

AN INVESTIGATION ON THE PRINTING OF METAL AND POLYMER POWDERS
USING ELECTROPHOTOGRAPHIC SOLID FREEFORM FABRICATION

By

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by

Ajay Kumar Das

Dedicated to my mother.

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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	xi
ABSTRACT	xv
CHAPTER	
1 INTRODUCTION	1
Electrophotographic Solid Freeform Fabrication (ESFF)	1
Past Research and Motivation for the Present Work	2
Chapter Layout	3
2 RAPID PROTOTYPING.....	6
Stereolithography Apparatus (SLA)	8
Solid Ground Curing (SGC)	9
Selective Laser Sintering (SLS).....	10
Fused Deposition Modeling (FDM)	11
Laminated Object Manufacturing (LOM)	12
3-D Printing	14
3 ELECTROPHOTOGRAPHY.....	16
The Electrophotographic Process	16
Photoconductor Material	18
Dark Decay	18
Charge Acceptance	19
Image Formation Time	19
Image Stability.....	19
Residual Image	19
Material Selection.....	20
Charging	21
Corona Charger	21
Charge Roller	23
Imaging.....	23

Development.....	24
Cascade Development	25
Magnetic Brush Development.....	26
Conductive Magnetic Brush Development	27
Mono-component Development.....	28
Charged and Discharged Area Development	28
Toner Powder Charging	30
Transfer.....	32
Fusing	33
Cleaning.....	33
4 ELECTROPHOTOGRAPHIC SOLID FREEFORM FABRICATION (ESFF).....	34
Development of ESFF Test-bed System.....	35
Motion Control System	36
Printing	37
Fusing	37
Software.....	38
Measurement of Charge and Mass of Powder.....	39
Measurement of Powder Properties.....	40
Improvement of Print Quality.....	40
Limitation on Part Height.....	40
Edge Growth (Solid Area Development)	42
Printing of Powders other than Toner.....	43
Study of Laser Imager System of Printer	45
5 DESIGN AND TESTING OF IMAGE DEVELOPERS.....	47
Developer Design	48
Powder Box	50
Developer Roller	50
Developer Roller Casing	51
Pivoting Blade Powder Developer	53
Development of Charge and Mass Measurement Test Setup.....	56
Discussion on Development of First Test Setup and Testing Concepts.....	56
Improvement in the Design of Test Setup.....	59
Independent Charge and Mass Measurement Test Setup	63
Design Considerations.....	64
Stages of Charge and Mass Measurement Test Cycle.....	67
Design and Building of the Charge and Mass Measurement Test Setup	68
Transfer Drum Assembly	68
Cleaner Box Assembly	70
Motor and Stand Assembly	71
Experimental Results	73
Experiments with Iron Powder.....	73
Experiments with Nylon – 12 Powder.....	75

6	METAL POWDER DEVELOPMENT AND PRINTING.....	77
	Metal Powder Development	78
	Metal Development Theory	80
	Constant Parameters used in Calculations.....	80
	Charge per Unit Mass (Q/M) Calculations.....	81
	Maximum Surface Charge Density	83
	Electric Field Range	84
	Calculation of Forces Involved During Development.....	85
	Calculation of Maximum Powder Particle Radius for Development.....	86
	Metal Powder Transfer Process Theory	87
	Powder Transfer Methods	88
	Capacitor Method of Powder Transfer (Conceptual)	89
	Experimental Results	91
	Determination of Discharging Voltage	92
	Determination of Frequency of Discharging Voltage	94
	Variation of Powder Development with Voltage	95
	Calculating Mass of Monolayer Development.....	97
	Variation of Powder Developed with Development Gap.....	99
	Powder Transfer Experiments	101
	Powder transfer on printed toner layer	103
7	POLYMER POWDER DEVELOPMENT AND PRINTING	107
	Test of Powder Properties.....	108
	Resistivity Test	108
	Permittivity Measurement	110
	Test of Development Characteristics of Polymers	113
	Experimental Setup	114
	Polyvinyl Alcohol.....	115
	Nylon – 12	116
	Nylon – 6	116
	ABS (Acrylonitrile Butadiene Styrene).....	117
	PVC (Polyvinyl Chloride)	117
	Discussion.....	118
8	FLAT PHOTOCONDUCTOR PLATE TEST BED	120
	Electrophotography Cycle and Test Bed Design Concept	122
	Charging	123
	Imaging.....	123
	Developing	124
	Printing	125
	Fusing and Compacting	125
	Cleaning and Discharging	125
	Photoconductor Plate Motion.....	126
	Photoconductor Plate.....	126

Design and Building of Charger-Imager-Developer Assembly	128
Developer Design	129
Developer Design	130
Charger-Imager-Developer Assembly.....	132
Experiments and Results.....	135
Metal Powder Development using Flat Photoconductor Plate Test Bed	135
Polymer Powder Development using Flat Photoconductor Plate Test Bed	139
Printing of Polymer using Flat Photoconductor Plate Test Bed.....	140
9 CONCLUDING DISCUSSION AND FUTURE WORK.....	146
APPENDIX	
MEASUREMENT WITH KEITHLEY ELECTROMETER	150
Resistivity Measurement using Keithley 6517A Electrometer and Test-point Software	150
Permittivity Measurement Using Keithley 6517A Electrometer and Test-point Software	153
Step by Step Procedure for Performing the Tests:.....	156
Common Steps for All Tests	156
Steps for Resistivity Test.....	156
Connections	156
Software	157
Steps for Permittivity Test.....	157
Finding Time Constant.....	157
Finding Resistance	158
Finding Permittivity	158
LIST OF REFERENCES.....	159
BIOGRAPHICAL SKETCH	161

LIST OF TABLES

<u>Table</u>	<u>page</u>
5-1 Q/M and M/A calculations of toner using QMM test setup.....	61
5-2 Variation of the Q/M readings with the number of revolutions of the transfer roller	73
5-3 Variation of Q/M measurement with the increase in voltage supplied for development while the number of revolutions of the transfer drum remains constant.....	74
5-4 Variation of the Q/M readings with the number of revolutions of the transfer roller	75
5-5 Variation of Q/M measurement with the increase in voltage supplied for development while the number of revolutions of the transfer drum remains constant.....	76
6-1 Experiment to determine the effective discharging and neutralizing ac voltage	93
6-2 Experiment to determine the frequency of the ac voltage for effective discharging	94
6-3 Experiment to determine the dependence of powder development on the development voltage applied to developing electrode	96
6-4 Experiment to determine the relation of powder development with gap between the two electrodes.....	100
6-5 Measurement of efficiency of powder transfer from developed electrode to transferred electrode.....	103
6-6 Iron powder transfer on previously printed and fused toner layer by applying positive voltage to the build platform	105
6-7 Iron powder transfer on previously printed and fused toner layer by applying negative voltage to the transfer plate.....	105
7-1 Resistivity of polymer powders in Ω cm.....	110

7-2	Resistivity of polymer powders calculated above in Ω m.....	110
7-3	Resistance values of the polymer powders	111
7-4	Time constants of the RC discharge curve.....	112
7-5	Permittivity of polymer powders.....	113
8-1	Development of iron powder by providing voltage to the development roller and grounding the photoconductor plate (Data 1).....	136
8-2	Development of iron powder by providing voltage to the photoconductor plate and grounding the developer roller (Data 2)	136
8-3	Development of iron powder by charging the photoconductor surface and grounding both photoconductor and developer roller (Data 3).....	136
8-4	Amount of powder developed with change of voltage in the positive range	139
8-5	Amount of powder developed with change of voltage in the negative range	139

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
2.1 Flowchart of the Rapid Prototyping Process.....	7
2.2 Schematic of Stereolithography Apparatus (SLA).....	8
2.3 Schematic of Selective Laser Sintering (SLS)	11
2.4 Schematic Representation of Fused Deposition Modeling (FDM).....	12
2.5 Schematic Representation of Laminated Object Manufacturing (LOM).....	13
2.6 Schematic Representation of 3D Printing Process	15
3-1 Schematic of the Electrophotography Print Cycle	17
3-2 Schematic of Corotron Charger.....	22
3-3 Schematic of Scorotron Charger	22
3-4 Image Formation in Organic Photoconductor Drum by UV Laser.....	24
3-5 Schematic Representation of Developer System.....	25
3-6 Schematic of Cascade Development	26
3-7 Magnetic Brush Development System	27
3-8 Charged Area Development (CAD).....	29
3-9 Discharged Area Development (DAD).....	30
3-10 Schematic of Transfer of Toner to the Paper	32
4-1 The ESFF Test-bed.....	36
4-2 Parts Printed using Corona Charging of the Top Printed Layer before the Next Print.	41
4-3 Parts Printed Using Patterns.....	43

4-4	Toner Powder Printed over Insulating Alumina Powder Bed.....	44
4-5	Diagram of Laser Jet 4 Imager Assembly.....	45
5-1	Solid Model Assembly of Powder Developer.....	49
5-2	Front End of the Toner Powder Cartridge.....	52
5-3	Cross-section of Developer Assembled with the Front End.....	52
5-4	Solid Model of Developer Assembly for Pivoting Doctor Blade Powder Developer (with Cross-sectional View).....	54
5-5	Cross-sectional View of the Developer Assembly.....	55
5-6	Cross-section of Developer Front End Assembly with the Pivoted Doctor Blade.....	55
5-7	Schematic of Charge and Mass Measurement Test Setup.....	56
5-8	Charge Measurement Setup for Direct Charge Measurement.....	57
5-9	Solid Model of the Assembly of Toner Powder Developer and Charge and Mass Measurement Test Setup.....	59
5-10	Cross-section View of Charge and Mass Measurement Test Setup.....	60
5-11	Solid Model of Assembly of Developer and Charge and Mass Measurement Test Setup.....	62
5-12	Cross-section of Charge and Mass Measurement Test Setup with Improved Developer Assembly.....	63
5-13	Schematic Illustration of Behavior of Conductive Powder Particle in the Presence of Conductive and Insulative Electrode Surfaces.....	65
5-14	Different Stages of the Test Cycle with respect to the Cross-sectional view of the Charge and Mass Measurement Test Setup.....	67
5-15	Solid Model of Transfer Drum and Cleaner Box Assembly (with cross-sectional view).....	69
5-16	Front view and Side Cross-sectional view of the Transfer Drum Assembly and the Cleaner Box Assembly.....	71
5-17	Solid Model of Motor and Stand Assembly.....	72
5-18	Complete Assembly of Powder Developer with Charge and Mass Measurement Test Setup.....	72

6-1	Concept of the New Modified Test Bed.....	78
6-2	Forces Acting on a Powder Particle During Development	81
6-3	Schematic Model of the Capacitor Method of Powder Transfer (Conceptual)	90
6-4	Schematic of the Test Setup for Development.....	92
6-5	Plot of Variation of Mass of Powder Developed with respect to the Surface Voltage Available for Development.	97
6-6	Dimensions of the Milled Slot	98
6-7	Packing of Iron Powder Particles in a Monolayer.....	98
6-8	Graph Showing Decrease in Amount of Developed Powder with Increase in the Gap Between the Powder and the Insulated Electrode.....	101
6-9	Schematic for Test Setup for Powder Transfer	102
7-1	Schematic of Resistivity Test Cell	108
7-2	Schematic of Capacitance Test Cell.....	111
7-3	Cross-section of Polymer Powder Developer	114
8-1	Schematic of the Concept of Flat Photoconductor Plate Test Bed Assembly	122
8-2	Schematic of Laser Imager.....	124
8-3	Solid Model of Photoconductor Belt Assembly.....	128
8-4	Solid Model of the Powder Developer Assembly	130
8-5	Cross-sectional view of the Powder Developer Assembly	131
8-6	Solid Model of Charger-Imager-Developer Assembly	132
8-7	Cross-section of Charger-Imager-Developer Assembly	133
8-8	Cross-sectional Image of Charger-Imager-Developer Assembly with Photoconductor Belt Assembly on top.....	134
8-9	Close-up of Solid Model of Test Bed showing the Flat Photoconductor Plate Developer Assembly	135
8-10	Charge Flow Through the Ground during Development	137

8-11	Variation of Amount of Powder Developed with Change in Voltage	138
8-12	Electrodes Shaped in Different Patterns.....	141
8-13	Patterned Electrodes after Developed with Nylon – 12 Powder	142
8-14	Build Platform for Printing Nylon – 12	142
8-15	Intended Assembly of Patterns.....	143
8-16	Actual Printing of Assembly of Patterns using Nylon – 12	143
8-17	Print of Assembly of Patterns on PET Sheet Surface.	145
A-1	Parallel Plate Powder Resistivity Test Cell.....	152
A-2	Test Window for Resistivity Measurements.	153
A-3	Parallel Plate Powder Capacitance Test Cell.	154
A-4	Hi-R Step Response Window.....	155
A-5	Step Response Settings.....	155

Abstract of Thesis Presented to the Graduate School
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Electrophotographic solid freeform fabrication (ESFF) is a novel method of manufacturing which is under development at the Design and Rapid Prototyping Laboratory of the Department of Mechanical and Aerospace Engineering at University of Florida. Electrophotographic solid freeform fabrication uses the principle used in laser printer to print layers of material, one over the other, to form the final three dimensional objects. In past experiments a test bed was built to test the concept of printing in layers using toner powder. Toner powder was successfully shown to be printed in layers.

The material used as the toner powder is not suitable as a structural or functional material, and there was a need to explore the use of other materials including metal and polymer powders as structural material in layer by layer printing using ESFF. Powder developers were designed to develop thin uniform layers of metal or polymer powders on the photoconductor surface. A Charge and mass measurement test setup was built to evaluate these developers on the basis of their ability to charge the powders and the

amount of powder developed. The powder properties and development and transfer characteristics were studied for metal and polymer powders.

A simpler version of the test bed to develop and print metal and polymer powders was proposed. This new concept was less dependent on available commercial laser printing technology and was based on development of powder on a flat photoconductor plate. This concept made the design modular for easy setup and debugging purposes. A developer was designed to print upwards against gravity on a photoconductor plate (facing downwards). This developer was assembled with the charge roller and the laser imager assembly. A flexible build platform was assembled which could align itself to the photoconductor plate orientation for effective transfer of powder layers. The developer was tested for its efficiency in charging and developing powders. The developed powder was then transferred on the build platform to test the ability of the test setup to print powders in layers.

CHAPTER 1 INTRODUCTION

Rapid prototyping is a manufacturing technology that produces objects layer by layer without the need of elaborate tooling and clamping. The objects can have simple or complex geometries and can take any freeform shape. Manufacturing of these freeform objects in small quantities was expensive by conventional machining processes, but can now be achieved by rapid prototyping systems at a relatively low cost.

Electrophotographic Solid Freeform Fabrication (ESFF)

Electrophotographic solid freeform fabrication (ESFF) is a rapid prototyping technology based on electrophotography, which is under development at the University of Florida. Electrophotography is used in copiers and laser printers to print loose dry toner powder on paper and then fuse the powder to get the final permanent print. Electrophotography is based on a special property of some materials (photoconductors), which are generally insulators, but become conductive when light of a characteristic range of wavelengths is shined upon them. In electrophotography, a charge of either polarity is deposited and a laser is then shined on the photoconductor at specific spots to make the material conductive and discharge the surface at those spots. This creates an image of charged or discharged area, which is used to pick up charged powder particles using electrostatic force. This powder layer is then printed on a substrate (in the case of a printer it is paper), and then fused by applying heat to get the final print.

ESFF technology is being developed to use this concept to build objects by printing multiple layers of different materials. ESFF has some unique capabilities over other

commercially available rapid prototyping options on different counts. It has a higher resolution (600-1200 dpi) and can produce objects having fine details. This technology can produce blended objects with predetermined compositions. This makes it a suitable technology for semiconductor and electronics industry applications to produce miniature circuits and components.

Past Research and Motivation for the Present Work

Past works on the development of this technology were done mainly to understand electrophotography and study its behavior when used for printing multiple layers of toner powder. A test bed was built using a modified laser printer to print toner on a moving platform. The printed powder layer over the build platform was then moved under a fixed plate heater and compacted and fused to bind the loose powders. Experimental studies were done to find out the physical properties of toner, charge per unit mass (Q/M), mass per unit area (M/A), resistivity, permittivity and mass density. These are the important properties of toner, which affect the printing process and print quality. A number of models were proposed to explain the behavior of powder during development and transfer. Software was written to slice the 3D model of the object and then send the cross-sectional image to the printer to print.

The need to study the feasibility of printing powders other than the toner powder was the starting motivation for the work presented in this thesis. The physical properties including the resistivity, permittivity and mass density were measured and reported for polymer powders. To measure the charge per unit mass (Q/M) for powders, a test setup was built and experiments were done on it find out Q/M values for iron and polymer powders. A number of developers were designed and tested for their effectiveness to replace the toner powder developer in the laser printer and print powders directly on to

the photoconductor drum. The difficulties associated with the old ESFF test bed design were identified and a new design based on a flat photoconductor plate was proposed. The design and fabrication of the charger imager and developer assembly were done. A number of tests on the development characteristics of metals and polymers were conducted to identify suitable conditions for maximum development. Theoretical models were developed and analyzed for estimating the parameters and their influence on the development process.

To summarize, the thesis work presented in this text presents the effort to develop and print metal and polymer powders. The physical properties of the powder particles were determined and their suitability to be used as a structural material for ESFF applications was evaluated. A test bed was built to make it easier to develop and transfer powders of any kind. This research paves the path for further tests and experiments to determine the feasibility of this technology to print powders other than toner in layers to build three-dimensional objects.

Chapter Layout

The first chapter is a short introduction to the overall research project and the motivation behind the current research work and its significance in the overall development of the ESFF technology.

The second chapter discusses the rapid prototyping technology, how it is different from the other manufacturing technologies and its significance in the manufacturing world. Then different rapid prototyping technologies are discussed in brief with illustration.

The third chapter discusses electrophotography and its growth as a technology applied to laser printers and photocopiers. It describes the different components of

electrophotography and the way they influence the quality of print. The chapter also discusses various development techniques and the behavior of powders of different materials during electrophotography.

The fourth chapter presents the Electrostatic Solid Freeform Fabrication (ESFF) as an alternative rapid prototyping technology. It starts with an introduction to the concept of ESFF, and then goes on to describe the first design of the test bed. Brief highlights of the past works on this technology are discussed and the results that were obtained from those works are summarized.

The fifth chapter describes the evolution in the design of the powder developer and its evaluation at each stage by using charge per mass (Q/M) measurement device. The detailed design of the improved charge and mass measurement device is explained and the functions of the components are discussed. Finally, the results from charge and mass measurements from metal and polymer powders are reported.

The sixth chapter discusses the theory behind metal powder development and printing. The forces involved during development and printing of metal powders are identified and force equations are solved to determine critical parameters, including the particle size, and the magnitude of field developed. The methods of charging, developing and transferring powders are discussed with reference to their efficiency in printing powders. Experimental results found by preliminary tests done using iron powders are presented.

The seventh chapter discusses polymer powders and their properties, and the effectiveness of development and transfer by using them in the new test bed setup. The test results providing information about the resistivity, permittivity and mass density of

some polymer powders are presented. There is also a discussion on the behavior of these powders when they were developed on a photoconductor drum. The results indicated Nylon – 12 is the best suited powder to be used as a sample polymer for all further theoretical and experimental calculations.

The eighth chapter introduces the flat photoconductor plate test bed as a better alternative to the test bed based on commercial laser printers. The important features of the new test bed are highlighted and design challenges are discussed. The design of upward-facing developer and the assembly of charger, imager, and developer are described in detail. Experimental results from the use of iron and nylon – 12 powders in the improved test bed are presented.

Finally, the ninth chapter discusses the conclusions drawn from the theoretical and experimental work presented in this thesis. It also suggests the opportunities for future research on this project to develop it as a successful rapid prototyping technology.

CHAPTER 2 RAPID PROTOTYPING

Rapid prototyping is also known as Solid Freeform Fabrication and Layered Manufacturing. Each of the three names stands for an important characteristic of this technology. Rapid prototyping defines it as a technology to produce prototypes of conceptual models quickly without the need of any elaborate tooling and fixture design. The ability of rapid prototyping units to produce design prototypes quickly, shortens the design iteration cycle time significantly. In comparison conventional machining is faster than rapid prototyping, with tooling and fixtures in place. Machining process is also faster and economical when it comes to mass production of components. Solid freeform fabrication refers to the fact that this technology can be used to produce solid objects with any freeform surface. The last term, Layered Manufacturing, signifies that in this manufacturing technology objects are produced in layers.

In rapid prototyping the conceptual 3D solid model is first sliced into two dimensional layers using slicing algorithms. Each of these layers is the cross-sectional image of the object at a particular z – level. These layers are created one over another by using methods particular to different rapid prototyping technologies. Support structure is also provided along with the part building process to provide support to any overhanging structure in the part. In rapid prototyping there is no restriction on the structure and shape of the object as long as it can be sliced into layers and built within the space limitation of the machine. This allows the freedom to produce objects with any freeform surface as

desired. The activities, which are central to all rapid prototyping technologies, are presented in the form of a flowchart below.

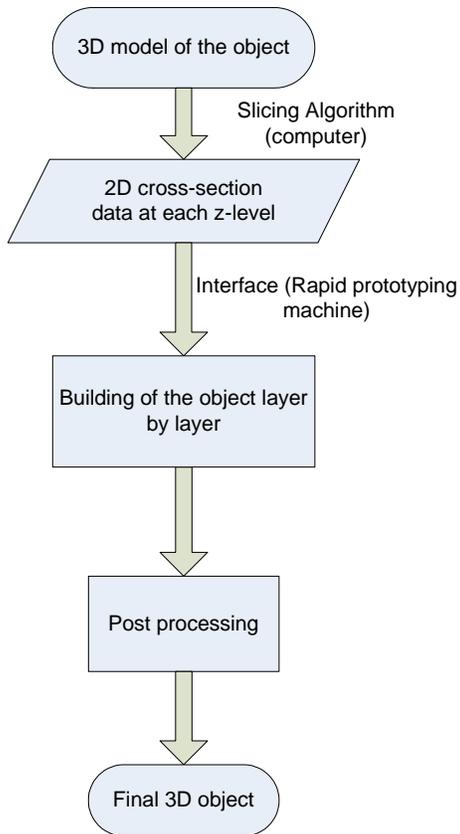


Figure 2.1 Flowchart of the Rapid Prototyping Process

There are many successful commercial rapid prototyping technologies, which are available in the market and there are others which are in their developmental stage and hold a lot of promise of becoming successful in future. The rapid prototyping technologies are characterized by

- material used to build the object
- process of binding layers together
- speed of build process and post processing requirements
- limit on the choice of geometry of the object that can be built

The process that is best suited for the given application is chosen from all different options based on the above criteria. Some successful commercial technologies are presented below.

Stereolithography Apparatus (SLA)

Stereolithography is based on the property of certain polymers, called photopolymers that solidify when UV light is shined upon them. The setup is made of a build platform immersed in a liquid polymer container. UV laser is shined on the polymer after being reflected by a mirror to form a crosshatch pattern on the polymer surface. The laser can penetrate only a small depth into the liquid and so it can harden only a thin layer of liquid polymer on the build platform in one scan of the surface. This is a limitation on the speed at which the object is built. Support structures are also built along the building of part, which are difficult and expensive to remove during post-processing. The schematic below shows the setup for a typical SLA machine.

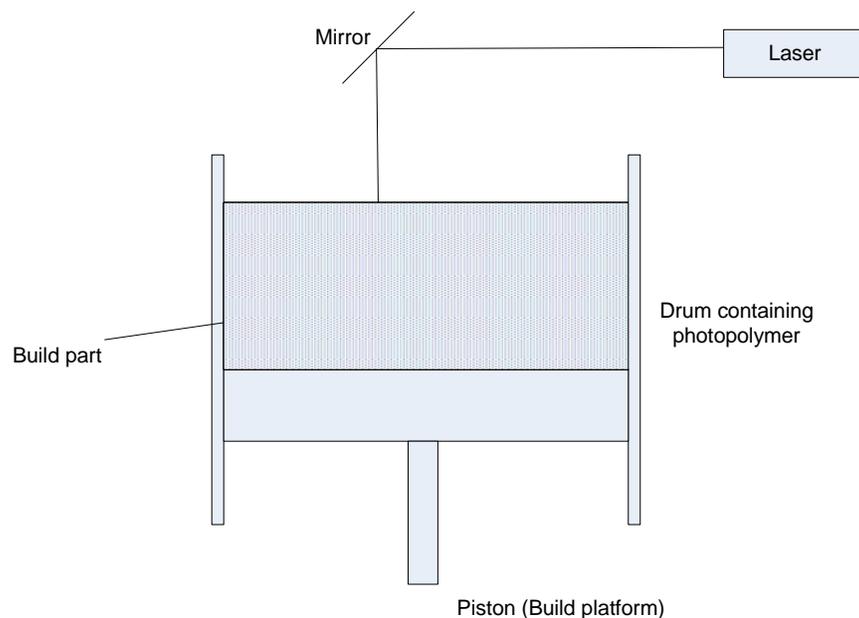


Figure 2.2 Schematic of Stereolithography Apparatus (SLA)

SLA is one of the earliest rapid prototyping technology, and first to be commercialized. It popularized the concept of rapid prototyping and was able to build objects, which were difficult to make conventionally. There can be unattended and continuous operation for 24 hours. The expensive and sophisticated process requirements made it prohibitive for wide use. Post processing also takes long time and the surface finish and tolerance is poor when compared to conventional machining due to non-uniformity of solidification of the photopolymer by laser.

Solid Ground Curing (SGC)

Solid ground curing (SGC) is another technology based on the same principle as SLA, which is hardening of photopolymer by using UV light. The difference is that in this technology hardening of the surface is done through a mask, which helps in hardening of the whole surface at once rather than tracing with a laser as in SLA. The mask is prepared by photocopying technology, which prints each cross-section on a glass plate, which is renewed by erasing the print. This is done in a separate process cycle called Mask Plotter cycle, which is different than the actual build cycle called Model Grower cycle.

In the model grower cycle the glass plate from the mask plotter cycle is used and a UV flashlight is shined through the glass plate on the polymer surface. The unused polymer is removed and the area is filled by wax. Wax solidifies and gives a strong support to the build structure. The surface of this layer is milled to make the layer uniform. This produces objects with high dimensional accuracy, as there is uniform hardening and avoidance of material tensions. Removal of support structure is easy as the wax can be melted and removed. An important disadvantage of the method is the

sophisticated equipment, which prohibits unmanned manufacturing process. This process also takes a long time because of the elaborate procedure involved.

Selective Laser Sintering (SLS)

Selective laser sintering (SLS) produces parts by heating powders on a powder bed to the temperature just below their melting point temperature. At these conditions the particles sinter and form strong bonds to build the object. The powder is stored in a reservoir and brought out by a piston. The powder layer is then spread uniformly on the top of the build platform by a leveling roller. Then a high power carbon dioxide laser is shined on this powder bed tracing the outline of the cross-section. The temperature of the powder inside the cross-section is raised to just below its melting point by scanning of the laser in a cross-hatch pattern so that the powder layers sinter and combine to form a solid mass. As the process is repeated, layers of powders are deposited and sintered to form the final object. The loose powder that was not sintered provides a natural support for the built part. The finished part can be easily taken out of the powder bed and the loose powder on the surface can be removed by blowing off with pressurized air. The schematic below shows the SLS process.

The SLS process has its own advantages and disadvantages. The advantage lies in the fact that this technology can be used for a variety of materials including different kinds of polymers and metals. The process is also fast with a build rate up to one inch per hour. Post processing is easier as the parts that come out have full strength and do not require additional processes. The major disadvantage of this method lies in the poor geometric accuracy and grainy surface finish. This is mainly dependent on the powder particle size. There is also the possibility that the neighboring powders, along the part boundary, may get sintered and become unwanted part of the object. The process is done

in a nitrogen chamber, and so nitrogen has to be continuously provided to the chamber. Also during sintering, toxic gases are released and have to be handled carefully. This mostly happens when sintering polymers.

