whereas knowledge represents the connections between items of data, the source of this knowledge, which contributes to an understanding of the results.

2.5.1 Sudan I

Sudan I is a photo inhibitor and prevents the exposure dose from penetrating deep into the polymer, which helps control the layer thickness. The second action of Sudan I is to increase the threshold light flux needed for polymerization. This decreases the sensitivity and makes it more difficult for stray light to polymerize the solution, effectively increasing the contrast of the system.

Sudan I (also commonly known as CI Solvent Yellow 14 and Solvent Orange R), is a lysochrome and diazo-conjugate dye with a chemical formula of 1-phenylazo-2-naphthol. Sudan I is a powdered substance with an orange-red appearance. The additive is mainly used to colour waxes, oils, petrol, solvents and polishes. Sudan I has also been adopted for colouring various foodstuffs, including particular brands of curry powder and chili powder, although the use of Sudan I in foods is now banned in many countries because Sudan I, Sudan III, and Sudan IV have been classified as category 3 carcinogens (Not classifiable as to its carcinogenicity to humans) by the International Agency for Research On Cancer (Refat et al, 2008).

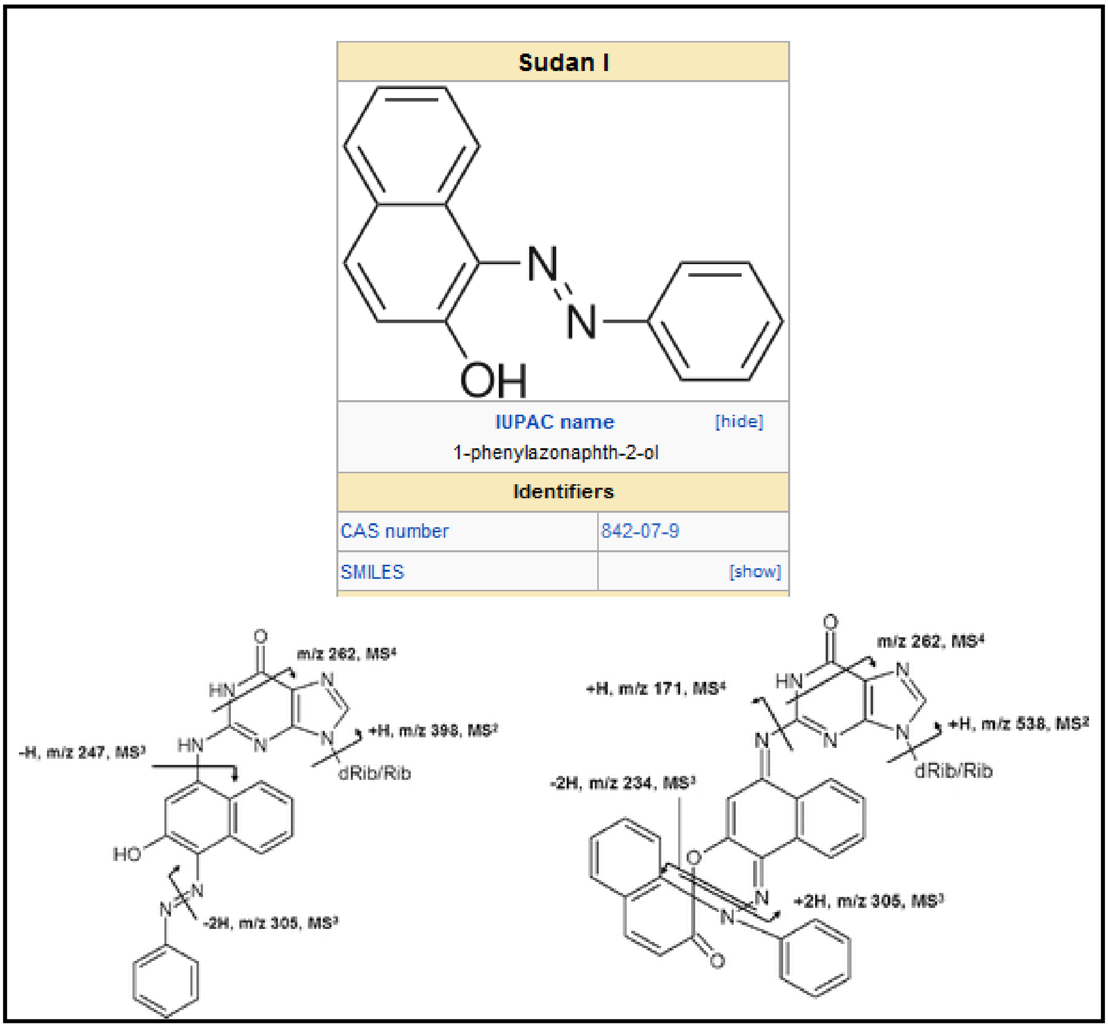

Figure 2.12: Properties of Sudan I (Kruth, 1991)

2.5.2 Phenylbis (2, 4, 6-trimethylbenzoyl) - phosphine oxide

Irgacure 819 is a photoinitiator that releases free radicals when it absorbs energy. This causes the monomers in solution to bind and polymerize. The presence of oxygen limits the number of free radicals available for polymerization. For this reason, in order to minimize the amount of exposure dose required, the system should be designed to minimize oxygen at the reaction surface. Experimental data have been collected for experiments in an oxygen environment and in a nitrogen environment.