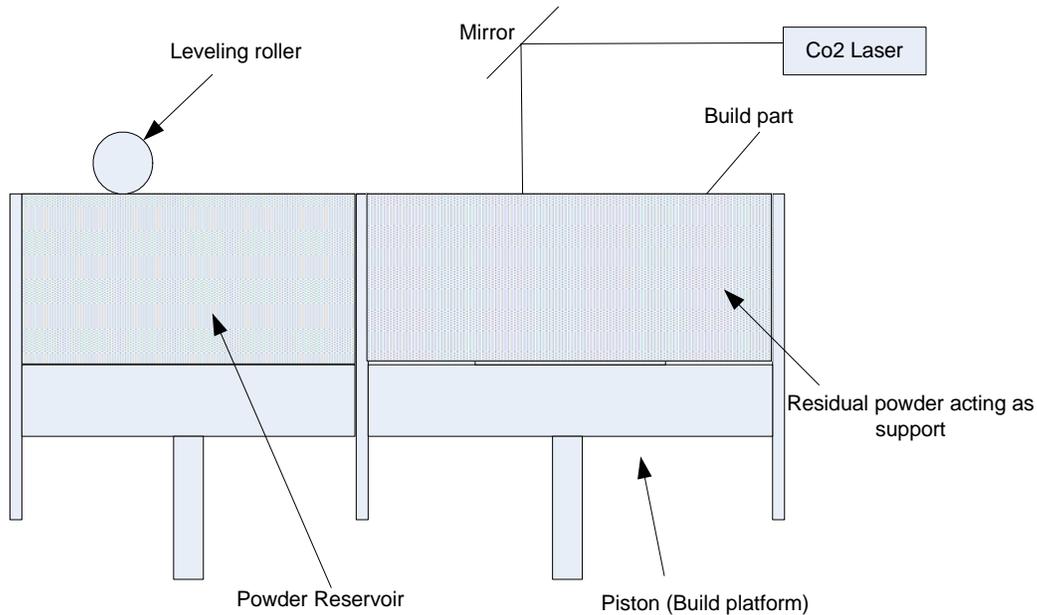


Figure 2.3 Schematic of Selective Laser Sintering (SLS)

Fused Deposition Modeling (FDM)

As the name suggests in the Fused Deposition Modeling (FDM) method certain material (plastic filament) is melted and deposited on a build platform in layers to form the final object. The part material is available in the form of filaments, which are coiled in the form of spools. These filaments get heated up when they are passed through a nozzle (FDM head), and the material leaves the nozzle in liquid state. This liquid material solidifies immediately at the ambient temperature. Due to this the nozzle has to be very close to the build platform while tracing the model cross-section. The FDM head is capable of translating in the X and Y directions and the build platform moves in the Z direction to accommodate the layer build height. The FDM head first traces the outline of the cross-sectional area and then fills the area with densely packed crosshatch pattern. In

addition to the part material nozzle, there is another nozzle which deposits the support material where needed. The support material is also a polymer filament, which is melted and deposited on the build platform along with the part material. This is a different polymer than the part material and is deposited to form thin wafer-like structures, to support the part material during building process and can be peeled off very easily using a little mechanical force. The schematic in figure 2.4 shows the concept of FDM technology.

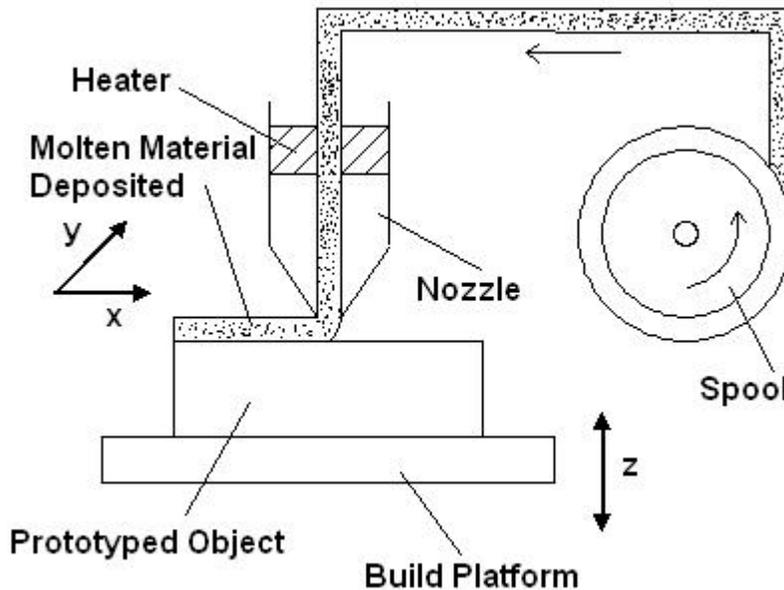


Figure 2.4 Schematic Representation of Fused Deposition Modeling (FDM)

The simplicity of the procedure makes this technology very popular and easy to setup and use. The procedure requires no cleaning and produces no waste, and no post-curing is required. As the filament has a diameter of 1.27mm, the resolution and dimensional accuracy is affected.

Laminated Object Manufacturing (LOM)

Laminated object manufacturing (LOM) is based on the simple method of sticking together thin sheets of material each representing the cross-section of the object at a

particular given height. The setup for LOM consists of a thin ribbon of sheet material wrapped around a supply roller and a take up roller passing over the build platform supported by several idler rollers. The sheet material starts from the supply roller and stops on the build platform. Then a heated roller is rolled over the piece of the ribbon on the build platform, which binds the sheet material to the top of the stack. A high power CO₂ laser is shined on the sheet material, after being reflected by mirrors that control the X and Y movement of the laser beam. The movement of the build platform provides the Z-axis movement. After the sheet material is bound to the top of the stack of sheets, the laser traces the boundary of the cross-section cutting it out of the sheet material. The unwanted portion is diced by the laser beam into crosshatched squares that provides support to the part. The remaining material is waste and is rolled around the take-up roller. By binding sheets one on top of the other the final object is produced.

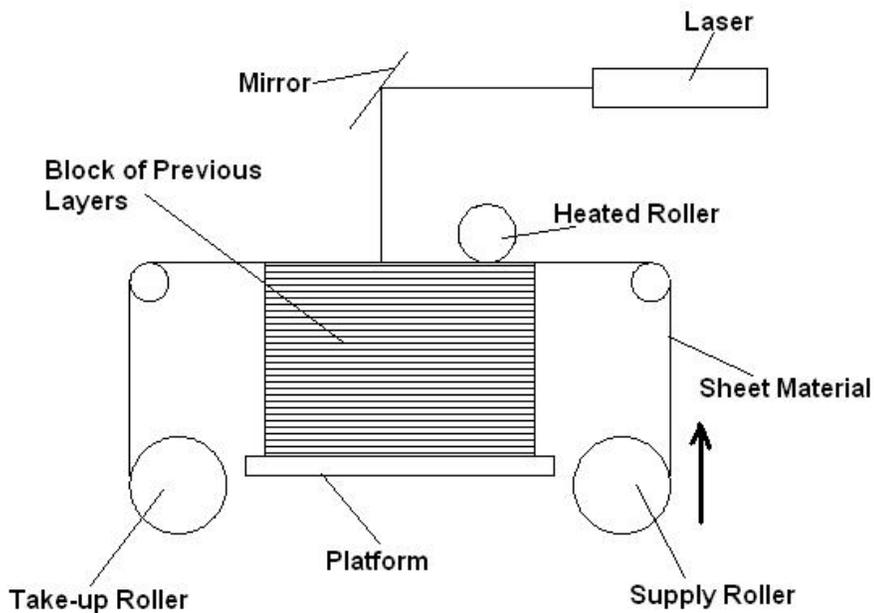


Figure 2.5 Schematic Representation of Laminated Object Manufacturing (LOM)

The object comes as embedded inside the cubic structure formed by the bound sheets. The post processing involves removing the unwanted material, which were diced during the building of the part. This process of dicing helps in easy removal of this unwanted material. A schematic of the LOM process is shown in the figure 2.5 above.

The ability to use a large variety of organic and inorganic materials is the biggest advantage of LOM technology. The process is also faster than the competitive technologies, as the laser has to only trace the outline of the cross-section and not the whole area. The layers stick to the stack very easily and so the process is faster. This method can be used to produce larger prototypes that are not possible by other technologies. The disadvantage of the method is that it produces parts with low strength in the Z-direction and so the objects produced cannot be used as functional prototypes. The other drawback of this system is that it produces a lot of waste during building of the object and during post-processing.

3-D Printing

The concept of 3-D printing is also based on gluing two layers together to form a part, but here the two layers are made of loose powders. The process starts with spreading of a thin uniform layer of powder. The powder layer is then selectively joined by ink-jet printing of binder material. The build platform, which is in the shape of a piston inside a cylinder containing the powder bed, is lowered and the next layer of powder is spread. The ink-jet print head scans the powder bed in the same way as it does while printing on paper. The only difference is that here instead of ink, binder material is used. The loose powder around the built part provides natural support and can be removed very easily during post processing. The part has green strength and can be consolidated by

application of heat, which will evaporate the binder. Figure 2.6 shows the schematic of detailed 3D printing process.

This method of rapid prototyping can be used to produce objects made of any material that can be powdered. When metal powder is used, the final part is put in the furnace to join the powder particles by melting. Copper infiltration is done to fill the pores left by evaporated binder to form dense and strong metal part. The disadvantage results from the granular nature of the material and the interactions between the binder and the powder. This has bad effect on the texture of the surfaces.

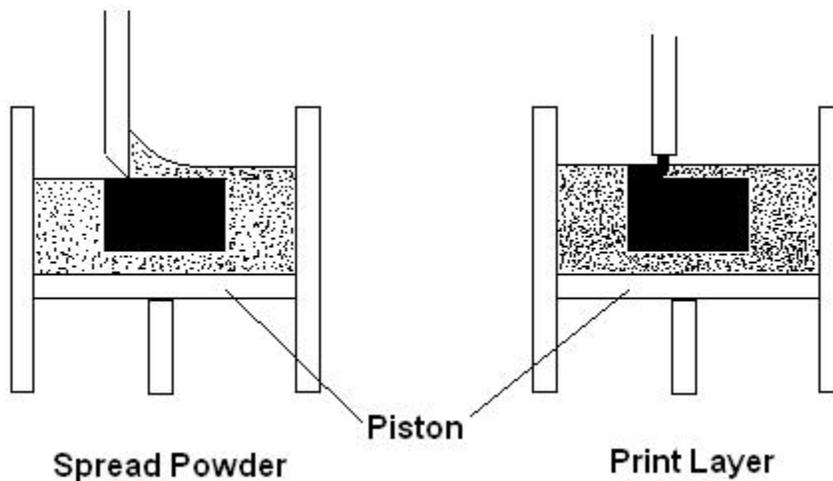


Figure 2.6 Schematic Representation of 3D Printing Process

CHAPTER 3 ELECTROPHOTOGRAPHY

Electrophotography is a method of printing image-wise arranged charged powders on a substrate and subsequently fused to form a permanent image. A special insulator material called photoconductor is used to form image patterns of charged or discharged areas by using its special property that turns it conductive when light of a particular wavelength falls on it. The photoconductor is applied as a coating on a roller or plate and is used for the charge imaging. The details of the working of the photoconductor material are explained later in the chapter. Figure 3-1 shows the electrophotographic cycle with the photoconductor material applied on a drum (photoconductor drum).

The Electrophotographic Process

The six major steps in electrophotography are

- **Charging:** In the charging process charge is deposited on the photoconductor surface.
- **Imaging:** In this process light of particular wavelength (in the form of laser) is shined on the charged photoconductor surface to discharge certain areas according to the image and produces either a charged image with discharged neighborhood or a discharged image with charged neighborhood.
- **Development:** In this step loose charged powder particles move towards the photoconductor surface due to the electrostatic force created between the photoconductor drum and powder. These powders get developed image-wise on the photoconductor surface due to attraction or repulsion by the charged areas on the surface according to the method used.
- **Transfer:** In the transfer process the image-wise developed powders are transferred on to a substrate either electro-statically or physically to form the print.
- **Fusing:** In this step heat is applied to the powder to melt it and fix it to the substrate to form the final permanent image.

- **Cleaning:** In this final step the photoconductor surface is cleaned off the residual powders remaining on its surface after transfer process. The photoconductor surface is also discharged to avoid the carry over of any charge patterns to the next print.

An example of electrophotography process is shown schematically in figure 3-1, which shows the way different steps are performed around a photoconductor drum. Most of the modern printers use photoconductor drums for printing as the drums help in making the design compact. This compact design makes it easy for the printer to be used easily as a desktop printer. All the processes are spread around the photoconductor drum and occur simultaneously in a cycle making printing faster. These processes are explained in detail below.

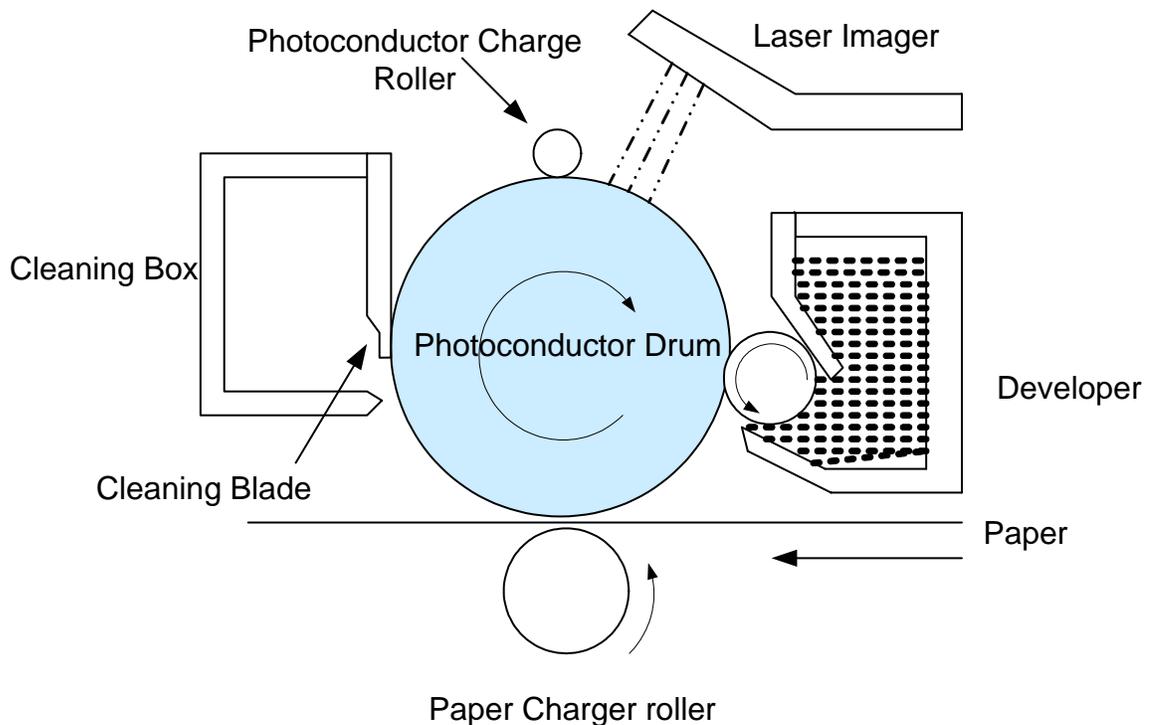


Figure 3-1. Schematic of the Electrophotography Print Cycle

As can be seen from the electrophotography print cycle, the photoconductor drum is central to the electrophotographic process. Therefore, it is essential to know more about the photoconductor and its characteristics to understand electrophotography.

Photoconductor Material

As discussed before, the photoconductor material has the unique property of becoming conductive when light of specific wavelengths falls on it. To form a charged image on the photoconductor drum, the drum is first charged with charge roller. Then the charged photoconductor surface is exposed to UV laser pulses which make the photoconductor material conductive and so the charge from the surface passes to the ground. This creates an image-wise charge distribution which picks up powder selectively. This powder image is then transferred to the build platform and fused to make a permanent image.

There are many materials that can be used as photoconductors and some of them were used in early versions of copiers and printers. The ones that were popular and widely used are amorphous selenium and organic photoreceptors. Amorphous selenium was used in the early generation of printers, while organic photoreceptors gained popularity later because of heavy demand of inexpensive compact desktop printers. The important parameters that are used to characterize a photoconductor are explained below.

Dark Decay

Dark decay is the ability of the photoconductor to retain the charged image when no light is falling on it. The photoconductor material is not a good insulator and even when no light is falling on its surface it allows charge leakage. The charge depletion is exponential in nature and the time in which the photoconductor loses half of its surface charge is called depletion time. Organic photoreceptors typically have shorter depletion time than amorphous selenium (Diamond 1991).

Charge Acceptance

The surface charge limit that can be deposited on the photoconductor surface is known as charge acceptance. This is generally decided by the dielectric property of the photoconductor material. The desirable surface charge on the photoconductor is what can be retained by the photoconductor and can create sufficient electric field to attract charged powders to get adhered to its surface. Anything more than this will increase the force of attraction between the powder and the photoconductor surface, which will make powder transfer difficult.

Image Formation Time

Image formation time is the time taken to discharge the photoconductor surface by imaging light. Image formation energy would have been a more specific term to consider, but in electrophotography it is time and not imaging light intensity, which is considered as an influencing variable. The speed at which printing is done is a more critical parameter to judge the efficiency of a copier or printer, which makes image formation time more critical.

Image Stability

Image stability is considered as the ability of the photoconductor to maintain a charged image on its surface. Image instability occurs due to the inability of the photoconductor to maintain a highly localized area of discharge on its surface against charge migration. Surface contamination also plays a role in migration and dissipation of charge on the surface itself.

Residual Image

Residual image occurs when the photoconductor surface is not completely discharged after the image transfer process. This can happen because of various reasons

and can be identified after many prints when images of previous prints, ghost images, begin to appear. To reduce this problem the photoconductor surface is cleaned and discharged after each print, but with high speed of print cycles this problem is not completely corrected.

Material Selection

As stated earlier, the amorphous selenium was replaced by more popular organic photoreceptor in the modern printers. This might seem counter intuitive since, compared to amorphous selenium, organic photoreceptors have less dark decay time and so cannot hold the image for a long time. Organic photoreceptors are softer and are prone to early wear and tear during operation and suffer gradual breakdown by environmental exposure.

The cost of organic photoreceptors is much less than amorphous selenium, even after considering the high frequency of replacing them during the printer lifetime. To help in maintenance of the photoconductor based on organic photoreceptor, it is made a part of the toner cartridge. While replacing or renewing the toner cartridge the organic photoconductor is inspected for any damage and recoated accordingly. This makes organic photoreceptor a popular photoconductor material for modern printers.

Dark decay is not much of a concern here because the modern printers and copiers have high-speed electrophotography cycles and the required time to hold charge and image is insignificantly small. Moreover amorphous selenium is sensitive to a wide range of wavelengths of light and has to be kept in a well covered dark area during operation which makes the printer design complicated. This is not a problem with the organic photoreceptor as it is only sensitive to a narrow band of wavelengths in the ultra-violet region, which makes it easier to use and results in a simpler printer design.

As can be seen from the last discussion, photoconductor material is the central to the electrophotography process. The following discussion describes in brief the stages which photoconductor goes through during electrophotography. As said before there are six steps in this electrophotographic print cycle. The cycle starts with charging of the photoconductor surface.

Charging

Charging is the first step in electrophotography. For a good print quality uniform charging of the photoconductor surface is necessary, which is done by depositing charge particles on the photoconductor surface. There are mainly two ways of charging; by using corona charger and by using charge roller.

Corona Charger

When high voltage is applied to a conducting body having low radius of curvature, high electric fields are generated locally which causes breakdown of air and ions are generated. This principle is put to practice in corona devices in which high voltage is applied to a thin wire enclosed in a metal shield at the same voltage, generally around 7000V (Schaffert 1975). This kind of device is called as corotron. In this the thin wire generates ions by dielectric breakdown of air and repels ions of the same sign. These ions are again repelled by the metal shield, which generates a steady stream of ions directed towards the body to be charged. There can be non-uniformity of charge generation due to ion winds and impurity on the wire due to toner and paper dust.

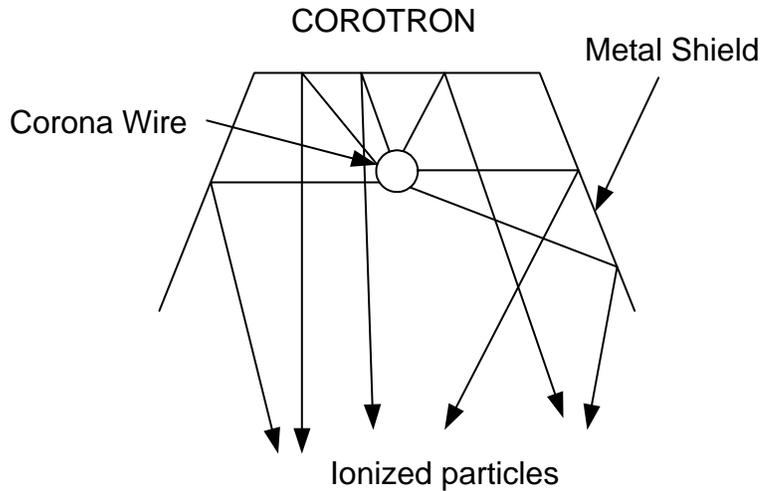


Figure 3-2. Schematic of Corotron Charger

To make the charge deposition more uniform, a device called as scorotron is used in which a screen is used to cover the opening of the metal shield. The screen restricts any ion that is not traveling perpendicular to the screen holes.

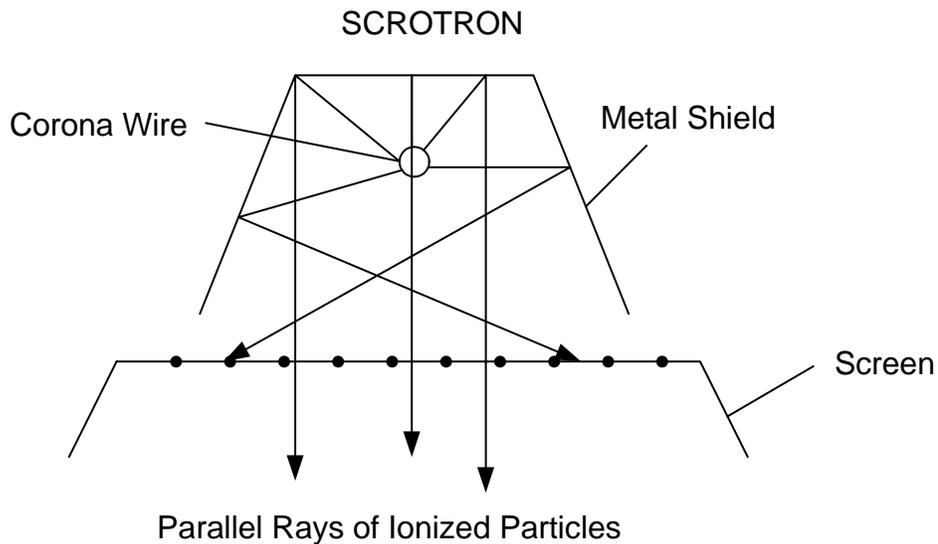


Figure 3-3. Schematic of Scorotron Charger

The corona charging device is associated with many reliability problems. It also generates ozone as a byproduct, which is harmful to health and has to be dissipated. All these problems associated with corona charger made this device less favored over the years.

Charge Roller

Roller charging is most popular method of charging in the modern printers. It is more compact and easy to use than the corona charger. The charge roller is made of a central metal rod covered by a thick layer of polymer material. This polymer is a special material due to its higher conductivity than regular polymer. The voltage applied to the charge roller is relatively lower than that applied to corona charger. When DC biased AC voltage is applied to the roller, small discharges occur between the irregular polymer surface and photoconductor surface (Hirakawa 1995). These small discharges deposit charge on the photoconductor surface. There is a uniform line contact between the charge roller surface and the photoconductor surface along the length of the photoconductor, which results in uniform charge deposition.

Imaging

After the photoconductor surface is charged, latent image is created on the surface by discharging the surface locally using laser of particular wavelength, which is in the UV range for organic photoconductors. The latent image is a charge pattern that mirrors the information to be transferred to the real image. The laser is shined on the photoconductor surface after getting reflected by a rotating polygonal mirror. The laser is turned on and off according to the image to create selective discharge points on the photoconductor surface. The print resolution is determined by the laser wavelength and the rate of switching of the laser.

The organic photoreceptor is divided into two layers. One is the charge generation layer (which is over the aluminum drum) and the other layer is the charge transport layer (which is over the charge generation layer). When UV laser falls on it, negative and positive charges separate and the charge which is of the opposite sign as the charge

deposited on the photoconductor travels to the surface and discharges the surface and the other charge flows to the ground through the drum.

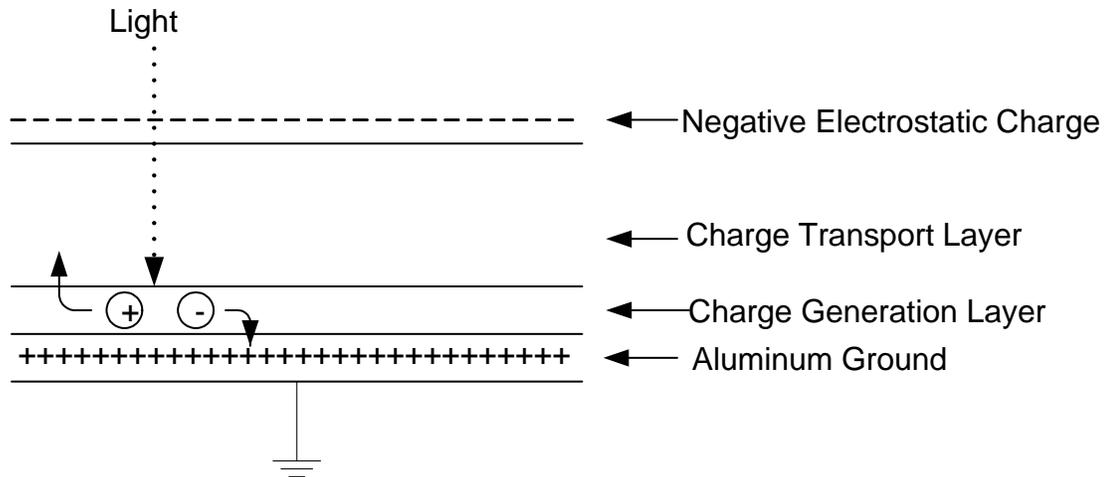


Figure 3-4. Image Formation in Organic Photoconductor Drum by UV Laser

Development

Development is the process of charging the toner powder and then transferring it on to the photoconductor surface. The charged toner powder experiences the electrostatic force due to the field created by charge distribution on the surface of the photoconductor drum and gets adhered to the latent image thus forming the real image.

The toner powder is an insulator and is triboelectrically charged to the required polarity. There are charge controlling agents added to the toner and they help in preferential charging of the toner with a specified polarity. The toner is brought into the vicinity of the photoconductor surface with the charged latent image. The amount of powder coming out of the powder reservoir is controlled by a doctor blade, which is a thin polymer or metal strip present at the opening for toner. The toner near the latent image jumps the gap between the developer and the photoconductor surface and gets developed. The schematic of a typical toner developer is shown in figure 3-5.

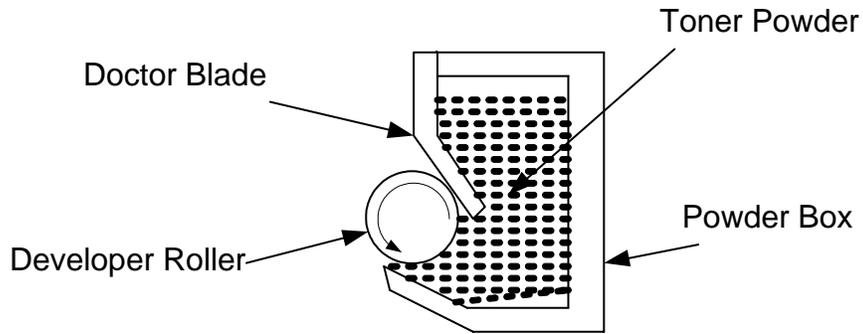


Figure 3-5. Schematic Representation of Developer System

Development is by far the most difficult process to understand and control. There has been a lot of research done on this subject resulting in gradual increase in understanding of the subject. The process was improved from cascade development to insulative magnetic brush development and then to the most efficient conductive magnetic brush development (Schein 1988). The toner used for these development techniques is a two-component toner, which has large carrier particles are covered with smaller toner particles. Some of the important development methods are discussed below.

Cascade Development

In cascade development the carrier beads covered with toner is made to flow over the photoconductor surface under the influence of gravity. The development using this method depends on a lot of factors including speed of fall of carrier beads, angle of the photoconductor plate to the horizontal and the bouncing of the beads. As the toner particles are attracted by the electric field generated by latent image rather than the charge itself, solid area development is very poor in this method, because the field generated by the charge image highest at the edges and decreases rapidly to the center of the image (Schein 1988). This is a very simple method of development and was used in the early printers and copiers.

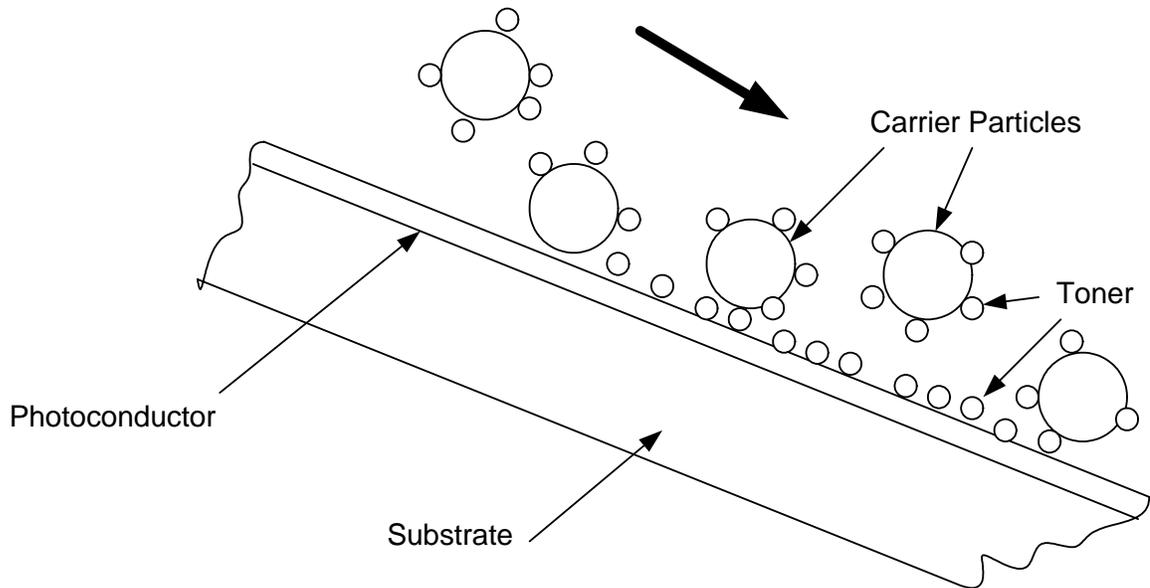


Figure 3-6. Schematic of Cascade Development

This method depends on a lot of parameters and forces and it is very difficult to control the powder behavior in these conditions. The development is not reliable and there is a lot of waste due to powder spillage. All these problems made this method less popular and there was a need for an alternative method of development and led to development of the magnetic brush development technology.

Magnetic Brush Development

Insulative magnetic brush development was a significant step in powder development history. In this method a roller rotates around a stationary magnet and carries magnetic carrier particles along with it by magnetic friction. The magnetic force provides a strong counter force for the electrostatic force and eliminates any other small forces that could bring uncertainty in the cascade development process. The magnetic force makes sure that the powders that are developed are well charged. This avoids any low charged powder from getting developed and attached loosely to the photoconductor surface. The carrier particles form a chain on the roller due to the magnetic field and appear as brush, and so the method is called magnetic brush development. The charged

toner was carried across the gap to the photoconductor drum when the electrostatic force exceeds the force that holds the toner to the carriers. The carrier beads were spherical and the development limit was decided by the balance between the charge on the carrier beads and the photoconductor surface (Schein 1988).

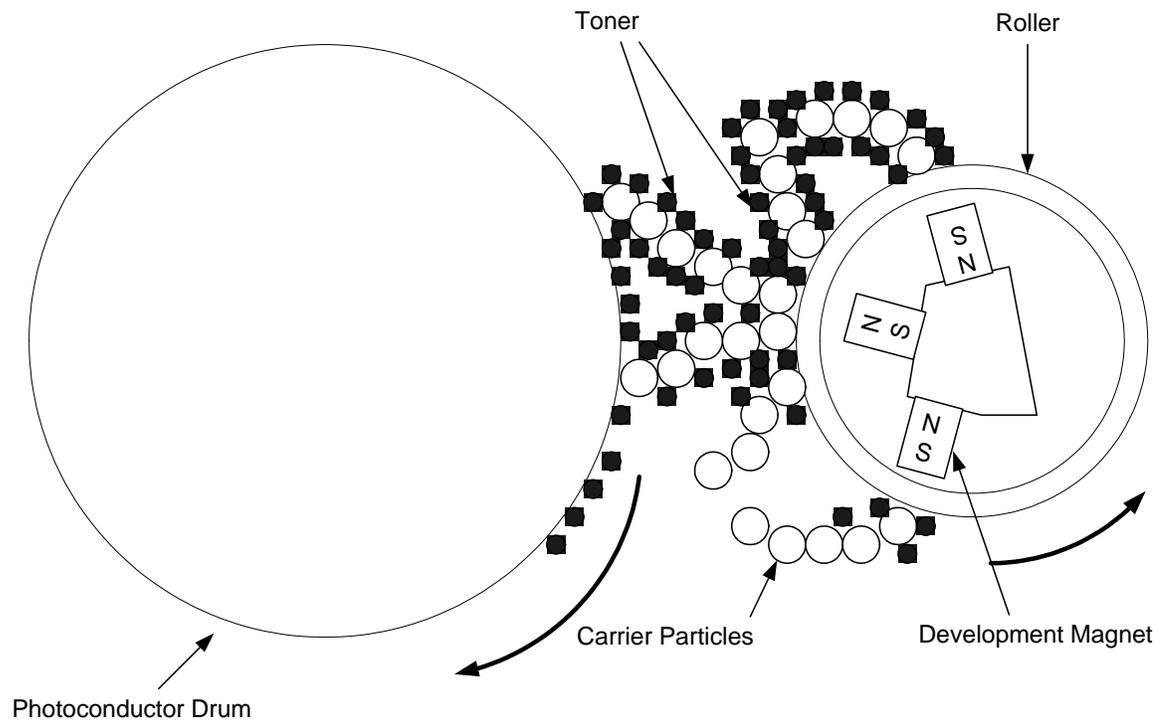


Figure 3-7. Magnetic Brush Development System

Conductive Magnetic Brush Development

The conductive magnetic brush was the most successful development technique invented for two-component development. The difference between this and the previous method was that the carrier particles are irregular in shape so that toner did not cover the whole carrier surface, that helped in maintaining conductive contact between the adjacent carrier particles and transmit current across development gap. There was no balancing of charge buildup on the carrier particles with the photoconductor surface and so more toner particles can be transferred (Kasper 1978). This resulted in darker prints and more solid area development.

In the dual component development, the large carrier particles take up more space in the toner powder box and so there was requirement of larger powder boxes and frequent refill of the toner powder. Due to this inconvenience, mono-component development was developed, which has toner without the carrier particles.

Mono-component Development

Mono-component development is the most common method of development in modern printers and copiers. It uses insulative polymer toners, which are transported using the same magnetic roller technique. The toner powder is made magnetic by doping the polymer with iron compounds during toner production. This also gives the black color to the toner powder. This black coloration of toner is not suitable to use in the color printers. So in color printers cascade development is used and that results in minor spillage. The magnetic roller transfer technique has the same advantage of force cancellation and control as it is in two-component magnetic brush development. The toner powder particles are charged and are stripped off the magnetic roller by the force of the electric field produced by the latent image on the photoconductor surface. To help in this process a DC biased AC voltage is applied in the development zone that makes the powder jump to and fro which forms a powder cloud. This process helps in further charging of toner powder, and the sufficiently charged toner powder adheres itself to the image.

Charged and Discharged Area Development

Depending on the nature of latent image created by the charged areas or the discharged areas, the method of development is named as charged area development (CAD) or discharged area development (DAD).

In CAD the image is created of charged particles by discharging the areas that are not a part of the image. The toner powder is charged to polarity opposite to the charge on the photoconductor surface. The powder is developed by the field created by the latent image made of charge.

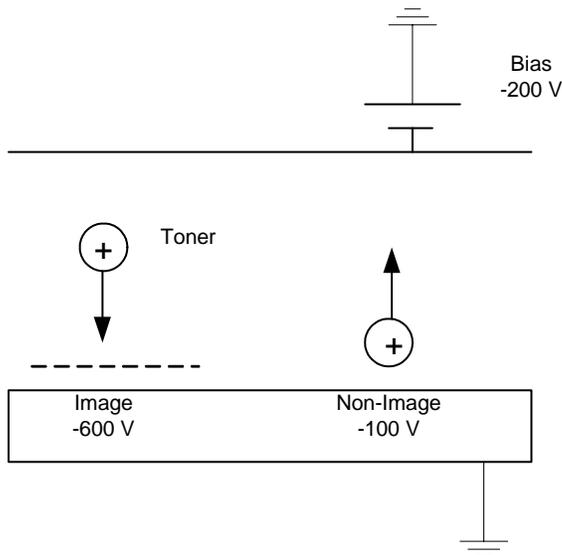


Figure 3-8. Charged Area Development (CAD)

In DAD the image is created by discharging the areas which are part of the image. The toner powder is charged with similar sign compared to the charge on the photoconductor surface. The photoconductor drum is grounded and there is a field created between the ground and the voltage on the developer roller. This field attracts the powder towards the photoconductor surface. When the powder is repelled by the same sign charge on the non-image areas, it is developed on to the discharged latent image on the photoconductor surface.

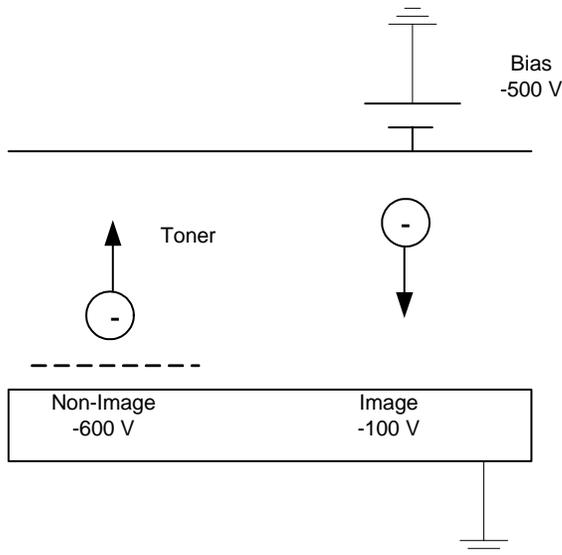


Figure 3-9. Discharged Area Development (DAD)

In DAD the photoreceptor dielectric strength uniformity is critical; otherwise small fringe fields associated with breakdowns are developed by the toner. In CAD the light source lifetime can be an issue because it is on approximately ten times longer than in DAD, as most of a page is usually white. In most of the modern printers DAD is used due to the high cost of laser imager, making it prohibitive to replace frequently.

Toner Powder Charging

There are several methods that are used to charge the toner powder. Some of them are specific to the nature of the powder and use the powder properties to charge them. Others charge toner by depositing charge on it externally.

Toners may self-charge due to triboelectric effects and chemical charging. Two component toners often charge triboelectrically by friction between the toner and the carrier particles, which charges them oppositely to each other. This makes toner stick to the surface of the carrier particles. Liquid toners are charged chemically, in which the charge is exchanged between the liquid and the toner particles. Liquid toners are used for fine powder prints, are suspended in liquid due to the difficulty in handling such fine

powders. Chemical charging is also done in mono-component toner to some extent due to the addition of charge controlling agents, which makes the toner susceptible to be charged with a predetermined polarity.

There are also direct ways of charging toner powder. Corona charger is used to deposit charge particles on the toner powder to charge them. This method is very similar to that of charging photoconductor surface using corona charger and faces similar difficulties of being bulky and non-uniform in charging. The toner powder also can get deposited on the corona wire and render it inoperable.

In mono-component development the toner powder gets charged by getting rubbed against the parts of the developer. This is a popular method of charging toner powder because the charge controlling agents make the toner active to be charged preferentially (Schein 1988). In case of conductive powder, the powder gets charged by being present in the electrostatic field between the photoconductor surface and the developer surface. The conductive powder can also be charged by inductive charging in which an electrode at a distance can induce charge of opposite sign on the powder, if the powder is grounded. Insulating toner powders can also get charged by injection charging in which the toner is moved rapidly around a roller in presence of electric field. The actual mechanics of the charging is poorly understood (Nelson 1978).

The charging of toner is essential to control, because the amount of charge deposited on the toner particle determines the charge per unit mass of the toner, which is an important parameter for the quality of toner development. If the charge per unit mass is less than required then the electrostatic force will not be enough to strip the toner out of the magnetic roller. If charge per unit mass is higher, then only a small amount of toner

will be able to discharge the image and there will be a thin layer of development. Thus the process should be designed to have the powder optimally charged depending on the magnetic field of the developer roller.

Transfer

After the toner powder is developed on to the latent image on the photoconductor surface, it has to be transferred to the paper to transfer the image on to the paper surface. The transfer is accomplished by using both electrostatic and mechanical methods. During transfer the paper is pressed against the photoconductor surface using force by a charge roller which deposits a charge opposite to that of the toner and creates field across the paper to make the toner powder transfer to the paper. This process also holds the toner temporarily to the paper surface by squeezing the toner and pressing it against the paper.

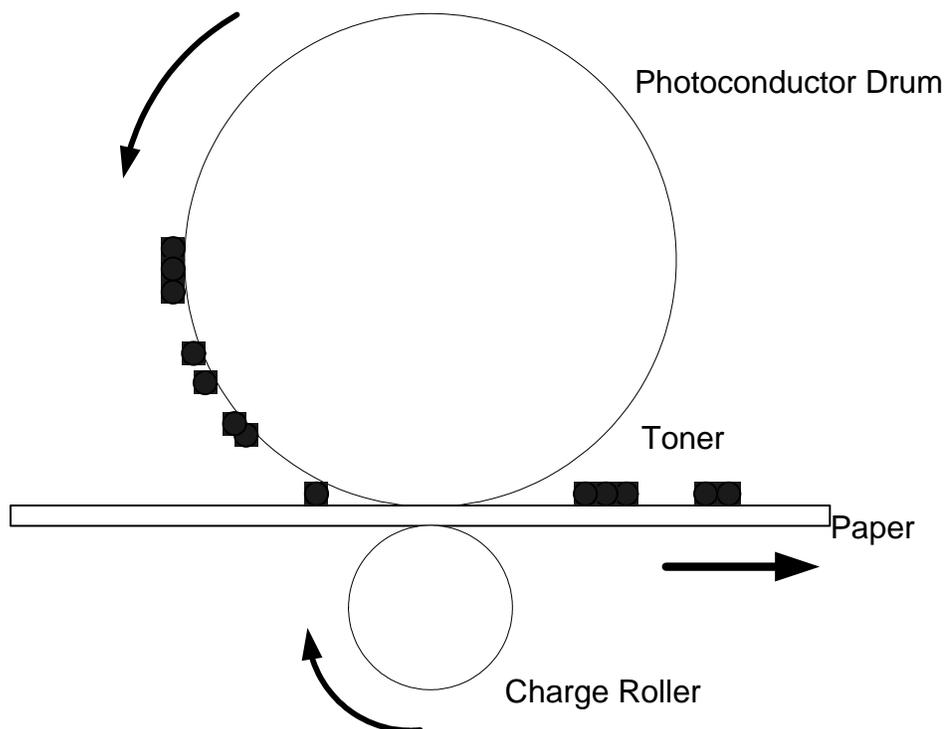


Figure 3-10. Schematic of Transfer of Toner to the Paper

Fusing

After powder transfer, it has to be fused and fixed to the paper surface to create a permanent image. In early days of electrophotography, specialized powders were used as toners and were fixed on to wax papers or papers with adhesives to make a permanent print. In the modern printers the toners are specially created to have fixing characteristics, which enables the use of ordinary paper. The toner is mostly composed of polystyrene, which has low melting point. The paper with the toner is subjected to heat so that the toner melts and gets fixed to the paper. In some printers radiant heaters are used. Most of the printers now use heat rollers to fuse toner. The problem with the heat rollers is that they tend to pick up some toner during heating which may smudge the image. For this reason non-stick coatings, like Teflon, are used on the heat rollers.

Cleaning

After the transfer of powder from the photoconductor surface, the remaining powder is cleaned before the next electrophotography cycle. In current printers using photoconductor drums, the cleaning is done as a part of the cycle. For cleaning, a blade which is a thin flexible polymer sheet is used to scrape off the toner from the photoconductor surface. This waste toner is stored in a receptacle, which is emptied periodically. Generally this receptacle is made big enough so that it does not get overfilled before the developer, along with the receptacle, is replaced.

After cleaning the next step is to discharge the photoconductor surface to clean any residual charge remaining on the surface that may cause background printing. This discharge is done by using corona charger or a charge roller supplied with DC biased AC voltage.

CHAPTER 4 ELECTROPHOTOGRAPHIC SOLID FREEFORM FABRICATION (ESFF)

Currently research is being conducted on the development of a novel method of solid freeform fabrication at Design and Rapid Prototyping Laboratory of the Mechanical and Aerospace Engineering Department at the University of Florida. This method uses the technology of electrophotography to form the image of the two-dimensional slices of the three-dimensional object and print layers of these cross-sectional images to form the final part. This technology is called electrophotographic solid freeform fabrication (ESFF), named after the underlying technology to produce solid freeform objects.

As mentioned earlier, ESFF is not just another way to do rapid prototyping, but it has the advantage of printing thin layers with high resolution using various types of materials, which aims to satisfy some unfulfilled requirements in the rapid prototyping industry. Electrophotography is a fast printing process due to advancement in high speed printing. In electrophotography, the whole image is transferred in one step, compared to the crosshatch scanning of the cross-section area done by some other RP technologies, which makes the formation of individual layers faster. Although the thickness of layer in each print is small, the time taken for each print can be made faster to reduce the overall printing time.

Any material which is available in powdered form and can be charged is a potential candidate for ESFF, although the actual print characteristics may vary. The corona charger is shown to deposit charge on any material, which can be used to charge the powders. Even if a powder cannot be fused, it can be used with a binder printed between

two layers of the part powder. This suggests that there can be a wide choice of material for building parts using ESFF. The other advantage of this method is in the ability to print materials in pre-estimated gradient percentage. This could give some new properties to materials, which may be used for special applications. The laser printer prints with a high resolution up to 1200 dpi (dots per inch). This makes it possible for ESFF to be able to print materials in finer resolutions and tolerances.

The major hurdle in developing this technology has been the extreme complexity and unreliability of electrophotographic process when applied to powders other than the popular toner powder. ESFF deals with complex problems like powder flow characteristics, powder-charging methods, charged powder behavior and problems of adhesion of powder to surfaces and agglomeration. These are not so well understood subjects and are still under active research work.

Development of ESFF Test-bed System

ESFF research started with a test-bed design and fabrication to conduct the experiments to test the concept of the ESFF technology. The requirements of the system were to have a two-axis motion control of the platform on which the part would be built. There should be a printing system for printing of layers of toner powder, which could be later modified to print powders of other materials. The print also has to be fused to make it permanent on the build platform. All these requirements were taken into consideration while designing and building of a test bed using a modified laser printer (Zhang 2001). The schematic of the printer is shown in figure 4.1.

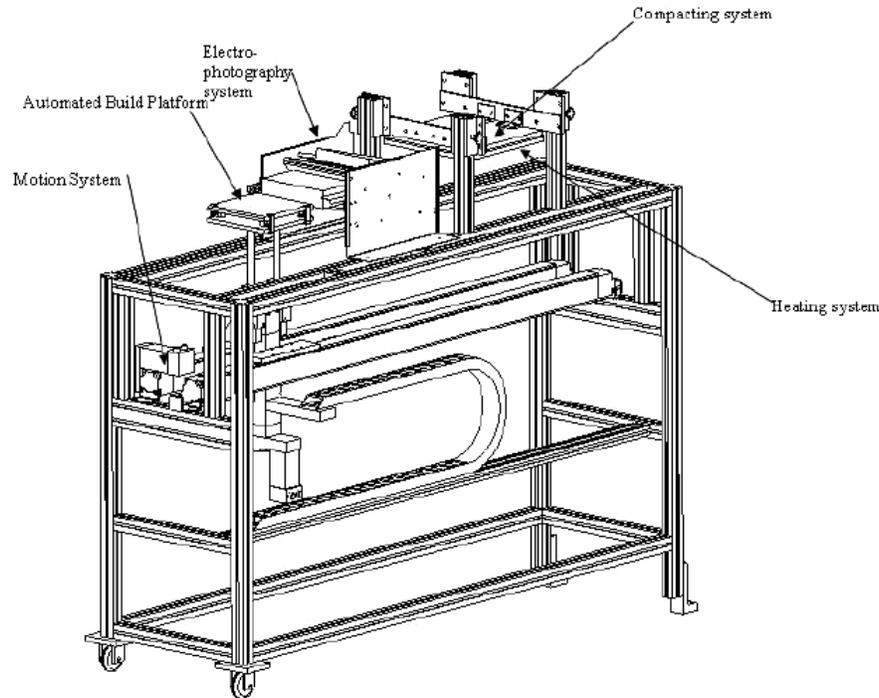


Figure 4-1. The ESFF Test-bed Dutta (2002)

Motion Control System

The build platform was required to move in two-axes. One of the motions is in the horizontal direction (X-axis) for the printing process and another in the vertical direction (Z-axis) for part height adjustment. These motions were provided by a combination of servomotors. These servomotors are a part of the Parker automation system, which is controlled by Galil-DMC motion controller. The Galil controller was interfaced with the computer using the Galil software. In this software, interface commands can be written to move the motors with precise speed and acceleration and stop after predetermined number of rotations. A program in C++ was written to generate such motion commands to synchronize the motion of the platform with print cycle.

The build platform was an aluminum plate supported by springs to compensate for the error in positioning of the platform surface and photoconductor drum with respect to horizontal plane. This also helps in pressing the build platform against the

photoconductor drum without damaging the drum surface. The other place where springs are helpful is during fusing, by correcting any misalignment of the build platform while getting pressed against the fusing plate. A position sensor mounted below the top plate of the platform sends signal when the platform reaches a particular height during compaction of toner.

Printing

A modified laser printer was used to achieve the task of printing on the build platform. The printer used for this purpose was the “Laser Jet 4” printer made by Hewlett Packard. The paper handling system of the printer was removed to clear the path below the photoconductor drum, which gave access of the photoconductor drum surface to the build platform for printing. There are sensors to detect the passing of the paper so that the events associated with printing can be synchronized and also paper jam can be avoided. These sensors are sent right signals at the right time from the computer to keep the printer from detecting error in the normal operation. This ensures proper operation of ESFF process.

Fusing

The toner after getting printed on the build platform has to be fused to form a permanent print, which was done initially by a non-contact radiant heater. This radiant heater was made of a heating coil placed at the focal point of a concave mirror for distribution of the heat pattern uniformly on the build platform. This heat distribution was observed to be concentrated at some places in real operation causing differential fusing of toner image. It was also necessary to compact the print to correct any errors due to non-uniform powder deposition. There was also the need of discharging volume charge of the printed toner layer by making it contact with a grounded metal plate during fusing and

compaction. These considerations led to changing the heater to a contact type plate heater. This heater was made of a mica strip heating element sandwiched between two aluminum plates. The lower plate had a uniformly heated smooth surface, which compressed the toner powder layer when the upward moving build platform was pressed against it. This also discharged the volume charge contained in the toner powder layer by contact with the conductive heater surface during fusing and compression. During the fusion of powder the molten toner sticks to the heater surface causing distortion in the print. This distortion in print is also increased due to the spreading of toner layer after compaction. This affects the dimensional accuracy of the object produced by using ESFF. The sticking of toner to the heater surface was later reduced by attaching a Teflon coated plate below the lower aluminum plate to create a nonstick surface.

Software

Software programs were developed in C++ to generate control commands for the Galil motion controller software interface and Parker automation systems to control motion of the build platform (Dutta 2002). This program also sends signals to the sensors in the modified printer to ensure normal printer behavior. This C++ software code is stored as a dynamic link library, which is called by a Java program (Bhaskarapanditha 2002). This Java program called “SolidSlicer” has slicing algorithms, which use the data from a solid 3D CAD model of an object stored in STL format and determine the cross-section of each layer at different Z-heights. These cross-sectional images are then sent to the printer for printing. The software has a good user interface that allows positioning of multiple part prints on the build platform. This automates the building process and also creates information which is stored in log files.

The initial ESFF test-bed provided a platform to perform basic experiments on the issues of concern during printing of toner powder as the structural material for producing 3D parts. Various parameters could be varied and the resultant effects measured to compare the change in process due to any change in these process parameters. The quality and the print pattern could be changed by modifying the software. Sensors and actuators can be placed on the frame of the test-bed to collect data during experiments. In this test-bed, the printer was used as a “Black Box” and the only change made to the printer was to replace the paper handling system with the moving build platform.

Measurement of Charge and Mass of Powder

Charging of toner powder is very important in the process of printing. It should be high enough so that the toner can get developed on the photoconductor surface, but not very high which can make it difficult for the powder to be transferred to the build platform. The effectiveness of a powder developer depends on the charging characteristics and the amount of powder it can develop on the photoconductor surface. This can be estimated by measuring the charge per unit mass of the developed powder. In situ measurement of charge per mass is difficult to accomplish. It is also difficult to isolate the charge on the powder from other charges present during measurement and moreover the charged powder developed on to the photoconductor drum is difficult to rescue and measure. This made it necessary to develop a stand-alone system that can accomplish the task (Gokhale 2001). The development of powder developer and the development of the experimental setup to measure charge per unit mass of the developed powder are discussed in more detail in chapter 5.

Measurement of Powder Properties

The important physical properties of the powder, to be used in ESFF technology, are volume resistivity, permittivity and mass density. These were measured for toner powder using a test cell and the Keithley electrometer (Dutta 2002). In chapter 7, results of similar tests to determine the above properties for polymer powders other than the toner powder are reported.

Improvement of Print Quality

Limitation on Part Height

There are many issues related to the printing of toner which are amplified when multiple layers of toner powder are printed in ESFF. The first observation was that the printing stops after the part height is around one millimeter. By theoretical calculations (Dutta 2002) it was found that multiple layers of insulative toner powder increases the voltage drop across printed layer and the electric field available for development decreases significantly, which in turn decreases the amount of powder transferred. This problem gets worse when charge gets trapped inside the volume of the printed toner part due to inefficient discharging of the toner layer after each print. This volume charge distribution, which is the same as charged toner, repels the toner and tries to prevent it from getting printed.

An attempt was made to solve this problem by depositing charge on the top of the printed toner layer using corona discharge, which is of opposite sign to that of trapped volume charge. The field created by this deposited charge layer cancels the repulsive field created by the volume charge and also creates an attractive force for toner powder printing. Moreover the charge deposited on the surface of the top layer is not affected by the thickness of the toner layer.

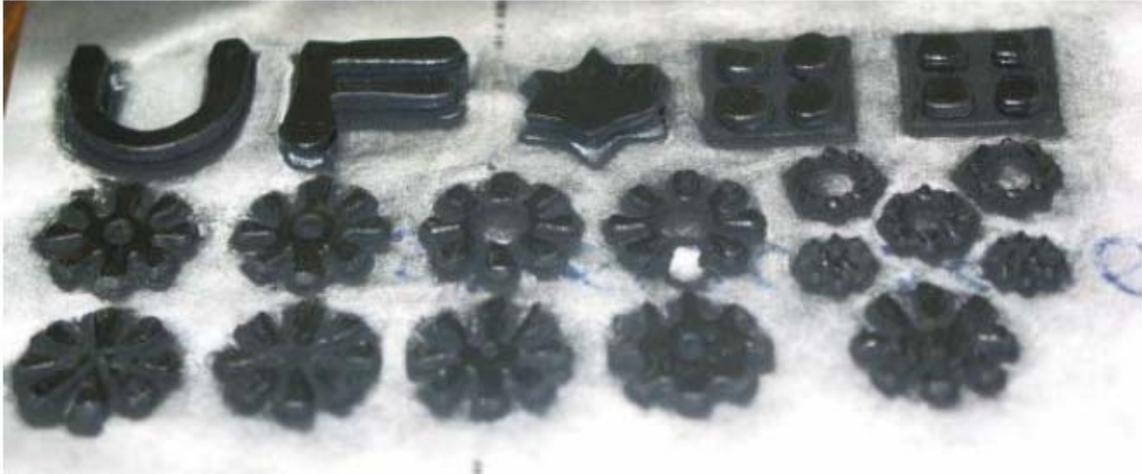


Figure 4-2. Parts Printed Using Corona Charging of the Top Printed Layer Before the next Print (Dutta 2002)

This method has its own limitations. It is known that corona deposition on a surface, when the grounded electrode is not near the surface, is limited by the breakdown strength of air (Gaussian Charge Limit). This is true for the toner powder printing because toner layer is insulating in nature and multiple layers of toner effectively move the grounded electrode far away from the top surface. The trapped volume charge in the printed part increases with every layer deposited and it can reach a value where the repulsion due to volume charge exceeds the attraction due to the fixed surface charge deposited by corona. This again creates a limitation on the part height that can be built using ESFF. In case of high volume charge density the decrease in the rate of increase in print layer thickness is faster. In the case where the fused toner is almost fully discharged the rate of increase in print layer thickness decreases very slowly and the part can be built having more thickness. This observation suggests that consistent complete discharge of the printed toner powder before fusing is necessary for building higher part thickness. Complete discharge of the volume charge of a printed insulator layer is very difficult to attain.

Edge Growth (Solid Area Development)

Edge growth is another problem associated with electrophotography, which is amplified due to multiple layer deposition. The cause for this is the nature of the electric field distribution in the image area, which is stronger at the edges and decreases rapidly towards the middle. This causes thicker development at the edges and near to zero development at the center. When the printing is done in many layers, there is a distinct difference between the edges and the solid area development.

An attempt to solve this problem was done by printing the solid area in patterns. These patterns create edges throughout the solid area fill and the field inside the solid area can be maintained at a particular level. Finite element analysis of the patterns is done to study the electric field distribution by pattern printing (Bhaskarapanditha 2002, Fay 2003).

It was concluded that there was a significant improvement in the electrostatic field distribution in the image area due to pattern printing. A series of experiments were performed to find out the pattern that gives the best print (Fay 2003). From the results it was found out that a broad black line with a broad white line is the best pattern to print. This pattern printing however cannot be used to print smaller parts with finer tolerances. The resolution of print has to be increased to produce finer patterns.