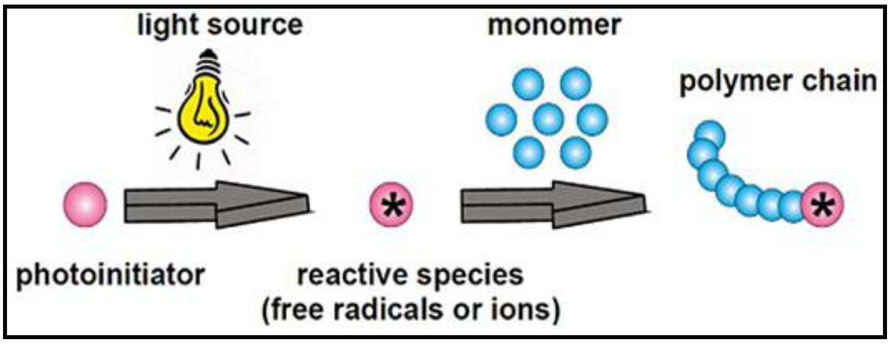

Figure2.13: Photo initiated polymerization (Yusuf et al, 2010)

2.5.3 Previous study for material preparations.

Table 2.3 shown the material preparation for their experiment.

Table 2.3: Previous study for material preparations

Research team	Light source	Materials compositions	Experiment environments
Mohamed Ashraf (2012)	LCD projector	- 1,6 - HexanediolDiacrylate (HDDA; CAS 13048-33-4) as photoreactive polymers – 98 ml - Phneylbis (Irgacure 819; CAS 162881-26-7) as photoinitiator) (2% by weight of HDDA) as photoabsorber - Sudan 1; (CAS 842-07-9) - concentration from 0.002%, 0.003%. and 0.006% by weight in HDDA	Atmosphere
Matthew Paul Alonso (2010)	LED	- 1, 6 - hexanediol diacrylate (HDDA; CAS 13048-33-4) - 1-phenylazo-2-naphthol (Sudan 1; CAS 842-07-9) (0 – 1.5% by weight in HDDA) as photoabsorber - phenylbis (2, 4, 6-trimethylbenzoyl) phosphine oxide (Irgacure 819; CAS 162881-26-7) as a photoinitiator fixed at a concentration of 2% by weight	Atmosphere and Nitrogen Environment
Ameya Shankar Limaye (2004)	UV lamp	- DSM SOMOS 10120 (composition is not mentioned)	Atmosphere

2.6 Polymerization process

Loosely defined, polymerization is the process of linking small molecules (known as monomers) into chain-like larger molecules (known as polymers). When the chain-like polymers are linked further to one another, a cross-linked polymer is said to be formed. Photo-polymerization is polymerization initiated by a photo-chemical process whereby the starting point is usually the induction of energy from an appropriate radiation source.

Polymerization of photo-polymers is normally an energetically favourable or exothermic reaction. However, in most cases, the formulation of photo-polymer can be stabilized to remain unreacted at ambient temperature. A catalyst is required for polymerization to take place at a reasonable rate. This catalyst is usually a free radical which may be generated either thermally or photo-chemically. The source of a photo-chemically generated radical is a photo-initiator, which reacts with an actinic photon to produce the radicals that catalyse the polymerization process. Figure 2.14 show schematic for a simplified free radical photo polymerization.

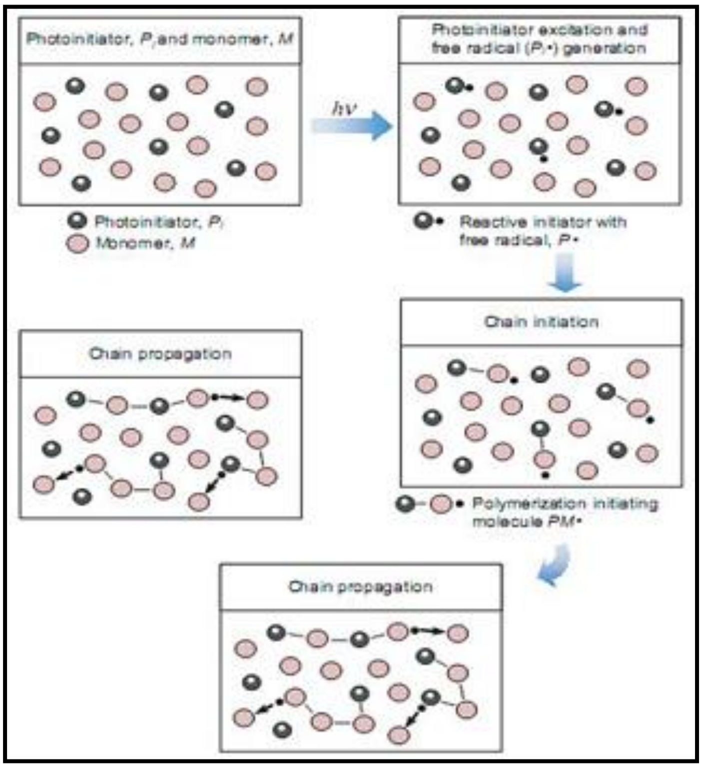

Figure 2.14: Schematic for a simplified free radical photo polymerization (Yusof et al, 2010)

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