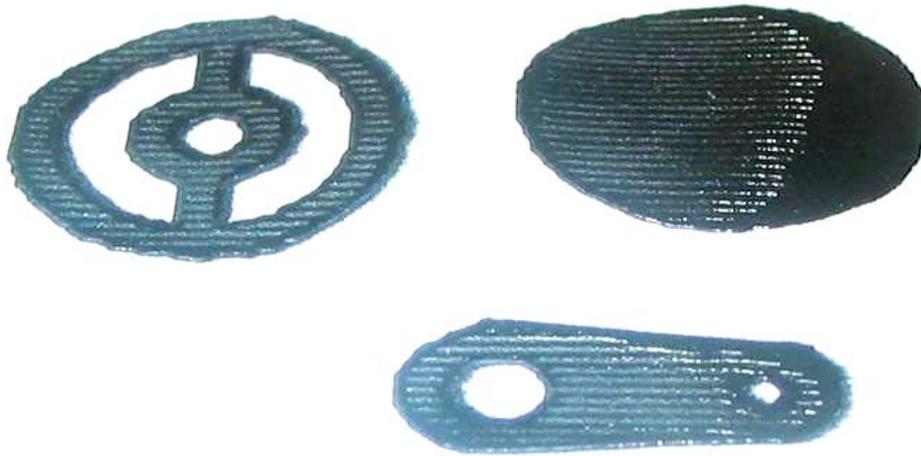


Figure 4-3. Parts Printed using Patterns (Fay 2003).

Printing of Powders other than Toner

Attempts were made to determine the feasibility of printing powders other than toner using the test-bed. A generic developer was designed to be able to develop powders of any physical property on the rotating photoconductor drum. The powder developers were designed to replace the toner developer in the toner cartridge assembly. The effectiveness of the developer was tested by using the charge and mass measurement setup. A detailed description of this testing is presented in chapter 5. The powder was brought out for development by cascading it using gravity. This had problems of powder leakage during development and so was not considered suitable replacement for the toner powder developer in the printer used in the test bed.

The alternative of the above method is to have two-powder development, in which one powder is used as part powder and the other is used as binder. In this method toner was chosen to be used as the binder due to its low melting temperature. For binding purposes, toner has to be printed image-wise on a uniform layer of part powder (Dutta 2002). In the two powder development the photoconductor surface has to contact the

abrasive part powder to print toner image that can damage the soft organic photoconductor drum surface. Due to this reason, the photoconductor drum surface was isolated from the abrasive part powder by introducing a transfer roller in between them, which would collect the image-wise toner powder pattern and transfer it over the part powder (Dutta 2002). This printed toner powder with the part powder would be fused to bind the part powder to form the real image and the surrounding loose powder would act as support.

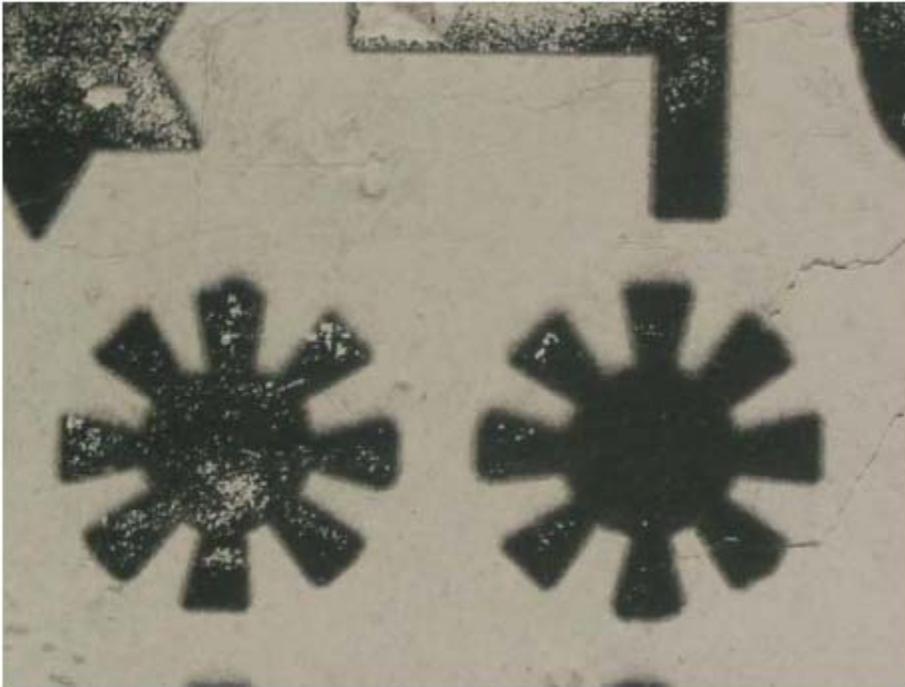


Figure 4-4. Toner Powder Printed over Insulating Alumina Powder Bed (Dutta 2002)

This method had problems associated with difficulties in printing a thin and uniform layer of part powder using the developers designed for cascade development. In addition to that, the toner powder becomes brittle when it solidifies after fusing, which makes it a bad adhesive. There is also the concern of keeping the support powder from falling off the flat build platform without proper support at the sides of the platform to

prevent powder spillage. Due to these problems associated with this method it was not pursued further in the research.

Study of Laser Imager System of Printer

The design of a new test bed configuration was necessary to avoid dependency on the use of complex commercial printers. Most of the basic activities performed by the printer can be replicated by using controllers, switches and sensor mechanisms. It is only the laser imager hardware that cannot be duplicated so easily and therefore an attempt was made to modify the laser imager from the HP Laserjet-4 printer, which can be used as an imaging unit for the new test-bed (Fay 2003). The schematic of the HP Laser Jet 4 imager is shown in Figure 4-5.

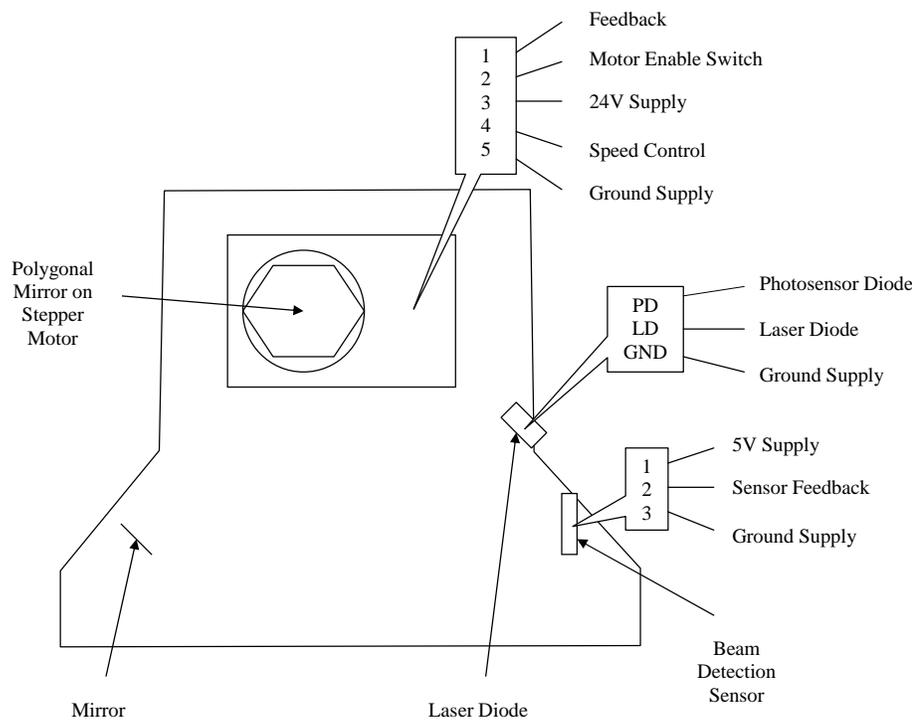


Figure 4-5. Diagram of Laser Jet 4 Imager Assembly (Fay 2003)

The imager is controlled by a “formatter” and a “dc controller”. The formatter decodes the image file sent from the computer and sends electrical pulses to the laser to go on and off according to the image data, while the dc controller controls the motors for

the movement of the laser beam. The modifications to the laser imager were done by replacing the formatter by sending electrical pulses directly to the laser from the computer and controlling the beam on and off according to the image data. The functions of the dc controller were replaced by controlling the motors and the sensors externally through Galil motion controller interfaced with the computer. These modifications removed any kind of dependency of the laser imager system on the printer and all the control was done from the computer. The design and development of the Flat Photoconductor Plate Test-bed is explained in detail in Chapter 8.

CHAPTER 5 DESIGN AND TESTING OF IMAGE DEVELOPERS

Toner powder is the only material that has been so far used successfully to print in layers on top of each other to form three-dimensional objects. When printed in multiple layers it suffers from quality and reliability problems as discussed in chapter 4. This is the motivation for exploring the feasibility of printing powders other than toner in multiple layers using ESFF to form 3D objects. These powders, which includes various conductive and insulative materials, have different properties than toner and may not have the limitations posed by toner powder during printing. This also gives us an opportunity to explore the possibility of making parts of different types of materials some of which can be used as functional prototypes.

For using variety of powders with different physical characteristics, image developers were designed and built to develop these powders on the photoconductor surface. These developers were based on cascade development system, due to the fact that the cascade development system uses gravitational force to supply powder for development and so is independent of physical properties of the powder. These image developers had to be tested before putting them on the test bed to be used as powder developers. The parameters to be tested in these developers are the effectiveness of charging of powder and the amount of powder developed on the photoconductor surface. These can be tested by measuring the total charge and mass of the powder developed on the photoconductor surface. From these readings we can estimate parameters like charge per unit mass (Q/M) and mass per unit area (M/A) which are important for the quality of

print (Schein 1988). The initial discussion is presented on the development in the powder developer design. This powder developer is designed to use variety of powders including both conducting and insulating powders. The later discussion is based on the development of charge and mass measurement test setup to test the powder developer efficiency in charging and developing powders.

Developer Design

To use powders other than the toner powder, developers were designed and fabricated which could replace the toner developer assembly in the toner cartridge of the printer. For testing the efficiency of these developers they have to be also suitable to be used in the charge and mass measurement test setup.

In Chapter 3 there is a detailed description on the developer system and its components. The function of the development system is also discussed with respect to the electrophotographic cycle. Again in Chapter 4 we discussed that to be able to print powders with varied physical properties, the developer should be designed on the basis of cascade development system and should have its own powder box and charging and powder supply mechanism suitable for cascade development. The following discussion describes the basic components of the developer assembly design and the realization of the latest version of powder developer through continuous improvements.

The function of the developer assembly is to store, charge, transport, and transfer the powder for development and re-circulate the residual powder. The developer assembly consists of the powder box and the “nib” assembly. The storage of the powder is done in a powder box which also acts as a powder hopper for maintaining the powder supply for development. The nib assembly consists of the developer roller, the doctor blade and a casing to hold these together. The charging of powder is achieved by

injection charging method. Voltage is supplied from high voltage source to a metal strip attached to doctor blade. As explained in Chapter 3, the doctor blade is a thin long plate which is kept pressed against the developer roller along the length of the roller. When the powder comes out through the gap between the roller surface and the blade surface, they get squeezed and rubbed against the metal plate attached to the doctor blade and get charged due to contact with the voltage supply.

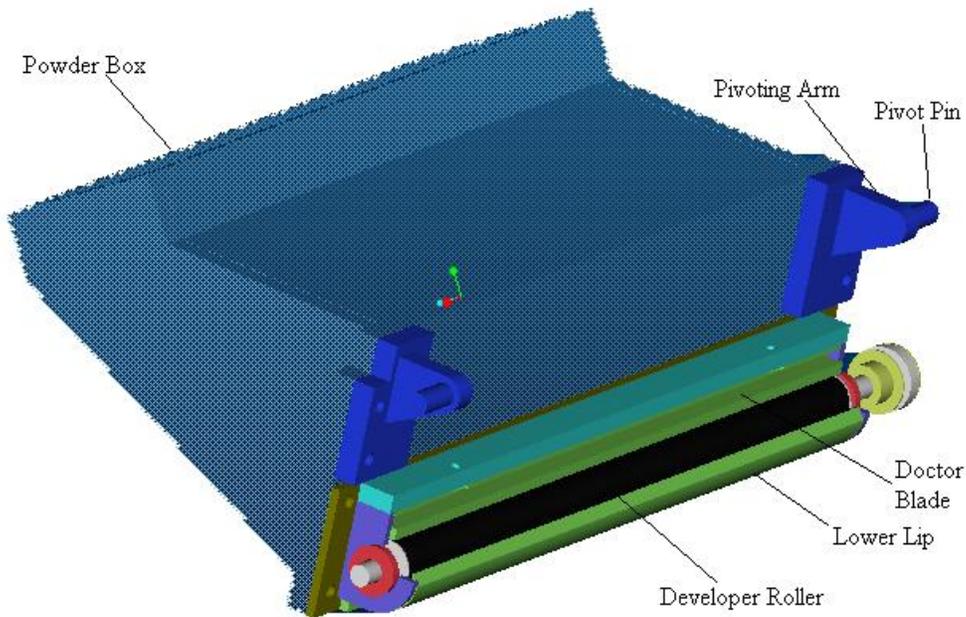


Figure 5-1. Solid Model Assembly of Powder Developer

The developer roller brings out the powder for development by friction. The roller has a rough surface which is porous and could trap the powder in these pores and bring them out. The powder also gets smeared on the roller due to squeezing action between roller and doctor blade. This helps in bringing out more powder for development. The powders also have Van der Waals force of attraction between each other and help in attracting more powder for transport to the development region. The transfer of powder is due to the field created between the developer roller and the photoconductor drum, which creates the appropriate force on the charged particles. The remaining powder which was

not developed is re-circulated by friction as the roller surface rubs against the inner surface of the developer roller casing. The fabrication and the improvement in the developer design are presented in the following discussion.

Powder Box

The powder box is made of transparent acrylic plates, which makes it easier to inspect the powder flow and the level of powder. The bottom plate of the powder box is made at an angle to the horizontal, which helps in the flow of powder due to gravity. In order to allow easy flow of powder, this angle should be greater than the angle of repose of the powder. The angle also should not be very steep because this will make all the powders accumulate at the bottom and increase the pressure on the developer roller, which will make it difficult for the powder to re-circulate back into the box. As an initial guess this angle is chosen as 34.1 degrees, which is the angle at which the toner cartridge sits in the laserjet printer. This angle worked well with most of the powders put in the box for development. The front plate of the powder box has a pair of arms attached to it by screws. These arms help in assembling and positioning of the developer with the charge and mass measurement setup, which will be discussed later in the chapter.

Developer Roller

The developer roller is made of conducting polymer with a metal axis. This enables to apply voltage to the powder to charge the powder and also create a field with the photoconductor surface during development. As said earlier, the rough surface of the polymer of developer roller helps in supplying powder to the development region. It also circulates back unused powder after development into the powder box. The recirculation of powder is made possible by a particular geometry of the lower cup like structure of the developer roller casing.

Developer Roller Casing

The casing is designed to accommodate the components of the nib (developer roller and doctor blade) and along with that ensure a smooth flow of powder in and out of the powder box without any leakage. The casing has flanges that help in attaching the nib to the powder box. The top part of the casing provides support to the blade. The bottom part of the casing provides support for the developer roller axis and has a cup like structure called ‘lower lip’ that protrudes below the developer conforming to the roller surface. This special geometry retains the undeveloped powders for their recirculation back into the powder box. The gap between the lower lip and the photoconductor drum is critical; a large gap will result in powder leakage and a small gap will bring the lip edge closer to the photoconductor drum and may scrape developed powder off the drum surface, which also may cause damage to the surface of the photoconductor drum. These requirements make the shape of the casing complicated and so it was manufactured out of ABS using rapid prototyping (FDM machine).

The developer was designed to not only fit the charge and mass measurement test setup, but also to be used as a powder developer replacement for the toner developer in the toner cartridge. The toner cartridge consists of the toner powder developer, which is attached by pivoting arrangement with another component assembly called “front-end” (Figure 5-2, which includes the photoconductor drum, the charging roller, the cleaner blade and the cleaner box). One of the early designs of the developer assembled with the “front end” is shown in Figure 5-3.

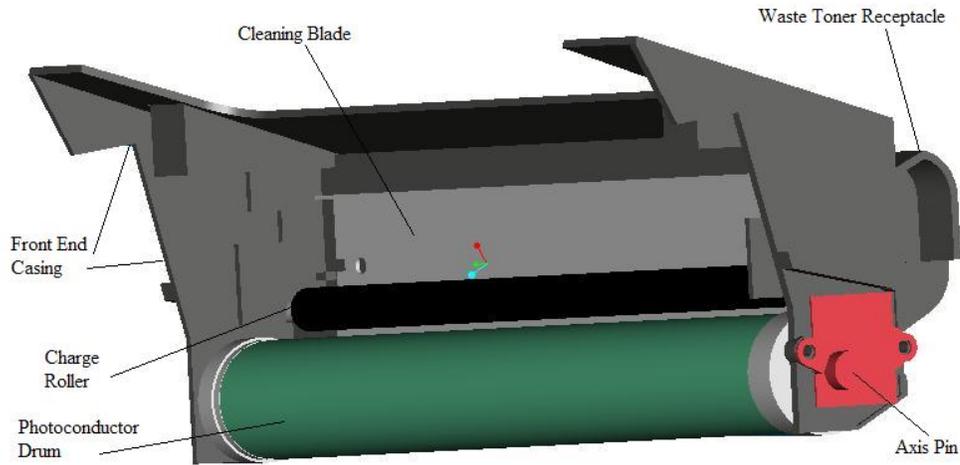


Figure 5-2. Front End of the Toner Powder Cartridge

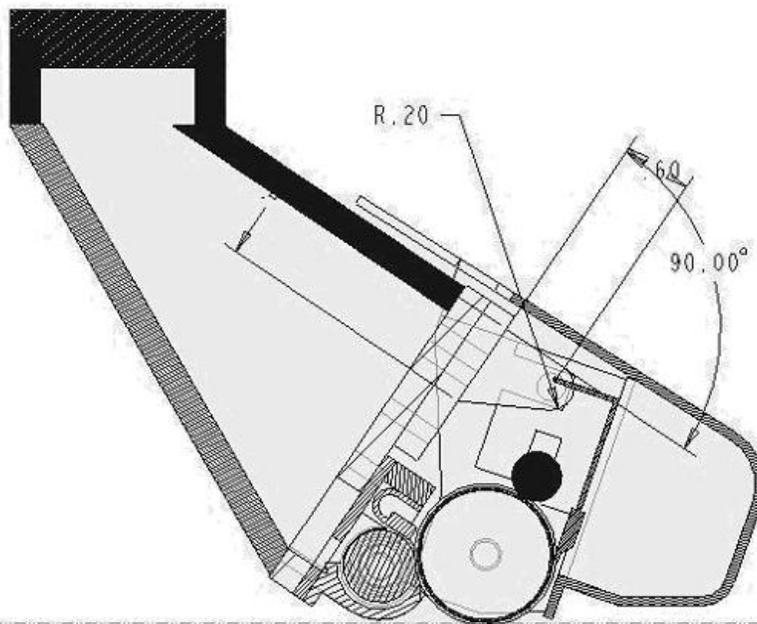


Figure 5-3. Cross-section of Developer Assembled with the Front End

The preliminary designs suffered from some serious drawbacks related to powder leakage. There was also the problem of inefficient powder charging and powder flow and recirculation control. Almost all the problems were related to the way the “nib” assembly was designed. This nib assembly was modified and improved with each new developer design (Fay 2003). In every next generation of developer design it was taken care that the

positive attributes of the previous version are implemented and the problems associated with it are solved.

The last developer that was designed solved most of the above mentioned common problems associated with the designs before that. It considerably reduced the powder leakage to be negligible and increased control over the powder flow. There is still some small amount of leakage associated with this design that can be removed when the developer is manufactured precisely by taking care of the close tolerances in the design.

It can also be mentioned here that, as long as cascade development is used as the method for development, the problem of powder leakage will remain. Even in commercial color printers which use non-magnetic toner powder and cascade development, there is a small leakage of powder. The issue of powder leakage may matter when the developer is used directly in the printer, but is not of a concern in the charge and mass measurement test setup. This is because the charge and mass readings are taken related to the powder that is actually developed on the photoconductor drum and so the leaked powder does not affect the readings.

Pivoting Blade Powder Developer

As mentioned before, the design of the nib assembly is the most challenging and has gone through a lot of modifications till the last one was designed with pivoting blade. The doctor blade has a hole in the middle to allow for pivoting by using pins to act as pivot points. These pins also hold the blade by these holes. The blade is bent at the middle, along the length, to allow the positioning of the developer roller in the compact unit and also enables the blade to be kept pressed against the developer roller. It is made of ABS by rapid prototyping (FDM machine). A copper sheet is glued to the bottom part of the blade (which is pressed against the roller) to charge the powder flowing through

the gap between the blade and the roller surface (by contact, injection charging). The blade also controls the amount of powder supply for development. This pivoting blade design has better control over powder flow as the angle of the pivot can be changed easily to change the gap between the blade and the roller surface. The conductive powders get charged by the field created between the developer roller and the photoconductor drum.

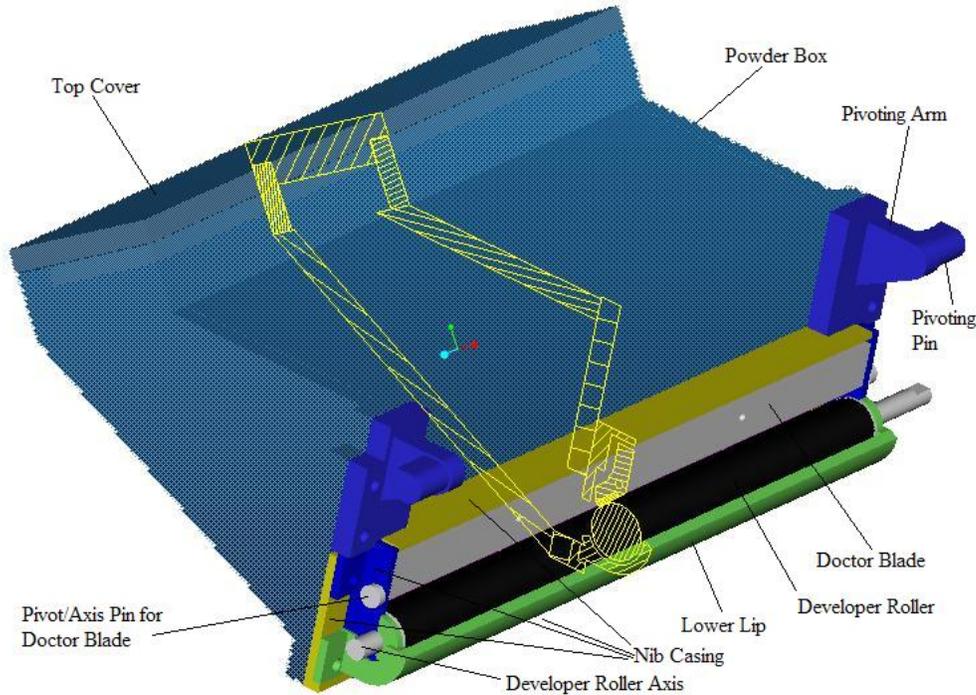


Figure 5-4. Solid Model of Developer Assembly for Pivoting Doctor Blade Powder Developer (with Cross-sectional view)

The schematic diagrams below show the developer cross-section (Figure 5-5), cross-section of assembly of developer with the “front end” assembly (Figure 5-6).

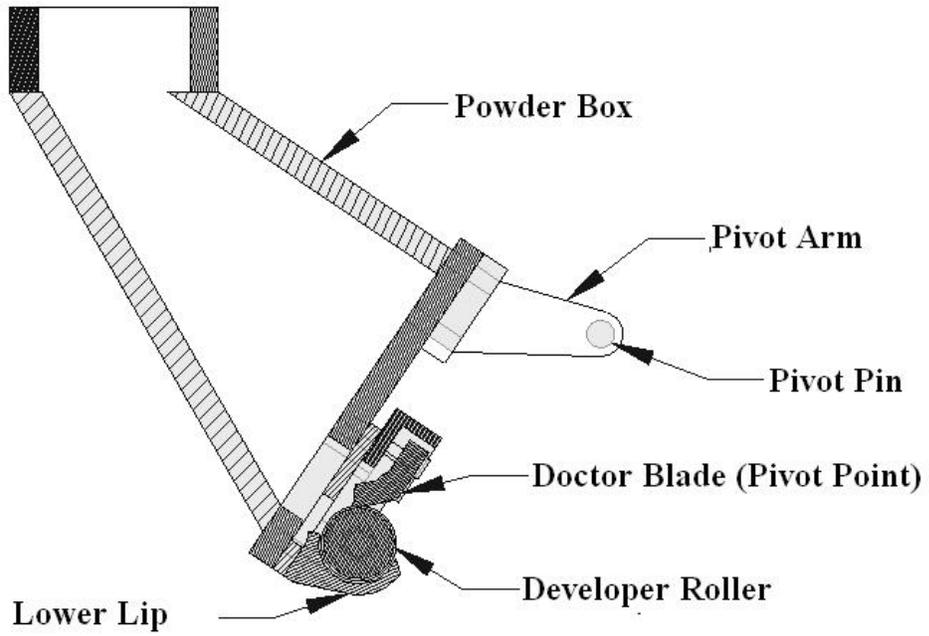


Figure 5-5. Cross-sectional view of the Developer Assembly

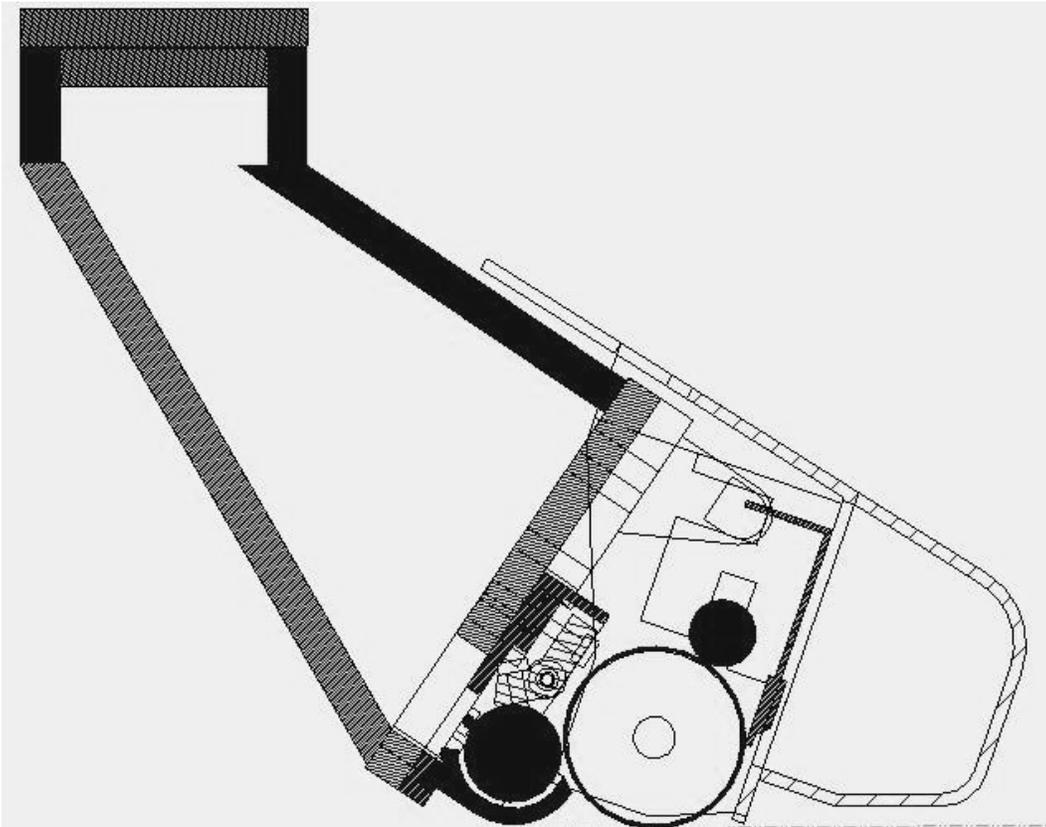


Figure 5-6. Cross-section of Developer Front End Assembly with the Pivoted Doctor Blade

Development of Charge and Mass Measurement Test Setup

Discussion on Development of First Test Setup and Testing Concepts

The first charge and mass measurement test setup was developed using the principle of Direct Charge measurement (Gokhale 2001). The schematic of the test setup is shown in Figure 5-7.

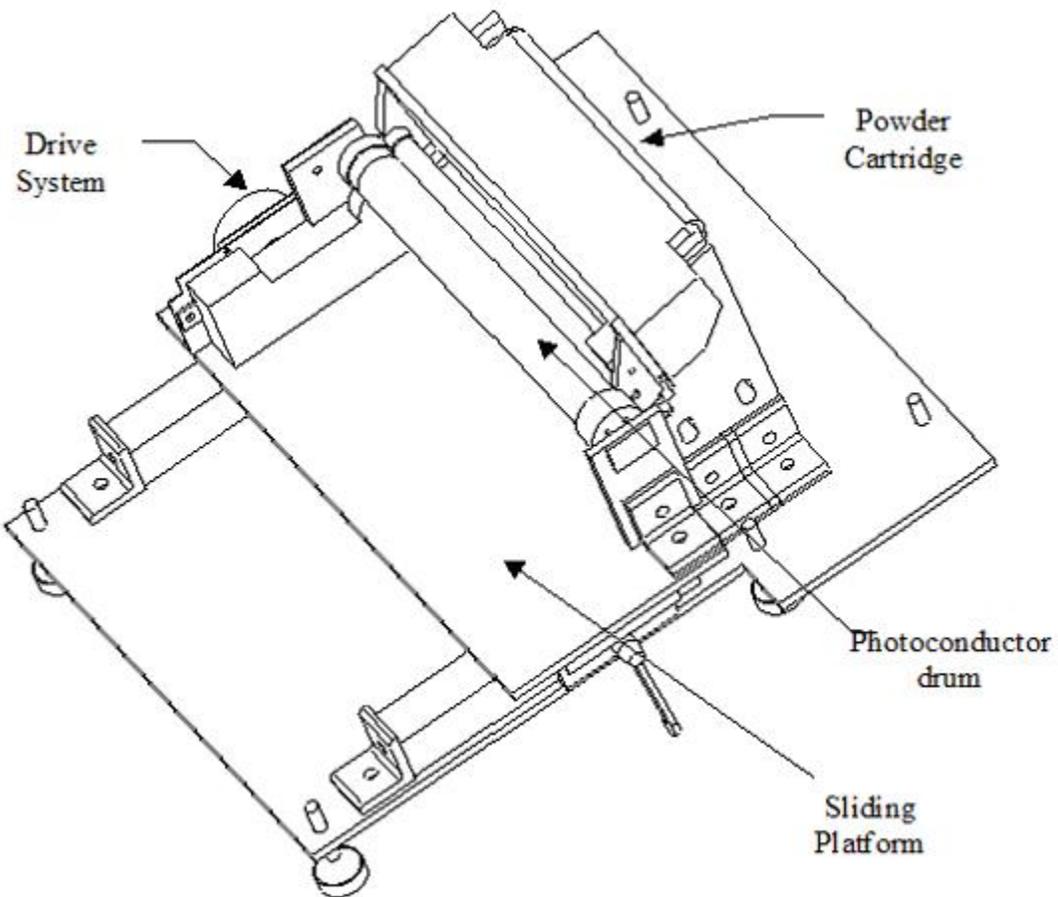


Figure 5-7. Schematic of Charge and Mass Measurement Test Setup (Gokhale 2001)

The charge and mass measurement test setup had an organic photoconductor drum driven by a stepper motor (This photoconductor drum and motor assembly was borrowed from the HP laserjet printer). The motor rotates the photoconductor drum with a fixed velocity equal to the velocity at which it originally rotates inside the laser printer. The

photoconductor drum along with the drive system is mounted on a movable platform, which slides on rails. The original toner powder developer taken from the printer was used and a custom made stand was made to hold the developer in place. This stand kept the developer at an angle (34.1 degrees) that is the same as that used for positioning the developer in the commercial printer. The photoconductor and the drive assembly mounted on the sliding platform are moved to engage with the developer assembly. The schematic below explains the method of Direct Charge measurement in the charge and mass measurement test setup.

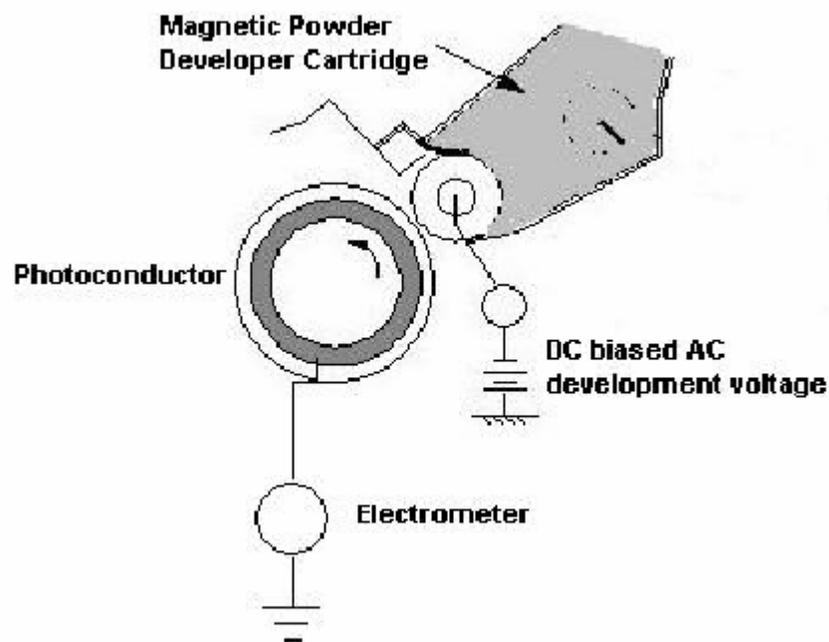


Figure 5-8. Charge Measurement Setup for Direct Charge Measurement (Gokhale 2001)

The toner developer is connected to a voltage source producing dc biased ac voltage to charge toner powder and create powder cloud in the development nip region. The photoconductor drum is connected to the ground through an electrometer. The electrometer has the ability of integrating current that passes through it to measure the

charge flow. The charged powders get developed on the grounded photoconductor drum surface. This deposited charge attracts equal and opposite charges from the ground to the aluminum drum through the electrometer, which measures the current flowing through from the ground to the aluminum drum. The electrometer then integrates the current with respect to time and displays the total amount charge flow from the ground. For the mass measurement, the photoconductor drum had to be removed from the set-up and weighed.

The drum is rotated for one revolution which allows using the value of the surface area of the drum for calculating mass of powder developed per unit area. Removing the photoconductor drum is a complicated process and this could affect the mass readings due to the possibility of powder loss from spillage. This is solved by covering a layer of Mylar sheet over the photoconductor surface and removing it for mass measurement, without removing the whole photoconductor as before.

This setup had problems because of the uncertainty of positioning the photoconductor drum with respect to the developer roller. When the rollers do not have a line contact at the development nip the toner development becomes non-uniform. Moreover, as the developer roller is driven by the meshing of its gear with that of the photoconductor drum the drive of the development roller can be shaky due to misalignment. The stand on which the toner developer sits is customized for the particular geometry of the developer and has to be changed for any change in the developer geometry. To solve the above problems the test setup was modified by focusing on redesigning of the mechanism by which the developer assembly engages with the photoconductor drum. In all the improvements done to the test setup, the basic principle of direct charge measurement is used as the method to measure charge.

Improvement in the Design of Test Setup

In the HP LaserJet 4 printer the developer assembly pivots by two pins and gets engaged to the photoconductor drum by its weight. This aligns the surface of the developer roller and the photoconductor drum to have a line contact for uniform development throughout the length of the photoconductor surface. This also provides the force, due to gravity, which keeps the gears of the developer roller and the photoconductor drum engaged. This pivoting concept was used in the improved charge and mass test setup. The solid model of the test setup with the toner powder developer is shown in the figure below.

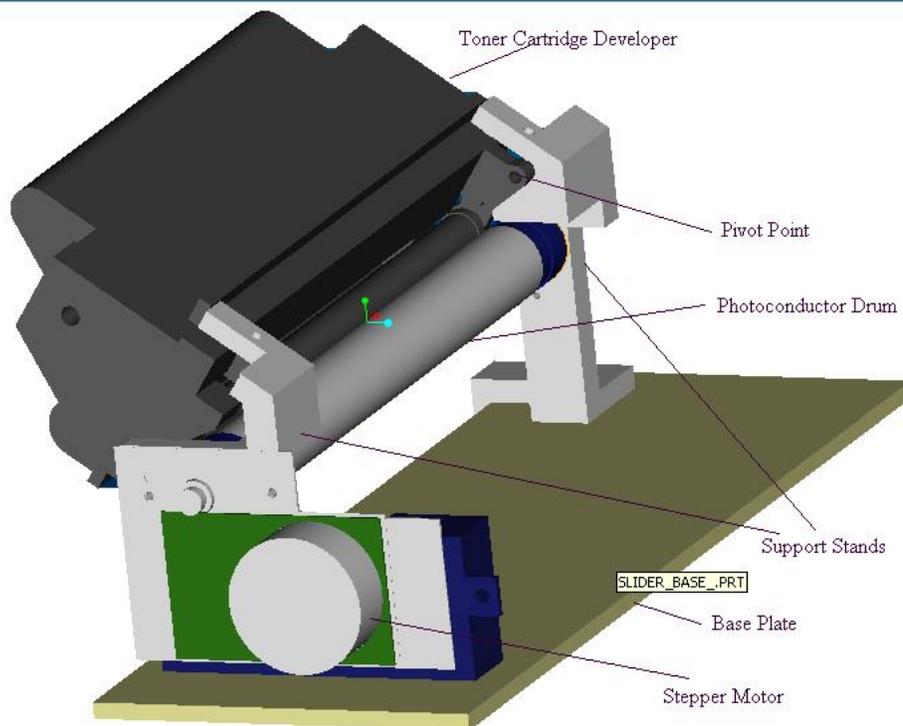


Figure 5-9. Solid Model of the Assembly of Toner Powder Developer and Charge and Mass Measurement Test Setup

The photoconductor drive assembly, which used to slide on rails in the last design, was removed from rails and used for this design. Side-supports were designed to hold the photoconductor drum in place. The side supports had circular slots made at a particular

angle to hold the developer assembly by its pins and allow it to pivot around the pins. The developer assembly comes to a halt when the developer gear meshes with the photoconductor gear. This type of engagement placed the developer exactly in the same orientation as that would be in the printer. This was a much simpler design and was easy to disassemble for mass measurements of the developed toner.

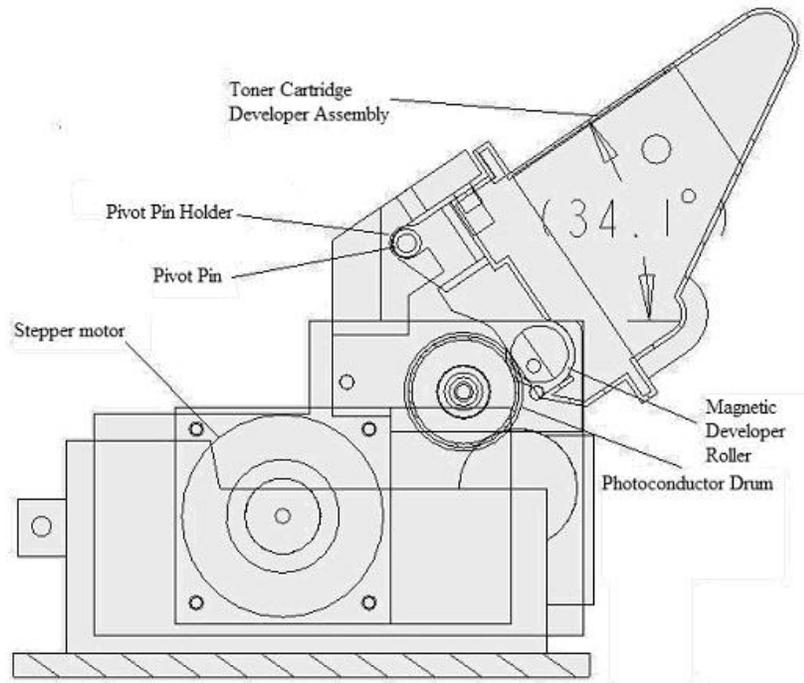


Figure 5-10. Cross-section View of Charge and Mass Measurement Test Setup

The development roller was provided with -570V dc biased ac voltage at 1780V (p-p) and 1754 Hz frequency from the voltage source to create powder cloud in the development nip, simulating similar conditions as there in the development region of the laser printer (Zhang 2000). The photoconductor drum was grounded through electrometer for measurement of charge flowing through the ground to balance the charge on the powder particles developed.

The toner was printed on a Mylar sheet wrapped around the photoconductor drum. The stepper motor was started, and stopped when the photoconductor had made one

revolution observed by visual inspection. Then the developer assembly was removed and the photoconductor drum taken out to measure the difference between weight of the photoconductor drum before development and after development to find the mass of the powder developed. The electrometer gave the charge reading and the area was taken to be the surface area of the photoconductor drum due to single rotation of the drum during development. The charge, mass and area readings were used to calculate charge per unit mass (Q/M) and mass per unit area (M/A). Tests were carried out using this setup to find out the Q/M and M/A of toner powder. The results are reported in table 5-1.

Table 5-1. Q/M and M/A calculations of toner using QMM test setup

M ₁ (gm)	M ₂ (gm)	Q (μC)	M=(M ₂ -M ₁) (gm)	Q/M (μC/gm)	A (cm ²)	M/A (gm/cm ²)
96.8690	97.0367	-1.238	0.167	-7.413	Overrun	
96.8678	97.0092	-1.0438	0.1414	-7.382	201.41	7.02x10 ⁻⁴
96.8676	97.0218	-1.254	0.1542	-8.1328	209.84	7.34x10 ⁻⁴
96.8653	97.0211	-1.2134	0.1558	-7.7878	209.84	7.42x10 ⁻⁴
96.8661	97.0251	-1.1401	0.159	-7.1706	209.84	7.57x10 ⁻⁴
			Average	-7.5772		7.34x10 ⁻⁴

The average Q/M was found out to be $-7.5772 \mu\text{C/gm}$ and the average M/A for toner powder was found out to be $7.34 \times 10^{-4} \text{ gm/cm}^2$. These values were found to be similar to the values obtained by the test done using QMM setup with fixed cartridge developer assembly and sliding photoconductor driver assembly (Gokhale 2001). This setup successfully replicated the older design results and had less complicated design and test procedure.

As discussed before, powder developers were designed and fabricated to be used with both the “front end” of the toner powder cartridge and the charge and mass measurement test setup. These powder developers enabled the development of powders other than toner. Similar to toner powder cartridge, these powder developers are engaged

with the front-end and the charge and mass measurement setup by the pivoting arrangement.

The powder box in the developer assembly has two protruding arms attached to its front plate by screws. These arms have pivoting pins protruding outwards that are hooked into the slots on the support provided in charge and mass measurement test setup. This enables the powder box to pivot around the pins and get positioned on the transfer drum by its weight. As the developer roller gear is driven by the photoconductor drum gear, the weight of the developer assembly helps in keeping the two gears engaged all the time without any extra arrangement. The positioning of the powder box can be adjusted by changing the arm length and the angle that the arm makes with the front plate. The assembly of powder developer with the charge and mass measurement test setup is shown in the figures below (figure 5-11, solid model) (figure 5-12, cross-section).

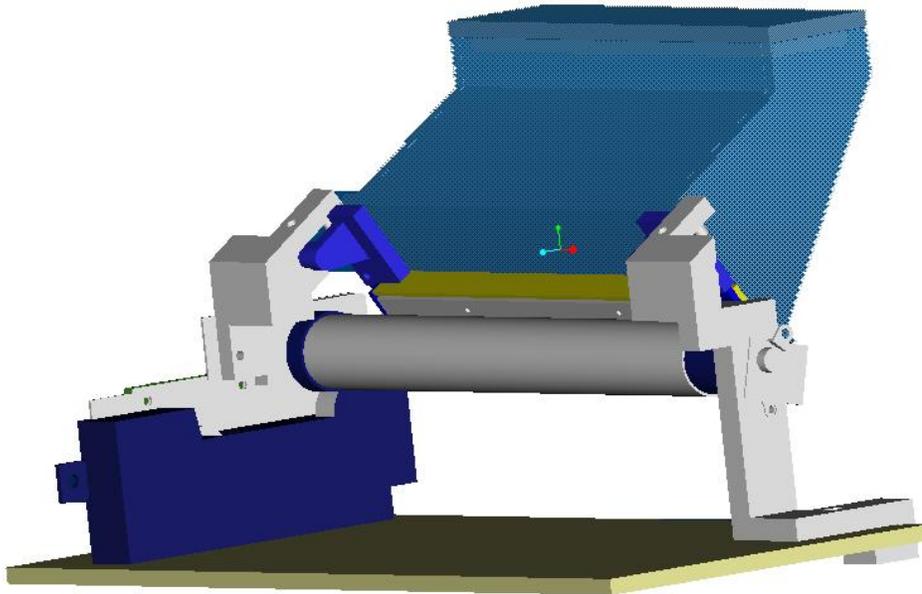


Figure 5-11. Solid Model of Assembly of Developer and Charge and Mass Measurement Test Setup

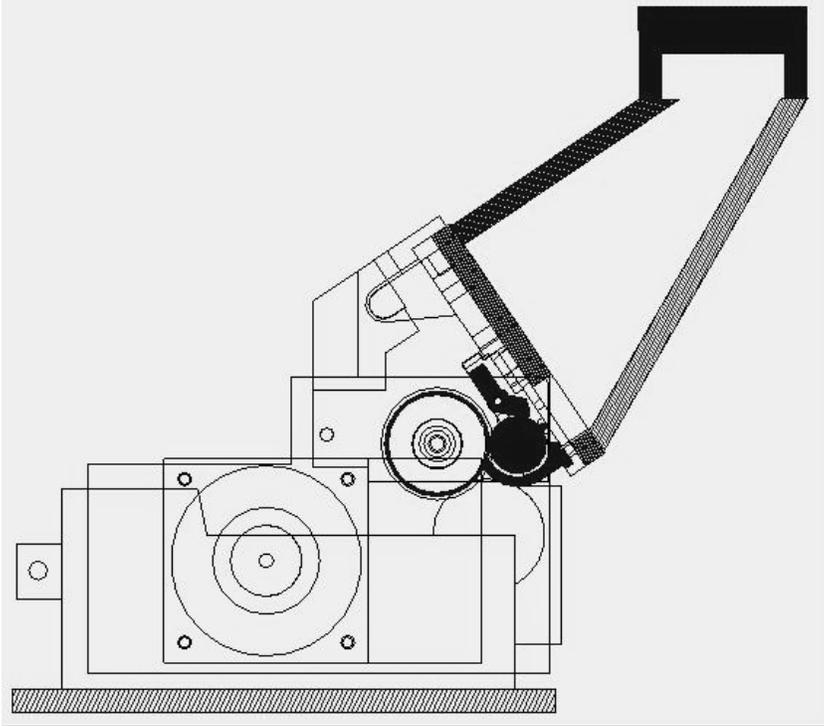


Figure 5-12. Cross-section of Charge and Mass Measurement Test Setup with Improved Developer Assembly

Independent Charge and Mass Measurement Test Setup

As seen in the last two charge and mass measurement test setups, both of them were based on developing of powder on the photoconductor drum driven by the stepper motor and gearbox assembly originally used in the Laser printer. The stepper motor rotates the photoconductor drum at a fixed speed and hence there is no speed control. It was also necessary to discharge and clean the photoconductor surface before it goes for the next cycle. This demanded more photoconductor surface area to be available for assembling these new additions which was not possible with the small diameter photoconductor drum available from the Laser printer.

Therefore it was decided to build a charge and mass measurement test setup independent of the restrictions of borrowed laser printer mechanisms. This new design

configuration has its own controllable drive motor, transfer roller, developer, charger, and cleaning mechanism. Before going into the detail design of the charge and mass measurement test setup, some basic knowledge about powder behavior and photoconductor cycle is essential.

This particular charge and mass measurement test setup was designed to be used with powders of any kind including polymers and metals. Polymers and metals represent the two categories of materials available based on their response to electricity; while polymers represent insulator family, metals represent the conductor family. For the charge and mass measurement tests conducted with the powders, iron and nylon-12 are chosen from the conductor and insulator families respectively. Iron is used due to its easy availability and nylon-12 is used because of its good developing characteristics on photoconductor drum (details presented in chapter 7).

Design Considerations

The insulators can be charged triboelectrically when they are rubbed against the doctor blade and developer roller. They also get charged when rubbed against a conductor surface connected to the voltage source (injection charging). They have surface and volume charge densities and do not get discharged easily. The charged polymers can develop over conducting as well as insulating surfaces. Consider a charged polymer powder placed on a conducting plate (which provides charge to the polymer by injection). If a grounded electrode is brought near this plate, a field will be created which will produce force on the charged polymer powder to travel to the grounded electrode. Once the polymer powder reaches the grounded electrode, it remains attached to the electrode due to the image forces created by the opposite charges flown to the grounded plate from ground due to the presence of the developed polymer powder. It does not matter if the

grounded plate surface is conductive or insulative, as the insulative polymer powder does not lose charge even when in contact with a conductive grounded surface. This is not the case with conductive powders.

The metals on other hand get charged when they are placed in an electric field created by charged surface (induction charging) and also when they are in contact with conducting bodies connected to voltage supply. Metals cannot support volume charge density and all the charges are present on them are on the surface. Conductors cannot get developed on a conducting surface, which can be explained as follows.

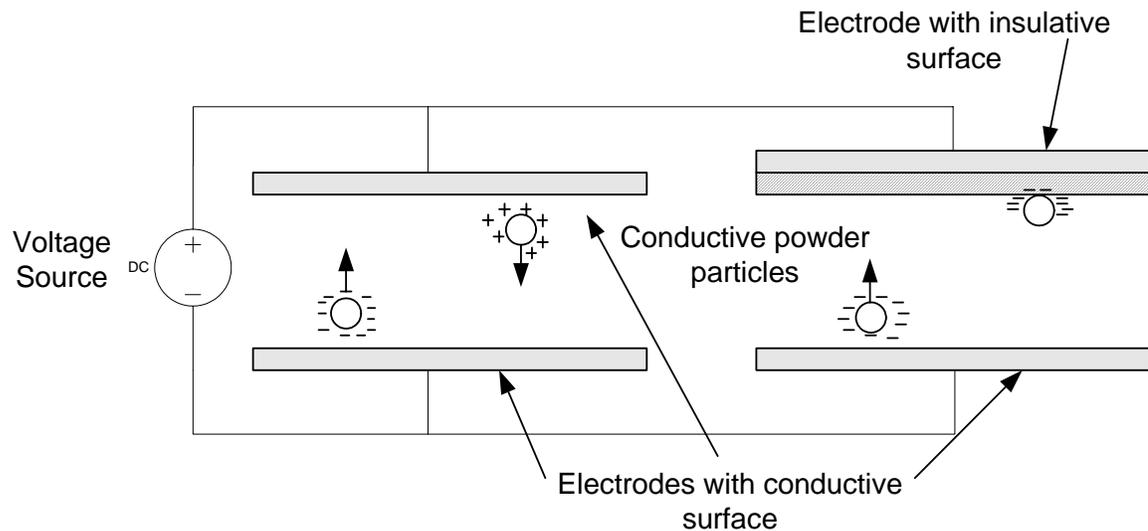


Figure 5-13. Schematic Illustration of Behavior of Conductive Powder Particle in the Presence of Conductive and Insulative Electrode Surfaces

Consider a metal particle in an electrostatic field between two metal electrodes. One of the electrodes is provided with positive voltage and the other with negative voltage. If initially the particle is in contact with the negative electrode, it will get charged negative and move in the direction of the positive electrode. When it reaches the positive electrode it will lose its charge and get positively charged and move in the opposite direction towards the negative electrode. Once it touches the negative electrode it loses its charge and gets negatively charged and the cycle repeats. So, when we place

conductive powder particles between two electrodes with conductive surfaces a powder cloud is formed due to bouncing of particles between the electrodes.

When the charged metal particle encounters the insulator surface it does not lose its charge to the electrode. The particle is attached to the insulator surface by the electrostatic force of attraction by the opposite charge present in the electrode at the backside of the insulator. So, to develop conductive powder on a surface, the surface must be an insulator.

Due to the above considerations, the drum on which the powders would be developed in the QMM setup should be a metal drum with an insulator cover. It is more desirable if the insulator has a high dielectric strength to withstand high potential differences in the developing region. Mylar sheet is suitable for this requirement and so is used as the insulative covering over the metal transfer drum.

When one layer of charged powder gets developed and then cleaned off the drum surface to make the surface ready for the next layer of powder, the powders leave some of their charge on the surface. This charge is of the same sign as that of the freshly charged powders. If this is not neutralized before each development, the charge gets accumulated and prevents the development of more powder on the surface due to electrostatic repulsion. To prevent this, a charge roller is placed on the drum which discharges the surface of the transfer drum by getting rubbed against it after it has been cleaned. The charge roller is provided with ac voltage that tries to charge the surface in both signs, which effectively discharges it. The charge roller is placed between the cleaning region and the development region of the developer cycle.

Stages of Charge and Mass Measurement Test Cycle

The charge and mass measurement test setup is based on a part of the electrophotography cycle. The test cycle does not include some of the stages of the electrophotography cycle dealing with printing of developed powder on a substrate. The electrophotography cycle is explained in detail in chapter 3. In the charge and mass measurement test cycle, the events are distributed around the transfer drum. Powder is developed on the transfer drum from the developer roller and gets collected in the cleaner box when the cleaning blade cleans the surface of the drum. The drum surface is then discharged to make the surface ready for the next development.

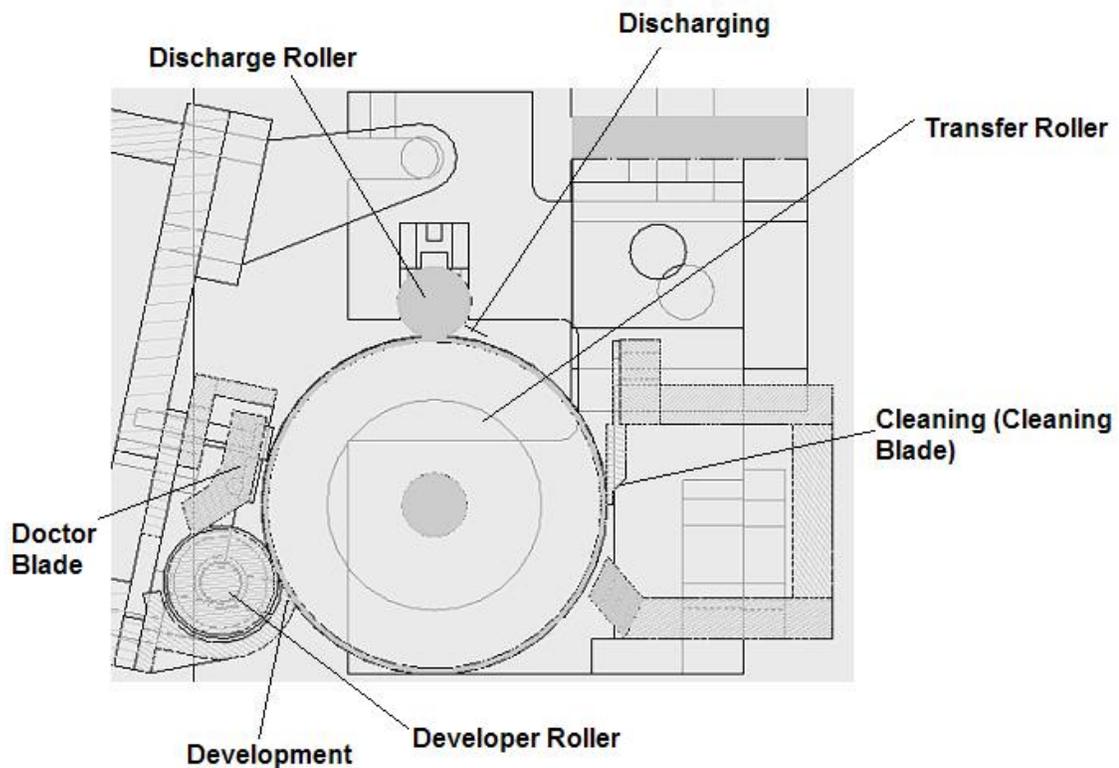


Figure 5-14. Different Stages of the Test Cycle with respect to the Cross-sectional view of the Charge and Mass Measurement Test Setup.

Design and Building of the Charge and Mass Measurement Test Setup

The discussions above serve as guidelines for the design and building of the charge and mass measurement test setup. In this section detailed design and assembly of the test setup is discussed. As a good design practice the design of the test setup was made in a modular fashion which allows individual parts to be assembled to form subassemblies and these subassemblies are assembled to form the final assembly. Each of these subassemblies is independent of each other and can be easily removed from the setup for experimental or repairing purposes. The charge and mass measurement test setup is made of three major subassemblies. These include the transfer drum assembly, the cleaner box assembly and the motor and frame assembly.

Transfer Drum Assembly

The transfer drum assembly is made of the transfer drum, the charge roller, drive attachments and support assembly to fix it to the frame of the charge and mass measurement setup. The transfer drum is made of a two-inch diameter aluminum pipe covered with Mylar sheet, which provides an insulative surface for conductive powder development. The end caps of the drum are made of high-density polymer and have interference fit with the drum. These end caps provide low frictional surface against side supports during rotation. A steel rod is used as the axis of the drum, which passes through the end caps and rests in the holes provided on the side support plate. These holes work as bearings for the axis to rotate.

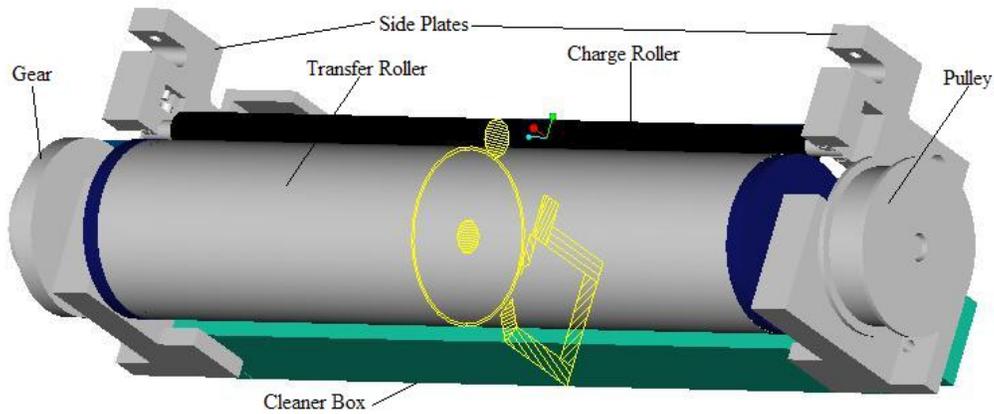


Figure 5-15. Solid Model of Transfer Drum and Cleaner Box Assembly (with Cross-sectional view)

On one side of the drum there is a pulley and on the other there is a gear, both tightly assembled with the axis of the drum. A servomotor, which is independently controlled by Galil Motion Controller, is used to drive the pulley through a timing belt. The timing pulley and belt drive provides a positive drive between the servomotor and the transfer drum without any slip. This also gives flexibility in the placement of the motor in the whole assembly, which is possible because the length of the belt can be altered to suit any convenient location for the motor and this is difficult to attain with a gear drive. The transfer roller drives the developer roller by gear arrangement. This gear drive is formed by meshing of gear of the transfer roller with the gear on the developer roller. This arrangement maintains the same surface velocities of the developer roller and the transfer drum at the development zone which is necessary for better development. This is because, if the surface velocity of the developer roller surface is slower than the transfer drum surface then very less powder will get developed and if it is faster then there will be more powder coming out of the box, when not developed, may get accumulated in the lower lip and leak.

The charge roller is placed pressed on the transfer drum surface and is located between the cleaner box assembly and the developer assembly. Its role is to discharge the surface of the development roller after the surface is cleaned off the developed powder. This discharging of the surface removes any unwanted charge buildup on the transfer roller surface which may affect the powder development.

The charge roller is a steel rod covered with a conductive polymer and is held pressed against the transfer roller surface by spring-loaded holders. The surface of the charge roller is smooth for uniform discharge of the transfer roller surface. This roller rolls on the transfer drum surface by friction.

Cleaner Box Assembly

The cleaner box is a rectangular box with a cleaning blade attached to it. The cleaning blade which was originally used to clean the photoconductor drum in the laser printer cartridge is modified to be used to clean the transfer drum in this application. It has a high friction flexible polymer sheet attached at its end to clean the roller surface. The cleaner-box has flanges on both of its sides that have screw holes to fix the assembly with the rest of the charge and mass measurement setup. By tightening or loosening these screws the pressure at which the blade is pressed against the transfer drum surface is varied. This kind of arrangement makes it easier to weigh the developed powder mass by removing the cleaner box from the assembly and weighing it with the powder in it. There is a chance of powder leaking by not getting caught by the bottom lip of the cleaner box during the cleaning process. This is avoided by attaching a thin flexible polymer sheet at the bottom edge of the box that acts as a one way valve as it allows the developed powder to pass through, but does not allow any cleaned powder falling down to leak. The

schematic below shows the transfer drum assembly and the cleaner box assembly with the relative position of the components.

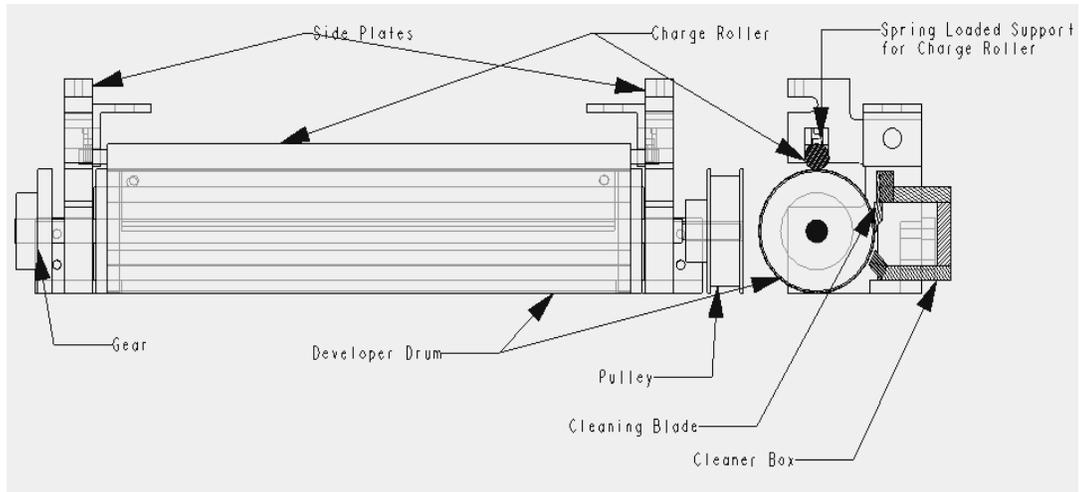


Figure 5-16. Front view and Side Cross-sectional view of the Transfer Drum Assembly and the Cleaner Box Assembly.

Motor and Stand Assembly

The whole test setup is supported by an aluminum stand which has leg supports made of angle brackets. These angle brackets have holes at the base for the stand to be bolted down and fixed to any base plate for extra stability. The stand has holes on the top bridge to bolt the transfer drum assembly to it and hang from it. The cleaner box assembly is screwed onto the side plates of the transfer drum assembly and the developer assembly hangs from the pivot holes provided on the side plates of transfer assembly. The servomotor that drives the setup is attached by screws to one side of the stand. The screws are attached through elliptical slots made to adjust the position of the motor and tighten the timing belt by sliding the screws up or down along the slots. The Galil Motion controller controls the motion of the servomotor by providing signals generated from the commands given by the software interface. These signals are amplified for the motor

drive by using amplification circuitry. The figure below shows the complete assembly of the charge and mass measurement test setup with the powder developer.

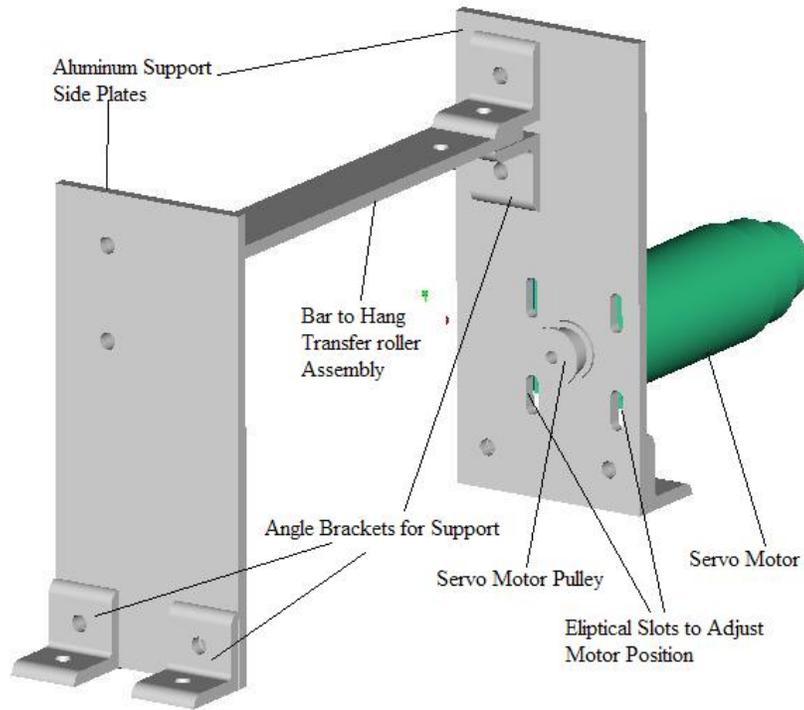


Figure 5-17. Solid Model of Motor and Stand Assembly

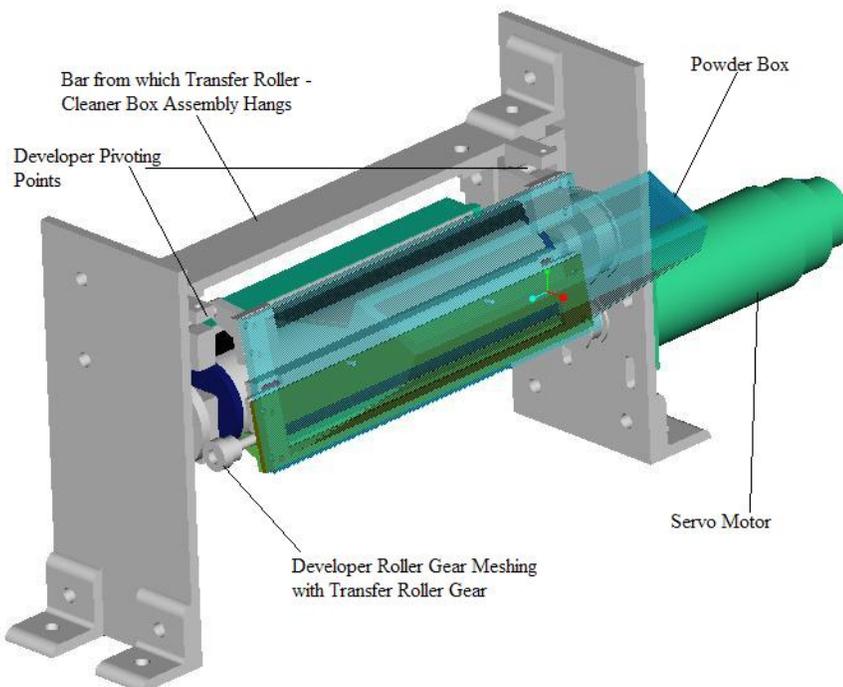


Figure 5-18. Complete Assembly of Powder Developer with Charge and Mass Measurement Test Setup

Experimental Results

Experiments were conducted to determine the charge per unit mass of iron and nylon –12 powders. The charge and mass measurement values were evaluated and the dependence of these values with the experimental variables was investigated. The following tables present the experiments done and the observations reported.

Experiments with Iron Powder

The following experiment was done to find out the effect of the number of revolutions of the transfer drum on the value of Q/M when the voltage applied remains constant.

Size of powder = 60 μ m diameter

Constant Charging Voltage = 500V

Voltage on Discharge Roller = 960V A.C. (p-p) 2.5KHz (explained in chapter 6)

Table 5-2. Variation of the Q/M readings with the number of revolutions of the transfer roller

Number of Revolutions	Initial Mass (M _i)	Final Mass	Initial Charge	Final Charge	Change in Mass(g)	Change in Charge(μ C)	Q/M (μ C/g)
2	230.931	231.727	83 nC	0.2 μ C	0.796	0.117	0.147
4	231.727	232.151	63 nC	0.15 μ C	0.424	0.087	0.205
6	232.151	233.328	-6 nC	-153nC	1.177	0.147	0.125
8	234.811	236.294	-32 nC	0.51 μ C	1.483	0.478	0.322
10	236.294	238.121	-10 nC	0.27 μ C	1.827	0.26	0.142

Other than the reading for eight revolutions, it can be seen that the value of Q/M remains almost constant with a small fluctuation which can be attributed to experimental errors. This can be explained by assuming that iron develops in a monolayer.

To find out the dependence of the value of Q/M on the voltage applied to charge the powder, we have the following experiment. In this experiment we increase the

voltage from 500V to 1500V and back to 500V. The number of revolutions of the transfer drum remains constant at 2.

Number of revolutions = 2

Voltage on Discharge Roller = 960V A.C. (p-p) 2.5KHz

Table 5-3. Variation of Q/M measurement with the increase in voltage supplied for development while the number of revolutions of the transfer drum remains constant.

Charging Voltage	Initial Mass	Final Mass	Initial Charge	Final Charge	Change in Mass	Change in Charge	Q/M ($\mu\text{C/g}$)
500	231.415	231.873	29nC	137nC	0.458	0.108	0.231
1000	231.873	232.295	81nC	0.53 μC	0.422	0.449	1.064
1500	232.295	232.812	63nC	1.52 μC	0.517	1.457	2.818
1500	232.812	233.323	35nC	0.91 μC	0.511	0.875	1.712
1000	233.323	233.775	19nC	0.22 μC	0.452	0.201	0.445
500	233.775	234.214	10nC	98nC	0.439	0.088	0.200

This indicates that Q/M depends on the applied voltage to charge the powder. The increase in voltage causes increase in the value of Q/M and vice versa. This can be explained for the metal powders as follows. When we apply higher charging voltage, the charge on the powder particle increases due to the relation $Q = CV$, where C is the capacitance of the powder and is dependent on the geometry of powder and the dielectric constant of the medium of development. So for a powder particle of a particular size developed in a particular medium, the charge on the powder depends on the voltage applied. When conductive powders develop, they form a monolayer of development. This limits the powder mass developed on the transfer drum surface. Therefore, when voltage increases, Q/M increases due to the increase of charge and constant mass development. These two trends can be observed from the table above.

Experiments with Nylon – 12 Powder

The following experiment was done to find out the effect of the number of revolutions of the transfer drum on the value of Q/M when the voltage applied remains constant.

Size of powder = 25 - 30 μ m diameter

Constant Charging Voltage = -500V

Voltage on Discharge Roller = 960V A.C. (p-p) 2.5KHz

Table 5-4. Variation of the Q/M readings with the number of revolutions of the transfer roller

Number of Revolutions	Initial Mass (M _i)	Final Mass	Initial Charge	Final Charge	Change in Mass(g)	Change in Charge(μ C)	Q/M (μ C/g)
2	230.269	230.275	134 nC	0.193 μ C	0.006	0.059	9.833
4	230.275	230.293	23 nC	0.258 μ C	0.008	0.235	29.375
6	230.293	230.303	35 nC	0.420 μ C	0.010	0.385	38.5
8	230.303	230.316	47 nC	0.612 μ C	0.013	0.565	43.46
10	230.316	230.342	47 nC	0.763 μ C	0.026	0.716	27.538

It can be seen that the value of Q/M is fluctuating. Except the last reading, we can see an increase in the Q/M value as the number of revolutions is increased. This can be explained by considering that the charge on the developed polymer powders is due to triboelectric charging by rubbing against the roller and the blade. More number of revolutions means more rubbing action for triboelectric charging and so the charge on each particle goes up.

To find out the dependence of the value of Q/M on the voltage applied to charge the powder, we have the following experiment. In this experiment we increase the voltage from -500V to -3000V. The number of revolutions of the transfer drum remains constant at 3.

Number of revolutions = 3

Voltage on Discharge Roller = 960V A.C. (p-p) 2.5KHz

Table 5-5. Variation of Q/M measurement with the increase in voltage supplied for development while the number of revolutions of the transfer drum remains constant.

Charging Voltage	Initial Mass	Final Mass	Initial Charge	Final Charge	Change in Mass	Change in Charge	Q/M ($\mu\text{C/g}$)
-500	230.342	230.348	4nC	0.220 μC	0.006	0.196	32.67
-1000	230.381	230.432	25nC	0.156 μC	0.051	0.131	2.569
-1500	230.432	230.491	49nC	0.126 μC	0.059	0.077	1.305
-2000	230.491	230.548	12nC	0.078 μC	0.057	0.066	1.158
-2500	230.548	230.689	13nC	0.024 μC	0.141	0.011	0.078
-3000	230.689	230.805	15nC	0.056 μC	0.116	0.041	0.353

This clearly indicates that Q/M depends on the applied voltage to charge the powder. Interestingly, the increase in voltage causes a decrease in charge per unit mass readings, while it is normally expected to be not so when compared to conductive powders. Nylon – 12 is an insulator and the charged particles do not carry large charges like conductors. This can be seen by comparing the charge values of nylon with that of iron. The powders on the developer roller contain more number of low charged particles than highly charged particles. When the voltage is low the electric field in the development zone is good for only highly charged particles to get developed. As the voltage increases, the development field also increases and so now it is possible for the low charged particles to get developed. These low charged particles compete with the highly charged particles which results in the marginal decrease in the charge measurement. The development of large number of these low charged particles explains the increase in the mass measurement. Due to the combination of both the effects there is a high rate of decrease in the value of charge per unit mass (Q/M) measurement.

CHAPTER 6 METAL POWDER DEVELOPMENT AND PRINTING

Printing of metal powder using electrophotography has many applications like printing circuit boards and making functional prototypes. As discussed in last chapter, there has been a lot of attempt in designing developer based on cascade development technology to help in printing of powders other than the commercial toner powder. All these developers were designed to replace the toner powder developer from the commercial laser printer. It takes a lot of time and effort to modify a commercial laser printer before it can be used for printing using ESFF. Each new model of printer released to the market becomes obsolete in 2-3 years. This makes the repair of the test bed difficult owing to the less availability of spare parts due to the phasing out of the printer.

There was a need to design and build a test bed which is independent of the use of laser printers and is modular so that any debugging of problems can be done easily. Chapter 8 discusses in detail about the design and building of the modified test bed. A simplified schematic in figure 6-1 explains the concept of the design.

The concept is based on the movement of a photoconductor plate in a straight line passing through the different stages of electrophotography. The development process is done by first charging the photoconductor plate, imaging with the laser imager and then developing powder upward, against the gravity, on the downward facing photoconductor plate. The photoconductor then reaches the build platform and prints the image of the powder. The discussion in this chapter is on the feasibility of such development and printing processes used for this concept. This will generate essential feedback

information on the designing and operating the test bed based on the flat photoconductor plate.

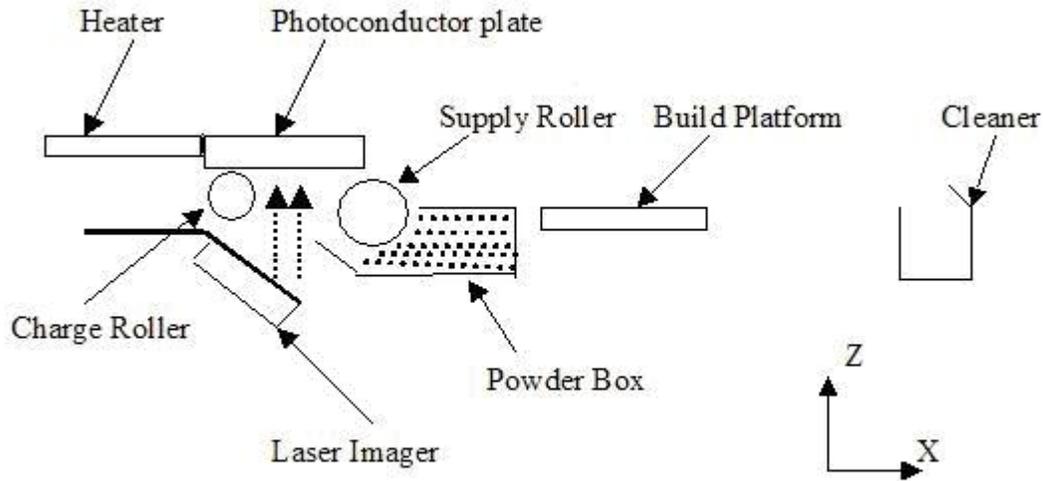


Figure 6-1. Concept of the New Modified Test Bed

Metal Powder Development

Powder development in the new test bed is done against gravity. This may create some limitations on this process as discussed in this chapter. The metal powder has some special properties related to development and transfer using electrostatic force, which is shared by all conductive powders. So, the discussions and experimental results presented in this chapter can be applied to any conductive powder. Iron powder was used for the experiments due to its easy availability, and the results are reported at the end of the chapter.

Metal powders can be developed in three ways:

- Applying voltage to the developer roller and grounding photoconductor plate
- Applying voltage to photoconductor plate and grounding developer roller
- Grounding both developer roller and photoconductor plate and charging the photoconductor surface

The first two methods are fundamentally the same as they both create electrostatic field between them by the application of voltage source to either the developer roller or the photoconductor plate while the other one is grounded.

In the first method the metal powder will get charged by being in contact with the developer roller when the grounded photoconductor is above the developer roller and an electric field is created between them. Development occurs due to the force created by the presence of the charged particle in electric field.

In the second method metal powder gets charged by induction when the photoconductor plate, connected to voltage supply, comes over the grounded developer roller and a field is created between them. The field creates force on the charged particle, which overcomes the gravitational pull to develop the powder on the photoconductor surface.

In the third method voltage supply is given to the charge roller, which is used to deposit charge on the photoconductor surface. The powder is charged by induction due to the field created by the charge on the photoconductor surface. In this case also the force due to electric field has to overcome the gravitational pull for the development to occur.

This third method is different than the first two methods because in the third method image can be created by discharging the deposited charge by UV laser. The powder gets charged oppositely to the charged areas in the image and gets attracted towards the charged regions, which limits the metal powder development to charged area development (CAD) only. So, this is the only method, which could integrate imaging as a part of the development process. The other two methods are only capable of printing

metal powders in thin uniform layers. In those cases, imaging can be done by the printing of image-wise layers of polymer adhesives between uniformly printed metal layers.

The metal powder development processes can be analyzed using standard electrostatic equations to determine the influential variables and the characteristic numbers, important for development process. This analysis is done in the following section.

Metal Development Theory

In the flat photoconductor plate test bed, development is done against gravity. As only the charged particles would experience the electrostatic force to overcome gravity and get developed on the photoconductor surface, this method of development helps in the separation of the charged and uncharged particles, which in turn helps in creation of sharper images and reduces background printing significantly. During development the powders have to overcome gravitational force, which would require large charge per unit mass. Later during transfer of the developed powder onto build platform the large charge per unit mass may make it difficult for the powder to overcome the electrostatic adhesion force and get printed on to the build platform. Therefore, a careful analysis of these processes has to be done to understand them well and be able to control them better.

Before getting on with calculation of different parameters for development, the basic properties of the iron powder used for the experiment are discussed below. The fundamental electrostatic parameters are also stated for reference.

Constant Parameters used in Calculations

The mass of a single iron powder particle is calculated below assuming the powder particle as a spherical particle with radius r .

Diameter of the iron powder particle used in experiment = 60 micron

$$\text{Volume of sphere} = \frac{4}{3}\pi r^3 = \frac{4}{3} \times 3.141 \times (30 \times 10^{-6})^3 = 1.131 \times 10^{-13} \text{ m}^3 \quad (1)$$

$$\text{Density of iron (approximately)} = 7.87 \times 10^3 \text{ Kg/m}^3$$

$$\text{Mass of a particle} = 1.131 \times 10^{-13} \text{ m}^3 \times 7.87 \times 10^3 \text{ Kg/m}^3 = 8.9 \times 10^{-10} \text{ Kg} \quad (2)$$

$$\text{Breakdown electric field of air} = 3.0 \times 10^6 \text{ V/m}$$

$$\text{Permittivity of air} = 8.854 \times 10^{-12} \text{ C}^2/(\text{N}\cdot\text{m}^2)$$

Charge per Unit Mass (Q/M) Calculations

As discussed before, charge per unit mass (Q/M) of the developing powders determines the electrostatic force on them and also the quality of development. In the calculations shown below, the minimum and the maximum allowed Q/M of iron powder particles used in the experiment are calculated.

The schematic below displays the simple force model of a single iron particle subjected to electrostatic and gravitational forces during development.

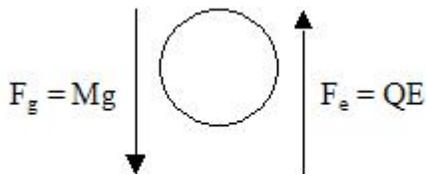


Figure 6-2. Forces Acting on a Powder Particle During Development

For powder development to occur, the electrostatic force (F_e) should be greater than or equal to the gravitational force (F_g). To calculate the minimum Q/M required for development, we use the condition when the electrostatic force on an iron powder particle is just able to overcome force of gravity. For this condition we have:

$$F_g = F_e \quad (5)$$

$$Mg = QE \quad (6)$$

$$\frac{Q}{M} = \frac{g}{E} \quad (7)$$

Here, 'g' is acceleration due to gravity and is constant. So, Q/M is controlled by the value of electrostatic field 'E'. By increasing the value of E we can reduce Q/M. The maximum value of E can reach 3.0×10^6 V/m. So, substituting the value of electric field we get the minimum value of Q/M to be,

$$\left(\frac{Q}{M}\right)_{\min} = \frac{9.81 \text{ m/s}^2}{3.0 \times 10^6 \text{ V/m}} = 3.27 \times 10^{-6} \text{ Coulomb/Kg} = 3.27 \text{ nC/gm} \quad (8)$$

To find the minimum charge on the iron powder particle used in the experiment to allow it to develop, we use the mass of the particle:

$$Q_{\min/\text{particle}} = 3.27 \times 10^{-6} \text{ Coulomb/Kg} \times 8.9 \times 10^{-10} \text{ Kg} = 2.91 \times 10^{-15} \text{ Coulomb} \quad (9)$$

The above calculation shows that $\left(\frac{Q}{M}\right)_{\min}$ is independent of the material properties of the powder used for development and can be used for any powder.

Again from Gauss Law we know that,

$$E = \frac{\sigma}{\epsilon_0} = \frac{Q/A}{\epsilon_0} = \frac{Q}{\epsilon_0(4\pi r^2)} \quad (10)$$

And,

$$M = \frac{4}{3} \pi r^3 \rho \quad (11)$$

$$\left(\frac{Q}{M}\right) = \frac{4\pi\epsilon_0 E r^2}{\frac{4}{3}\pi r^3 \rho} = \frac{3\epsilon_0 E}{\rho r} \quad (12)$$

$$\left(\frac{Q}{M}\right)_{\max} = \frac{3\epsilon_0 E_{\max}}{\rho r} = \frac{K}{\rho r} \quad (14)$$

$\left(\frac{Q}{M}\right)_{\max}$ is the maximum charge per unit mass that a powder particle can have before it

produces electric discharge due to breakdown of air. Unlike $\left(\frac{Q}{M}\right)_{\min}$, $\left(\frac{Q}{M}\right)_{\max}$ is

dependent on the powder size and is inversely proportional to the radius of the powder

particle. Finding $\left(\frac{Q}{M}\right)_{\max}$ for iron powder particle used in the experiment we get:

$$\begin{aligned}\left(\frac{Q}{M}\right)_{\max} &= \frac{3\varepsilon_0 E_{\max} r}{\rho r^2} = \frac{3\varepsilon_0 E_{\max}}{\rho r} = \frac{3 * 8.854 \times 10^{-12} * 3.0 \times 10^6}{7.87 \times 10^3 * 30 \times 10^{-6}} \\ \left(\frac{Q}{M}\right)_{\max} &= 3.375 \times 10^{-4} \frac{C}{Kg} = 3.375 \times 10^{-7} \mu C/gm = 0.338 \mu C/gm\end{aligned}\quad (15)$$

This gives the maximum charge an individual powder particle can have without sparking,

which is calculated as follows:

$$Q_{\max/particle} = \left(\frac{Q}{M}\right)_{\max} M = 3.375 \times 10^{-4} \frac{C}{Kg} * 8.9 \times 10^{-10} Kg = 3.0042 \times 10^{-13}$$

Coulomb (16)

Maximum Surface Charge Density

The following calculation estimates the maximum surface charge density that can be sustained by the powder particles in air. The calculation is done considering electrical

breakdown field limit of air, $E_{\max} = 3.0 \times 10^6$ V/m.

From Gauss law,

$$E = \frac{Q}{A\varepsilon_0} = \frac{\sigma}{\varepsilon_0}$$

$$\sigma_{\max} = E_{\max} \varepsilon_0 = 3.0 \times 10^6 * 8.854 \times 10^{-12} = 2.656 \times 10^{-5} C/m^2$$

This is the maximum charge density that a surface can have when it is kept in air. This limit is called Gaussian Charge Limit. This is independent of the material properties.

Electric Field Range

We know that the maximum allowable field limit for powder development in air is 3.0×10^6 V/m. The following calculation finds the minimum field limit for powder development considering that the powder particle is charged to its maximum allowed charge limit, and the electrostatic force for development just overcomes the force of gravity.

$$QE = Mg$$

$$E_{\min} = \frac{Mg}{Q_{\max}}$$

For the iron particle used for the experiment, using the maximum charge value from equation 16, we get:

$$E_{\min} = \frac{Mg}{Q_{\max}} = \frac{8.73 \times 10^{-9}}{3.0042 \times 10^{-13}} = 2.9059 \times 10^4 \frac{V}{m}$$

This suggests the value of electrical field in the development zone should be within the range of 2.9×10^4 V/m to 3.0×10^6 V/m.

The maximum voltage available from the voltage source is 5000V. The gap between the developer roller and the photoconductor surface during development has a minimum limit to avoid breakdown of air. This gap is calculated as follows:

$$h_{\min(\text{experiment})} = \frac{V_{\max}}{E_{\max}} = \frac{5000V}{3.0 \times 10^6 \frac{V}{m}} = \frac{5}{3} \text{mm} = 1.67 \text{mm} .$$

During experiment the gap is taken to be more than or equal to 2mm to avoid any sparking due to air breakdown.

Calculation of Forces Involved During Development

The electrostatic force and the gravitational force on a powder particle are dependent on the size of the particle. This relation is evaluated below.

$$F_{e/\max} = Q_{\max} * E_{\max} = (E_{\max} 4\pi\epsilon_0 r^2) * E_{\max} = 4\pi\epsilon_0 (E_{\max})^2 r^2 = K_e r^2$$

$F_{e/\max}$ is directly proportional to the square of the radius of the powder particle.

$K_e = 4\pi\epsilon(E_{\max})^2$ where, ϵ = permittivity of the medium of development. Here, the medium of development is air so $\epsilon = \epsilon_0$. So, K_e does not depend on powder material but on the medium of development.

$$F_g = Mg = \rho v g = \rho \frac{4}{3} \pi r^3 g = \left(\rho \frac{4}{3} \pi g \right) r^3 = K_g r^3$$

F_g is directly proportional to the cube of the radius of the powder particle.

$K_g = \rho \frac{4}{3} \pi g$ where, ρ = density of powder material. So, K_g is dependent on the material used for development and not the medium of development.

To determine the ability of the electrostatic force available for development to overcome the gravitational force and develop the powder on the photoconductor surface, comparing these forces.

The force due to gravity on the powder particle is,

$$F_g = Mg = 8.9 \times 10^{-10} \text{ Kg} \times 9.81 \frac{m}{s^2} = 8.7309 \times 10^{-9} \text{ N}$$

The maximum electrostatic force available for development is found out by multiplying the maximum charge that can be attained by a powder particle (equation 16) and the maximum field limit due to air breakdown.

$$F_{e/\max} = Q_{\max} * E_{\max} = 3.0042 \times 10^{-13} \text{ Coulomb} * 3.0 \times 10^6 \frac{\text{V}}{\text{m}} = 9.0126 \times 10^{-7} \text{ N}$$

The ratio between these forces is:

$$\frac{F_{e/\max}}{F_g} = \frac{9.0126 \times 10^{-7}}{8.7309 \times 10^{-9}} = 103.23$$

So, the maximum electrostatic force available for development is 100 times stronger than the gravitational pull. This gives a wide range for the electrostatic force to be less than the maximum value and still be good for development.

Calculation of Maximum Powder Particle Radius for Development

By considering the last calculations relating electrostatic and gravitational forces to the powder particle size it can be seen that the force of gravity is directly proportional to the cube of the particle radius and its rate of increase with increase in radius is more than the rate of increase of the electrostatic force, which in turn is directly proportional to the square of the radius. This indicates that there is a particular powder particle radius beyond which there can be no development. This radius limit is calculated by equating both the forces.

$$\begin{aligned} F_{e/\max} &= F_g \\ K_e r^2 &= K_g r^3 \\ r_{\max} &= \frac{K_e}{K_g} = \frac{4\pi\epsilon_0 (E_{\max})^2}{\rho \frac{4}{3} \pi g} = \frac{3\epsilon_0 (E_{\max})^2}{\rho g} \end{aligned}$$

Calculating this radius for the iron powder developed in air:

$$r_{\max} = \frac{3 \times 8.8542 \times 10^{-12} \times (3.0 \times 10^6)^2}{7.87 \times 10^3 \times 9.81} = 3.1 \times 10^{-3} \text{ m} = 3.1 \text{ mm}$$

3.1 mm = 3100 μm = 6200 μm diameter = 3.5 mesh (ASTM US standard)

This derivation suggests that it will be difficult to develop any iron powder particle with radius above 3.1mm, when air is the medium of development. This argument is applicable to this particular type flat plate development method where development is done against gravity.

This analysis does not take into account the other forces acting against the electrostatic force, like the van der waal's force of attraction between the iron particles themselves and between an iron particle and the surface of the supply roller. If these forces are also taken into consideration then the maximum limit on the powder radius will be less than the current value.

Metal Powder Transfer Process Theory

After development, the photoconductor plate is moved over to the build platform where the powder is transferred electrostatically on to the built part as the next build layer. During this transportation the powder should not fall off the photoconductor surface due to gravity. This is avoided by the electrostatic force due to the image charge on the photoconductor, which keeps the powder from falling. This force is calculated as:

$$F_{im} = \frac{Q^2}{4\pi\epsilon_0(2r)^2} = \frac{(E4\pi\epsilon_0r^2)^2}{4\pi\epsilon_0(2r)^2} = \pi\epsilon_0E^2r^2$$

$$F_{im/\max} = \pi\epsilon_0(E_{\max})^2r^2 = K_{im}r^2$$

$F_{im/\max}$ is directly proportional to the square of the radius.

$$F_g = Mg = \rho vg = \rho \frac{4}{3} \pi r^3 g = \left(\rho \frac{4}{3} \pi g \right) r^3 = K_g r^3$$

It can be observed by comparing the dependence of $F_{im/\max}$ and F_g on the change in particle size, that there is a maximum radius of powder particle exists more than which

the photoconductor plate will not be able to hold the powder on its surface. This maximum radius limit of a particle can be found out by equating both the forces.

$$F_{im/\max} = F_g$$

$$\pi\epsilon_0(E_{\max})^2 r^2 = \left(\rho \frac{4}{3} \pi g\right) r^3$$

$$r_{\max} = \frac{\pi\epsilon_0(E_{\max})^2}{\rho \frac{4}{3} \pi g} = \frac{3\epsilon_0(E_{\max})^2}{4\rho g}$$

This value of r_{\max} is 1/4th of the value of r_{\max} calculated by equating the electrostatic and gravitational forces during development.

$$\text{So, } r_{\max} = \frac{3.1 \times 10^{-3}}{4} m = 0.775 mm = 775 \mu m = 20 - 25 \text{ mesh}$$

The iron powder particle used for experiment has diameter of 60 microns which is less than the above calculated value of powder radius and so it can be developed on to the photoconductor and retained by it until the powder layer is transferred and printed over the build platform. This value of maximum radius of particle to hold on to the photoconductor surface is calculated without taking Van der waal's force between the powder particle and the photoconductor surface. If that is taken into consideration then this maximum radius limit will increase.

Powder Transfer Methods

The developed powder is transferred onto the build platform by creating electrostatic field between the photoconductor plate and the build platform. Field creation for transfer can be done in four ways.

- Applying voltage to the build platform and grounding the photoconductor plate
- Applying voltage to the photoconductor plate and grounding the build platform

- Grounding photoconductor plate and charging the top surface of the built part on the build platform to attract the developed powder to print
- Create a field on the backside of the photoconductor plate to repel the developed powder.

The first two methods are effective when the part height is small. When the part is made of insulator material, there is a voltage drop across the part height and so with increase in part height the voltage difference for powder transfer decreases leading to decrease in electrostatic field and which finally leads to decrease in powder transfer. Even when metal powder is transferred to form metal parts, there has to be insulated layers between two layers of metal powder (as metal powders do not develop on metal or conductive surfaces as explained in chapter 5) which can cause the voltage drop.

The other two methods use the field created by deposited charge on the top surface of the part and on the backside of photoconductor plate respectively. A corona charger is used to charge the top layer of the built part for creating a field. The surface of built part top layer can be charged by passing a corona charger over it (Dutta, 2002). The maximum charge that can be deposited is $2.64 \times 10^{-6} \text{Cm}^{-2}$ (Cross, 1987). This surface charge will have field of $3.0 \times 10^5 \text{Vm}^{-1}$, which is an order less than that the breakdown field of air. The surface cannot be charged till the field reaches the breakdown field of air because a field around the value shown above repels the incoming ions and they do not get deposited on the surface. This leaves us with the last method of creating field, by accumulating charge on the backside of the photoconductor plate to repel the powder off the surface as the field created by this method can go up to the breakdown field of air.

Capacitor Method of Powder Transfer (Conceptual)

A capacitor can be created at the backside of the photoconductor plate to accumulate charge. To form the capacitor, a metal plate may be placed on the backside of

the photoconductor plate. This plate will act as one of the electrodes for the capacitor, where the photoconductor plate acts as the other electrode. There is a dielectric layer covering over the conductive layer on the backside of the photoconductive material. This dielectric layer acts as the dielectric of the capacitor. The conceptual arrangement of the capacitor is presented in the schematic below. The capacitor back plate is supplied with voltage and the photoconductor plate is grounded. The charged powder is attached to the photoconductor plate by the attractive force of the image charge and van der waals force. For transfer this attractive force should be cancelled by repulsive force created by the charge accumulated in the above mentioned capacitor. This capacitor is illustrated in the following parallel plate model:

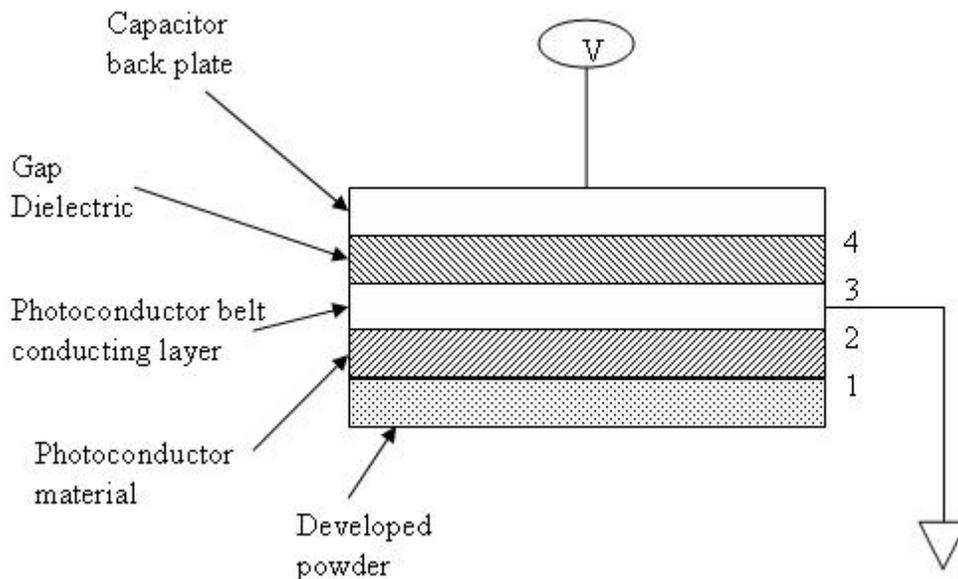


Figure 6-3. Schematic Model of the Capacitor Method of Powder Transfer (Conceptual)

As the voltage is applied to the capacitor back plate and the photoconductor plate is grounded, there is charge accumulation on either side of the capacitor. The applied voltage polarity is chosen to be opposite to that of the powder, so that the photoconductor plate accumulates charge of the same polarity as that of the developed powder, which

helps in repelling like charged developed powder. Then the connection to the ground from the photoconductor plate is cut off and so the charge is trapped in the photoconductor plate. The field by the charge accumulated in the capacitor still remains between the photoconductor plate and capacitor back plate. Then the voltage polarity of the capacitor back plate is reversed and so all the field lines due to the charge trapped in the photoconductor plate are directed towards the developed powder to repel the powder off the surface. This method can create higher fields than the other methods and does not require a field between the photoconductor plate and the build platform for the powder to transfer. This makes it a very useful technique to build thicker parts, and so it is necessary to understand this concept in detail. To experimentally verify the feasibility of this concept a very well designed setup is required due to the high likelihood of charge leak due to leakage current which can happen easily if the capacitor is not insulated properly. Attempts had been made to try to transfer powder using this method by using simple experimental setups which were not successful due to the sensitivity of the experiment. This concept is not further investigated in this thesis work.

Experimental Results

Before building the flat photoconductor plate test bed, it was necessary to simulate the development and printing process using a simple setup, to perform feasibility analysis of developing and transferring metal powder for printing using electrostatic forces. The setup consisted of a powder bed, developer electrode and transfer electrode.

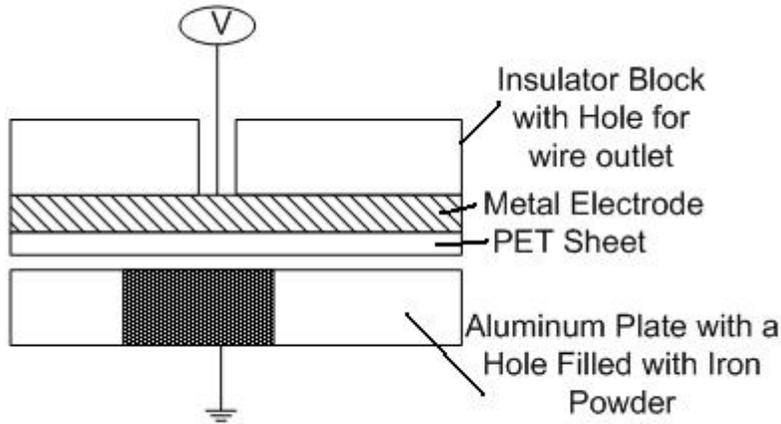


Figure 6-4. Schematic of the Test Setup for Development

The powder bed was made by depositing iron powder in an elliptical slot made in an aluminum plate. Voltage can be applied to this plate to create the field for development, and to charge the powder. The top surface of this powder bed can be leveled to form a uniform surface for development. For powder transfer experiments, the developer and the transfer electrodes are made similar to each other. They both have a sheet metal plate which is attached to an insulator block using PET. This PET also acts as the insulating cover on the surface of the electrode. The insulator blocks have through holes to allow electrical connection to the electrodes.

When the developed powder is wiped from the insulator surface, it leaves some charge behind. This charge buildup has to be neutralized by rolling a charge roller connected to ac voltage supply on the insulated surface. This step is necessary for continuing development on the surface. The first two experiments were done to identify the ideal ac voltage and the frequency to discharge the surface.

Determination of Discharging Voltage

The following experiment was done using the developer electrode to determine the ac voltage at which there is maximum discharging of the surface resulting in a neutral or

close to neutral surface. Some initial tests were done to narrow down the voltage range for approximate estimation. These tests revealed that a range between 950V ac p-p and 1050V ac p-p is the effective surface neutralizing voltage range. The readings taken between this range is presented. The test is done by first charging the PET surface by rubbing a piece of paper on it (triboelectric charging) then discharging it by rolling over a charge roller supplied with ac voltage. The surface voltage of PET surface is measured by using electrostatic voltmeter, which is a non-contact voltmeter. The frequency of ac voltage was at 500Hz.

Table 6-1. Experiment to determine the effective discharging and neutralizing ac voltage

AC Voltage	Surface voltage before discharge (V_1)	Surface voltage after discharge (V_2)	$V_1 - V_2$
950	1540	207	1333
	1206	274	932
960	526	170	356
	778	230	548
970	591	-86	677
	665	-60	725
980	782	-70	852
	316	-86	402
990	671	-230	901
	428	85	343
1000	916	310	606
	660	273	387
1010	490	114	376
	450	297	153
1020	535	70	465
	486	-145	631
1030	409	112	297
	548	22	526
1040	440	98	342
	350	45	305
1050	290	168	122
	550	166	384

By observing the third and fourth column we see that the combination of discharging of the charged surface to near zero with a large difference between the initial voltage and the final voltage is seen for 970V and 980V. For experimental purposes 970V ac p-p is chosen, as it is smaller between the two values.

Determination of Frequency of Discharging Voltage

This experiment was conducted to determine the frequency of ac voltage at which the discharging of the charged insulator surface of the developer electrode is the maximum. The procedure of this experiment is similar to that explained in the last experiment, but the only difference here is that the voltage is kept constant at 970V ac p-p and the frequency of the voltage is varied.

Table 6-2. Experiment to determine the frequency of the ac voltage for effective discharging

Frequency (Hz)	Surface Voltage before discharge (V_1)	Surface voltage after discharge (V_2)	Voltage difference ($V_1 - V_2$)
500	648	186	462
	602	282	320
1000	608	132	476
	750	247	503
1500	440	346	94
	835	276	559
2000	770	389	381
	500	373	127
2500	973	173	800
	952	116	836
3000	757	214	543
	668	168	500
3500	540	245	295
	804	251	553

Again for this experiment, looking at the third and the fourth column we observe that the combination of discharge of the surface to near zero with high voltage difference

between the initial and the final voltage readings is for 2500Hz. So, the discharging ac voltage should have a frequency of 2500 Hz for effective discharge.

From the above two experiments the discharging voltage that should be applied for discharging the photoconductor surface is 970V ac p-p at 2500 Hz. This value is an approximate experimental estimation and is used in other experiments for discharging developing surface.

Variation of Powder Development with Voltage

As stated before there are three methods of developing metal powder. This experiment attempts to find the relation between the amount of powder developed on the insulated developing electrode and the voltage applied to the developing electrode for development. In this experiment negative voltage is applied to the developing electrode, which induces positive charge on the iron powder. The positively charged powder gets developed on the PET surface. This charged powder when wiped clean from the surface, would leave positive charge on the PET surface. To discharge this we need a negatively biased ac voltage. The voltage for discharging/charging is taken to be $-1000V$ dc biased 970V ac p-p at 2500 Hz. The surface voltage of PET is measured after cleaning of the developed powder and after the discharging/charging process using electrostatic voltmeter. The electrode is weighed before and after development to find out the amount of powder developed. The experimental observations are presented below.

As seen from the table the amount of powder developed has no correlation with the increase in voltage. The amount of powder developed seems to be concentrated around a particular value, which supports the theory of monolayer development of conductive powder. The surface voltage measured after discharging is the combination of applied

voltage and the surface voltage as a result of discharging. The mass of powder developed is plotted with respect to the surface voltage using Matlab.

Table 6-3. Experiment to determine the dependence of powder development on the development voltage applied to developing electrode

DC voltage applied for development in V	Surface voltage before discharging (V_1) in V	Surface voltage after discharging (V_2) in V	Weight before development (W_1) gm	Weight after development (W_2) gm	Weight of powder developed ($W_2 - W_1$) gm
0	270	-302	61.810	61.861	0.051
	-460	-440	61.861	61.916	0.055
-100	-600	-418	61.917	61.983	0.066
	-433	-320	61.983	62.035	0.052
-200	-340	-395	62.035	62.087	0.052
	-439	-523	62.087	62.146	0.059
-300	-370	-345	62.146	62.202	0.056
	-256	-570	62.203	62.265	0.062
-400	-343	-407	62.264	62.314	0.050
	-312	-659	62.315	62.370	0.055
-500	368	-205	61.171	61.217	0.046
	52	-700	61.218	61.277	0.059
-600	-43	-703	61.278	61.331	0.053
	17	-320	61.332	61.383	0.051
-700	-20	-162	61.383	61.436	0.053
	69	-295	61.435	61.493	0.058
-800	125	-105	61.493	61.544	0.051
	-86	-530	61.544	61.596	0.052
-900	102	-193	61.596	61.654	0.058
	33	-188	61.653	61.706	0.053
-1000	203	-325	61.707	61.759	0.052
	21	-340	61.759	61.813	0.054

The figure below shows that increase in voltage does not have any significant effect on the amount of powder developed. This phenomenon can be explained by considering the theory of monolayer development. The following theoretical analysis evaluates the mass of the developed powder considering a monolayer development. This uses the value of area of development for calculation.

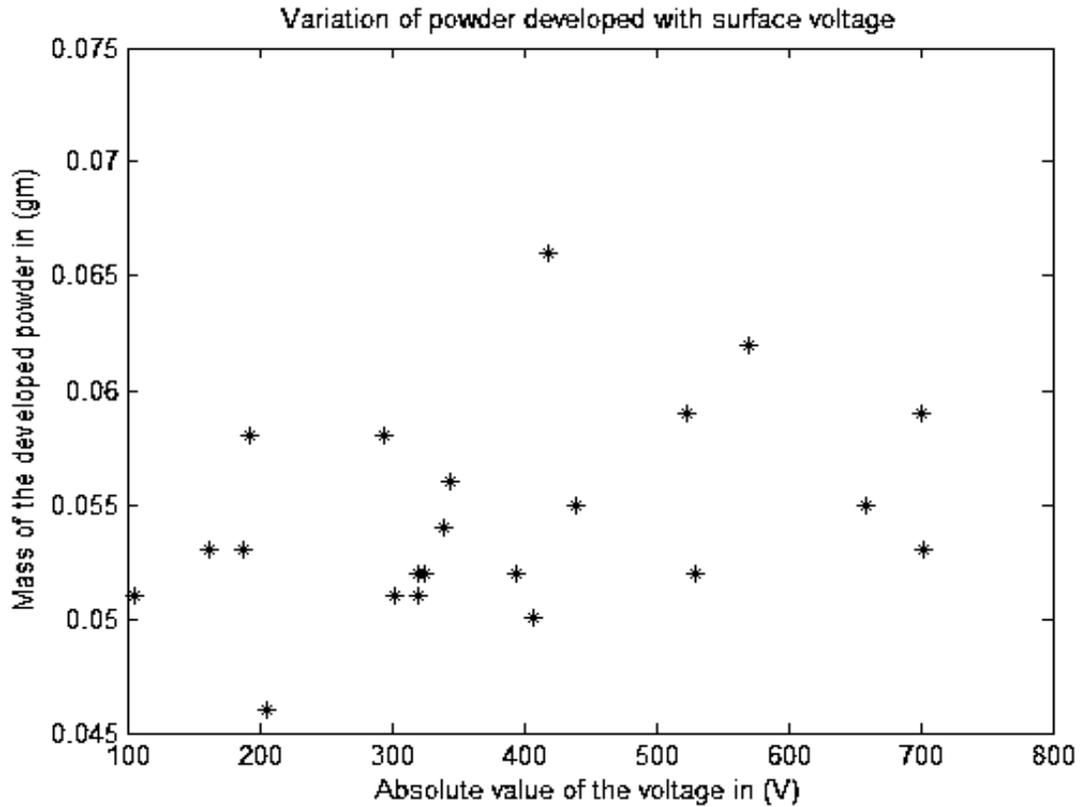


Figure 6-5. Plot of Variation of Mass of Powder Developed with respect to the Surface Voltage Available for Development

Calculating Mass of Monolayer Development

The mass of powder constituting a monolayer can be estimated if the area of development is known. The powder bed has a definite geometry because it is made by filling of a slot milled on an aluminum plate. The dimension of this slot is smaller than the dimension of the surface of the developing electrode, so that when there is a powder development, the image of the slot is printed on the PET surface due to uniform development. The mass of a monolayer forming this image is calculated by measuring dimension of the slot.

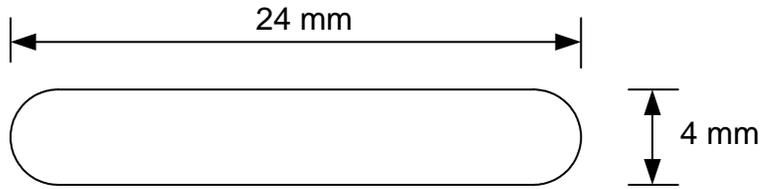


Figure 6-6. Dimensions of the Milled Slot

$$\begin{aligned} \text{Area of the slot} &= \text{Area of rectangle } (20 \times 4) + \text{Area of circle } (\pi \times 4^2 / 4) \\ &= 80 + 12.566 = 92.566 \text{ mm}^2 \end{aligned}$$

$$\text{Density of Iron} = 7870 \text{ Kg/m}^3$$

$$\text{Iron particle size} = 60 \text{ microns diameter}$$

$$\text{Volume of iron particle} = \frac{4}{3} \pi r^3 = 1.131 \times 10^{-13} \text{ m}^3$$

$$\text{Mass of a particle} = \text{Volume} \times \text{Density} = 8.9 \times 10^{-10} \text{ Kg}$$

$$\text{Cross-sectional area of the sphere} = \pi \times (30 \times 10^{-6})^2 \text{ m}^2 = 2.827 \times 10^{-9} \text{ m}^2$$

Let the powder be arranged on the surface in a configuration shown below.

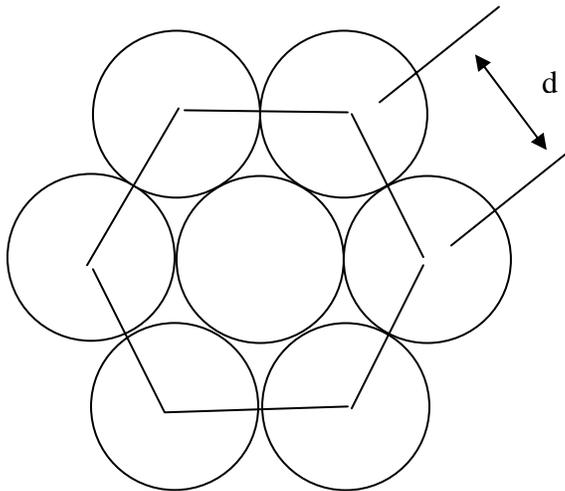


Figure 6-7. Packing of Iron Powder Particles in a Monolayer

$$\text{Number of spheres in the hexagon} = 6 \times (1/3) + 1 = 3$$

Surface area occupied by the spheres in the square = $3 \times \pi \times d^2/4$

$$\text{Surface area of the hexagon} = 6 \times \left(\frac{1}{2} \times a \times \frac{a}{\sqrt{2}} \right) = \frac{3a^2}{\sqrt{2}}$$

From the geometry $a = d$

Surface area occupied by spheres = $3 \times \pi \times a^2/4$

$$\text{Ratio of surface area occupied by the spheres to that of the square} = \frac{\sqrt{2}\pi}{4}$$

$$\text{Number of particles in the image} = \frac{\sqrt{2} \times (\pi/4) \times 92.566 \times 10^{-6} m^2}{2.827 \times 10^{-9} m^2} = 36369 \text{ particles}$$

$$\text{Mass of particles} = 36369 * 8.9 \times 10^{-10} \text{ Kg} = 3.237 \times 10^{-5} \text{ Kg} = 0.0324 \text{ gm}$$

The experimental readings show mass of development is greater than this value, which can be explained by cohesive force of attraction between two iron particles, and the probability that some iron particles agglomerate and develop. The mass of dirt and dust can also add to the mass readings.

Variation of Powder Developed with Development Gap

The following experiment was done to determine the dependence of the developed powder on the development gap. The gap between the PET surface and the powder bed surface is varied by adding paper pieces between them (thickness 0.1mm). The experimental results are presented in the table below.

Table 6-4. Experiment to determine the relation of powder development with gap between the two electrodes

Gap (mm)	Voltage before charging (V_1)	Voltage after charging (V_2)	Mass before development (M_1) gm	Mass after development (M_2) gm	Developed mass ($M_2 - M_1$) gm
No paper	-601	-350	62.686	62.754	0.068
	-384	-295	62.755	62.813	0.058
0.1	-439	-443	62.466	62.519	0.053
	-682	-712	62.519	62.573	0.054
0.2	-606	-827	62.357	62.407	0.050
	-705	-335	62.407	62.466	0.059
0.3	-732	-745	62.239	62.293	0.054
	-712	-724	62.293	62.355	0.052
0.4	-737	-763	62.131	62.183	0.052
	-686	-751	62.184	62.239	0.055
0.5	-621	-628	61.639	61.687	0.048
	-499	-562	61.687	61.726	0.039
0.6	-555	-526	61.725	61.764	0.039
	-618	-684	61.764	61.814	0.050
0.7	-386	-700	61.803	61.843	0.040
	-651	-721	61.843	61.879	0.036
0.8	-665	-527	61.879	61.902	0.023
	-681	-711	61.902	61.940	0.038
0.9	-652	-715	61.940	61.952	0.012
	-741	-699	61.951	61.968	0.017
1.0	-703	-765	62.001	62.021	0.020
	-700	-770	62.021	62.052	0.031

It can be seen clearly that with increase in the gap between the insulated electrode plate and powder level the amount of powder developed is decreased. This can be illustrated well in the following graph.

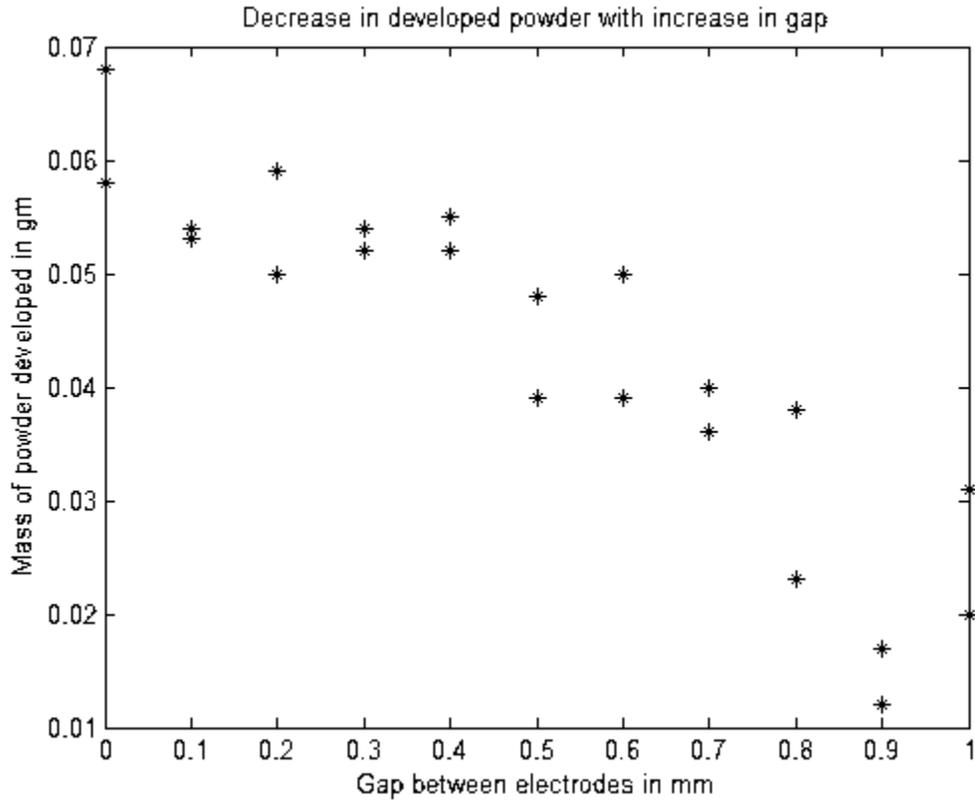


Figure 6-8. Graph Showing Decrease in Amount of Developed Powder with Increase in the Gap between the Powder and the Insulated Electrode

Powder Transfer Experiments

After experiments regarding the development of powder, some simple experiments were done for transfer of powder. After development the developing electrode is placed on the transfer electrode for powder transfer. The transfer electrode is placed with its insulating PET cover facing upwards. The developing electrode is placed on its top with the PET cover facing downwards with the developed powder on the PET surface. There is an air gap between the two insulative surfaces. The arrangement is better explained using the schematic.

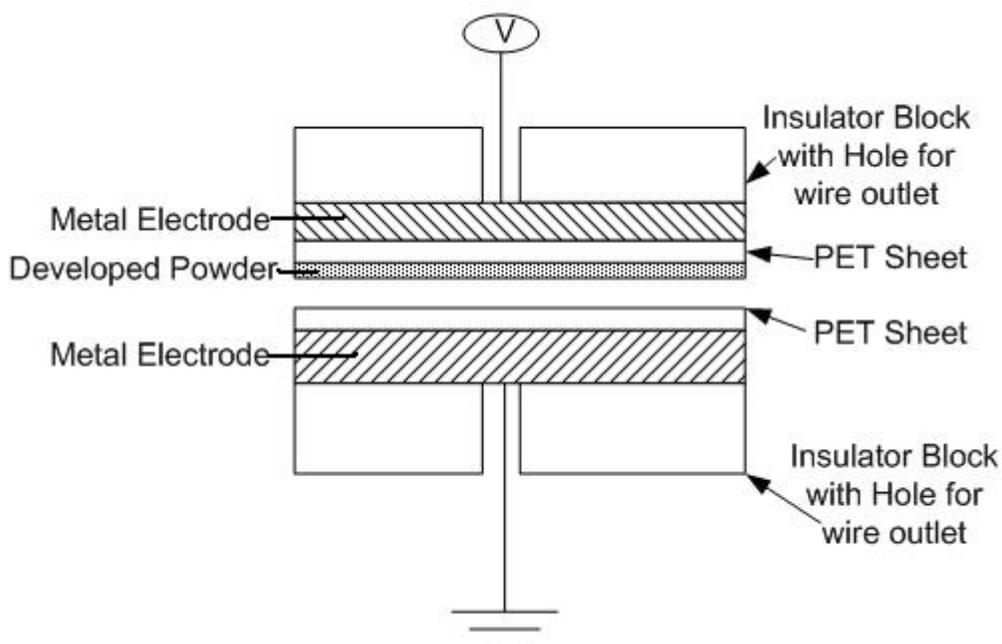


Figure 6-9. Schematic for Test setup for Powder Transfer

For development both the powder and the developing electrode are grounded. The insulative PET surface of the developing electrode is charged negative using a charge roller. The negative charge on the developing electrode charges the powder positive and the powder is developed onto the PET surface. The developing electrode with the developed powder is then placed with the PET surface facing down, on the PET surface of transfer electrode. Then negative voltage is applied to the transfer electrode (-5000V DC) to attract the positively charged powders. This process is repeated a number of times and the results are presented in Table 6-5.

For mass measurements, the initial mass of a container is noted (M_1). After transfer of powder, the transferred powder on the transfer electrode is poured into the container and weighed (M_2). The differential mass ($M_2 - M_1$) is the mass of the transferred powder. Then the remaining developed powder, which has not transferred to the transfer electrode, is poured in the container and weighed (M_3). Subtracting M_1 from M_3 gives the

total powder developed during the development process. The percentage of powder transferred with respect to total developed powder is given by

$$\eta\% = \frac{M_2 - M_1}{M_3 - M_1} \times 100$$

Table 6-5. Measurement of efficiency of powder transfer from developed electrode to transferred electrode

Index of attempt	M ₁ (gm)	M ₂ (gm)	M ₃ (gm)	M ₂ - M ₁ (gm)	M ₃ - M ₁ (gm)	Efficiency η%
1	62.888	62.912	62.926	0.024	0.038	63.16
2	62.928	62.956	62.976	0.028	0.048	58.33
3	62.976	63.004	63.022	0.028	0.046	60.86
4	63.022	63.039	63.062	0.017	0.040	42.50
5	63.061	63.089	63.101	0.028	0.040	70.00
6	63.101	63.120	63.136	0.019	0.035	54.59

Normally the percentage transfer of toner powder in commercial laser printing process is near 100%. There is a possibility that during powder transfer mostly the loosely held iron particles developed over the more strongly held powder monolayer got transferred, leaving behind the powder monolayer on the PET surface of the developer. The transfer process has to be improved as the percentage powder transferred is desired to be close to 100%.

Powder transfer on printed toner layer

To be able to print metal parts, each print of metal has to be alternated with a layer of insulative binding material. Printing of conductive iron powder with alternating layers of toner powder as binder can be considered as a possibility for building iron parts. The following experiment evaluates the possibility of iron powder getting transferred on a layer of toner. In this experiment two methods of transfer are examined; one is by providing voltage to the build platform and attracting the developed powder, the other one is by applying voltage to the developing electrode to repel the developed powder.

There may be the issue of toner powder “back developing” on the developing electrode due to the field. As the toner is negatively charged and retains some of the charge even after fusing, the build platform has to be provided with positive voltage and the transfer plate with negative voltage in the first and second method respectively. This puts restriction on the charging of the iron powder and it can only be charged negative. This will cause less transfer because of the repulsive force from the negatively charged toner, which is undesirable but preferred than toner getting printed back on the transfer plate.

First toner was printed and fused using laser printer based ESFF test bed. Iron powder is developed on the developing electrode by grounding the developing electrode and applying negative voltage (-2500V DC) to the powder. This development process is used for both the methods. For the first method, grounded developing electrode with powder developed on it is placed on the printed and fused toner layer. For the transfer to take place the build platform on which toner is printed is supplied positive voltage. In the second method the build platform is grounded and transfer plate is supplied with negative voltage to repel the negatively charged iron powder. The results for both the methods are presented below.

To make sure there is no charge buildup on the developing electrode during development, the PET surface is discharged using discharging ac voltage 970V AC (p-p) at 2500Hz. For mass measurements, first the developer electrode is weighed without any powder on it (M_0). After development the developer electrode is weighed along with the developed powder (M_1). After transfer the developer electrode is weighed with the remaining developed powder that was not transferred (M_2). The developed powder mass

is $(M_1 - M_0)$ and the transferred mass is $(M_1 - M_2)$. The percentage of transfer is then defined as

$$\eta\% = \frac{M_1 - M_2}{M_1 - M_0} \times 100$$

$$M_0 = 57.815 \text{ gm}$$

Table 6-6. Iron powder transfer on previously printed and fused toner layer by applying positive voltage to the build platform

Voltage on platform in V	Surface voltage before development -V	Mass before print (M_1) in gm	Mass after print (M_2) in gm	Percentage transfer ($\eta\%$)
1000	-101	57.892	57.871	27.30
	-160	57.881	57.870	16.67
2000	-174	57.893	57.872	26.90
	-110	57.873	57.858	25.86
3000	-136	57.883	57.865	26.47
	-175	57.880	57.863	26.15

Table 6-7. Iron powder transfer on previously printed and fused toner layer by applying negative voltage to the transfer plate

Voltage on transfer plate	Surface voltage before development -V	Mass before print (M_1)	Mass after print (M_2)	Percentage transfer ($\eta\%$)
-1000	-139	57.889	57.872	23.90
	135	57.900	57.873	32.90
-2000	166	57.890	57.865	30.49
	157	57.881	57.869	19.05
-3000	132	57.888	57.872	22.86
	171	57.887	57.861	37.68

When compared to the percentage transfer observed in table 6-5 this is a low percentage of transfer. This can happen for many reasons; two of them are discussed below.

In the experiment involving powder transfer between two electrodes insulated by PET (Table 6.5), the Van der Waals force between the PET sheet on the developing

electrode and the developed iron powder was balanced due to the presence of PET on the transfer electrode surface. This is not the case when transfer is done on printed toner as iron powder particles may have more Van der Waals attraction towards PET sheet than the toner resulting in less powder transfer while printing on toner.

The second reason for low transfer percentage may be because the iron powder is charged negative (to avoid toner from printing back onto the developing electrode surface) which may be repelled by the negative volume charge in the printed toner layer resulting in less powder transfer.

After verifying the feasibility of developing iron powder using the simple PET covered electrode plates, the flat photoconductor plate test bed was built and iron was developed from upward facing roller developer to the downward facing photoconductor plate. Experiments were done to study the various methods of powder development and they were compared with respect to different variables. The results are discussed in Chapter 8.

CHAPTER 7 POLYMER POWDER DEVELOPMENT AND PRINTING

Although toner is a polymer and has been widely researched and perfected for charging, developing and printing, it is not the suitable material for structural components. The powder is brittle when printed in multiple layers and it retains charge after fusion as volume charge and repels any additional print. To avoid such problems alternative polymers had to be explored and tested for their suitability to be printed in layers to form three-dimensional structural components.

Chapter 3 describes electrophotography which uses the popular magnetic insulative toner powder. Chapter 4 describes in brief the research done on printing toner powder in multiple layers to form three-dimensional objects and the problems associated with it. There are many other polymers available in the market and can be tested for their ability to print in multiple layers. Some of the powders used for testing are

- Nylon – 6
- PVA (Polyvinyl Alcohol)
- ABS (Acrylonitrile Butadiene Styrene)
- Nylon – 12
- PVC (Polyvinyl Chloride)

In this chapter the results of the experiments done on these powders are discussed and analyzed. These powders are insulators and also do not have any special characteristics which would help them in getting developed. So, the results and conclusions present in this chapter may be applicable to any general insulator.

Test of Powder Properties

The physical properties those are essential for powder charging, development and printing are (Dutta 2002)

- Volume resistivity
- Permittivity
- Mass density

Volume resistivity determines the most effective powder charging method. Permittivity of powder determines the electric field in the development zone. The packing fraction of the powder can be calculated from mass density if the density of the powder is known.

Resistivity Test

A resistivity test cell was designed and built to test the resistivity of powders (Dutta 2002). Figure 7-1 shows the schematic of the test cell with the components marked.

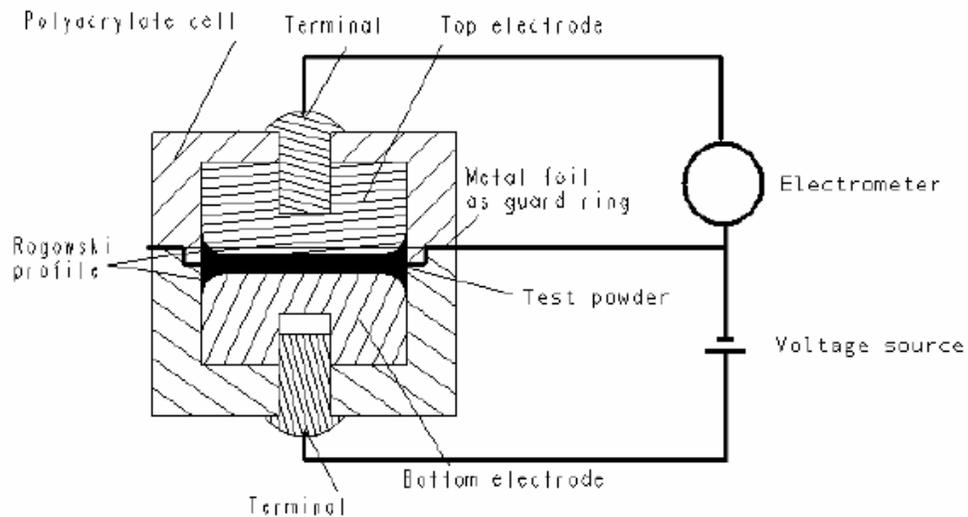


Figure 7-1. Schematic of Resistivity Test Cell (Dutta 2002)

The test cell electrode cross-section profile should have a particular shape called Rogowski profile (Cross, 1987). This is to avoid any fringe effects at the edges, which

may affect the results. In the absence of Rogowski profile the effective area of the electrode surface would be greater given by the equation

$$A_{eff} = \pi \left(\frac{D}{2} + B \frac{g}{2} \right)^2$$

Where, D is the outside diameter of the circular electrode, g is the gap between the guarded electrode and the ring electrode and B is the effective area coefficient. B is typically taken to be zero for test cells with small gap between the electrodes. So, in the present case it is approximated as zero.

The guard ring is grounded or connected to the low voltage electrode. This prevents any current flow between the electrodes through the surface because any such current generated is passed to the low electrode. The cell is made of Polyacrylate, which is a very good insulator.

Volume resistivity is a material property and does not depend on the dimensions of the object. It is calculated as

$$\rho = \frac{RA_{eff}}{d} = \frac{\left(\frac{V}{I} \right) A_{eff}}{d}$$

Where V is the applied voltage, I is the measured current, A_{eff} is the surface area of the electrode and d is the distance between electrodes.

Alternating polarity resistance test implemented in Keithley Electrometer is used for measuring volume resistivity. This uses the electrometer interface with PC and computes the resistivity by a weighted average of readings. First few readings are discarded as it takes time for the material to attain steady state. The steps to perform the experiment are described in the Appendix. The test is conducted with an alternating

voltage of $\pm 50V$ and measurements with a time gap of 15 seconds. The first 3 readings are discarded and in total 8 readings are kept which the software uses to find the average.

The observed readings are presented in table

Table 7-1. Resistivity of polymer powders in Ω cm

Number of attempt	Toner Powder	Nylon - 6	Polyvinyl Alcohol	ABS	Nylon-12	PVC
1	1.0281E15	1.3045E16	6.0241E12	1.2008E10	0.5294E16	1.3695E13
2	1.0146E15	1.7305E16	5.4006E12	1.9268E10	0.7902E16	1.4971E13
3	0.9131E15	2.1759E16	5.9668E12	2.7780E10	1.4709E16	1.6067E13
Mean (Ω cm)	0.9853E15	1.7369E16	5.7971E12	1.9685E10	0.9301E16	1.4911E13

The resistivity calculated is in ohm-cm. For reporting and calculating purposes they have to be converted to ohm-m.

Table 7-2. Resistivity of polymer powders calculated above in Ω m

Toner Powder	$0.9853 \times 10^{13} \Omega$ m
Nylon - 6	$1.7369 \times 10^{14} \Omega$ m
Polyvinyl Alcohol	$5.7971 \times 10^{10} \Omega$ m
ABS	$1.9685 \times 10^{08} \Omega$ m
Nylon - 12	$0.9301 \times 10^{14} \Omega$ m
PVC	$1.4911 \times 10^{11} \Omega$ m

Permittivity Measurement

The resistivity test cell was modified and used as capacitance cell. The schematic is shown below. As it can be seen in the figure, there is no guard ring. The electrometer was connected to the HI electrode. The electrometer was interfaced with PC for data collection and manipulation. The measurement process steps are presented in the Appendix.

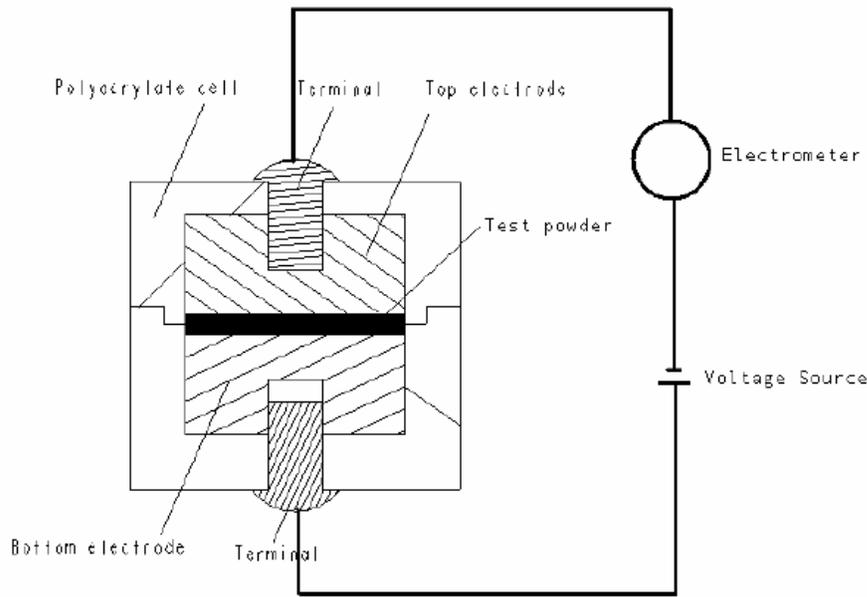


Figure 7-2. Schematic of Capacitance Test Cell (Dutta 2002)

There are two set of experiments that have to be done for evaluating the permittivity of the material. The first one is done to measure resistance using software used for resistivity test, which has an option to measure resistance (see Appendix A). The results are presented in the table below.

Table 7-3. Resistance values of the polymer powders

Number of attempt	Toner Powder	Nylon - 6	Polyvinyl Alcohol	ABS	Nylon-12	PVC
1	5.2455E10	6.1880E11	2.2460E11	7.1950E10	11.605E10	6.5505E11
2	5.3845E10	5.5132E11	2.9027E11	5.9442E10	9.5247E10	6.7850E11
3	5.0365E10	6.7544E11	2.0525E11	5.9013E10	2.6855E10	7.0465E11
Mean (Ω)	5.2221E10	6.1518E11	2.4004E11	6.3468E10	7.9384E10	6.7940E11

In the other test a step voltage is applied to the test cell for some time. Then the voltage is cut off and the capacitor is allowed to discharge. The characteristic exponential decay curve of an RC circuit was plotted by the test software. The time constant of the RC circuit is calculated from this graph. The user picks two points on the plotted graph

and the software fits an exponential curve passing through the two points. The time constant of the exponential curve is displayed. The step voltage is set to auto and the instrument chooses the suitable voltage for the material. The time constants for the polymer powders are reported in the table below. No time constant has been reported for Nylon 6 and PVC because of the nature of the discharge curve that was not suitable to curve fit an exponential decay curve.

Table 7-4. Time constants of the RC discharge curve

Number of attempt	Toner Powder	Nylon - 6	Polyvinyl Alcohol	ABS	Nylon-12	PVC
1	0.43102	-	1.1054	0.51776	0.75884	-
2	0.44076	-	1.0988	0.71383	0.74548	-
3	0.42942	-	1.1039	0.71317	0.79746	-
Mean (sec)	0.43373	-	1.1027	0.64825	0.76726	-

The value of the time constant is used to calculate the capacitance of the test cell using the relation

$$T = RC \Rightarrow C = \frac{T}{R}$$

Where, T = Time constant of exponentially decaying charge in RC circuit

C = Capacitance of the test cell

R = Resistance of the test cell

The value of capacitance is then used to calculate the permittivity of the powder material by using the test cell dimensions. This is done using the following relation for parallel plate capacitors

$$C = \frac{\epsilon_0 \epsilon_r A_{eff}}{d},$$

Where, C = capacitance of the test cell

ϵ_0 = permittivity of air

ϵ_r = relative permittivity of material

A_{eff} = Effective surface area of the electrode

d = Gap between the two electrodes

For circular electrodes, as in the present case, the relation changes to

$$C = \frac{\epsilon_0 \epsilon_r \pi D^2}{4d} \Rightarrow \epsilon_r = \frac{C4d}{\epsilon_0 \pi D^2}$$

Where, D is the diameter of the circular electrode.

The values of relative permittivity for the polymer powders were estimated and reported in the table below

Table 7-5 Permittivity of polymer powders

Powders	T (Sec)	R ($\times 10^{10} \Omega$)	$C = \frac{T}{R}$ (picoFarad)	$A = \frac{\pi D^2}{4}$ ($\times 10^{-4} \text{ m}^2$)	d	$\epsilon_r = \frac{C4d}{\epsilon_0 \pi D^2}$
Toner	0.4337	5.2221	8.305	5.06451	0.001905	3.529
Nylon – 6	-	61.518	-	5.06451	0.001905	-
Polyvinyl Alcohol	1.1027	24.004	4.594	5.06451	0.001905	1.952
ABS	0.6482	6.3468	10.213	5.06451	0.001905	4.341
Nylon – 12	0.7672	7.9384	9.644	5.06451	0.001905	4.098
PVC	-	67.940	-	5.06451	0.001905	-

Test of Development Characteristics of Polymers

The five polymers were tested for the quality of their development and the visual observation was noted down. The qualitative assessment of powder development is an indicator of the behavior of the powder when they are placed under electrostatic field for development and transfer. This test also finds out if the powder is suitable to be developed by the cascade development method.

Experimental Setup

The experimental setup looked like the cross-sectional figure shown below. This is the cross-sectional image of one of the charge and mass measurement test setups. An elaborate discussion on the design of this setup is given in chapter 5. The same setup was used for this experiment by developing the polymer powder over the photoconductor drum.

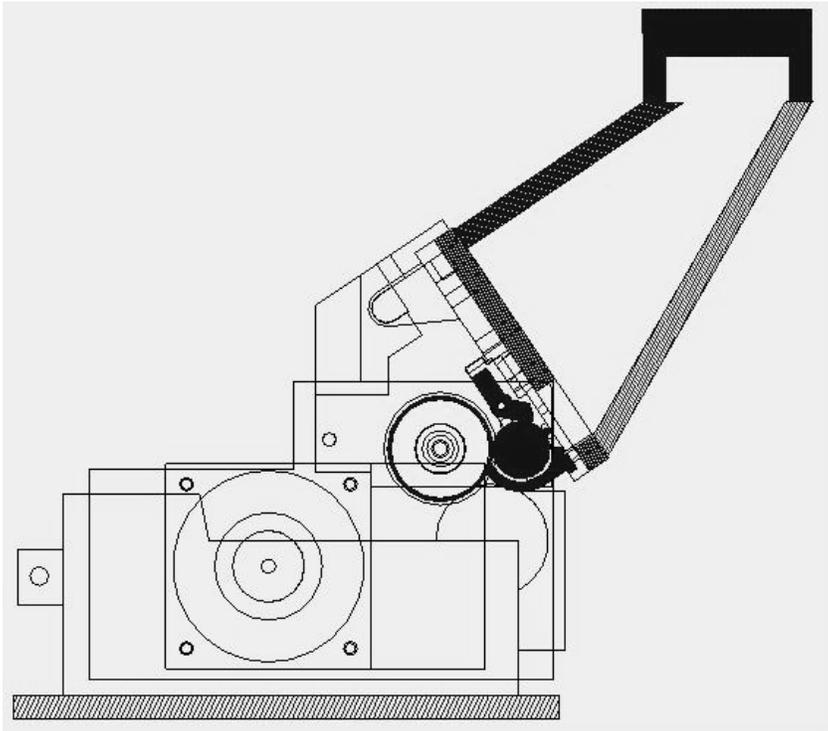


Figure 7-3. Cross-section of Polymer Powder Developer

The powder is stored in the powder box. Powder flows to the bottom of the box by gravity and stays near the opening. This puts pressure on the developer roller and the friction between the developer roller surface and powder mass increases which helps in both triboelectric charging of the powder and in bringing the powder out of the box to the development region. The powder particles get caught in the porous surface of the developer roller and squeeze through the doctor blade for development. This squeezing action also adds to the charging of the powder by getting rubbed against both the

developer roller and the doctor blade simultaneously. The doctor blade restricts the output of amount of powder to the development zone. The blade has a metal sheet in its front that is supplied with voltage to help in charging of powder and also to create field for development with the grounded photoconductor drum. The developer roller is not connected either to the voltage source or ground. The observations are listed below.

Polyvinyl Alcohol

When the setup was run without any voltage applied, there was no development. Then 500V DC voltage was applied to the blade and the test was run. The powder developed in thin layers and there were certain areas where the development was thicker than the neighboring regions. The voltage was increased in steps of 100V till 1500V, which resulted in increase in the development. Powder started dropping from particular spots where the thickness of developed layer was higher. On closer observation the size of powders dropping from these sites were much larger than the ones sticking to the drum. The voltage was switched off and the drum was cleaned. After placing back the photoconductor drum there was development of a layer of powder subsequently without the application of voltage.

From the observation it can be concluded that the powder particles get charged by injection charging when voltage is applied to the blade, which then gets developed. There may be certain regions in the blade that allowed more powders to get through and there was high development. These regions also allowed large sized particles to get developed and fall off the developer surface due to high gravitational force compared to electrostatic force. The powder retains charged after the voltage is switched off, which results in development of a layer of powder after voltage was off.

Nylon – 12

There was no development without application of voltage. Voltage application started at 500V DC and went up to 2000V DC. Development was started in small patches which were the centers for gradual spread of powder and after some time covered the whole drum with a thick uniform layer of nylon powder. There was no leakage of powder and therefore there was no spillage and drop off of powder. When the voltage was turned off the surface of the photoconductor was cleaned off powders and most of it went back into the reservoir and there were stray drop offs of powder.

It can be concluded that the charging of Nylon – 12 is highly dependent on the voltage applied. This powder got discharged by contact with the grounded doctor blade after the voltage is turned off and did not remain developed on the photoconductor drum and so the drum got cleaned off powder. The powder has a small size that helps in charging the powder. It also helps the powder to remain on the photoconductor drum after development. The powder gets into the porous surface very easily and so there is no leakage during development. The start of development in patches can be attributed to the unevenness of the doctor blade or any charge concentration at those spots on the photoconductor drum due to external contacts.

Nylon – 6

There was no development without the application of voltage. Voltage was applied from 300V DC to 1800V DC (stopped due to sparking). There was no development on the photoconductor drum after voltage was applied. The increase in voltage had no effect on the development and the test had to be stopped at 1800V DC due to sparking observed in the first test run.

Nylon – 6 was not getting charged properly by the application of voltage and so there was no development. This powder may not a suitable choice for printing using electrophotography.

ABS (Acrylonitrile Butadiene Styrene)

The sample powder was a mixture of small size and large size particles. The large size powder particles drop off the photoconductor drum during development. The powder started developing on the drum without the application of voltage. It forms a thick coating on the photoconductor drum. Then positive voltage of 500V DC was applied and increased up to 1600V DC. Due to the application of positive voltage, the developed powder started to leave the drum surface into the powder box and the drum got gradually cleaned. The photoconductor drum was cleaned and reassembled in the test setup. Negative voltage starting from –200V DC to –1600V DC was applied to the doctor blade and a thin layer of powder development was observed.

It can be concluded from the above observation that, the powder was maybe previously charged and so developed on the drum surface without any application of voltage. This may also mean that this powder retains charge for a long time. Powder was cleaned off the drum by the application of positive voltage indicates that the powder was charged negative and was attracted by the positively charged blade and went into the powder box. The development of powder due to application of negative voltage confirms that the powder has a bias towards getting charged negatively.

PVC (Polyvinyl Chloride)

This powder has a large particle size and develops on the drum without any application of voltage, but due to large size falls off the drum surface. Positive voltage was applied to the blade starting from 500V DC to 4000V DC. The powder layer

thickness on the developed region increased. Negative voltage was applied from –500V DC to –3000V DC. The amount of powder coming out exceeds the amount of powder recirculated, which results in leakage. The powder development spreads all over the photoconductor drum. There is a smooth cascade flow of the powder through the developer roller.

This powder is large in size and develops without any application of voltage, which makes this unsuitable for ESFF applications.

Discussion

The experiment was intended to identify the polymer that can be used for future developing and printing experiments. From the tests it can be seen that although the polymer powders are insulators, they behave differently in similar conditions. This experiment shows how important is the right selection of powder for different applications.

From the result presented it is concluded that Nylon – 12 is the most favorable powder to be used for ESFF applications. The characteristics of this powder that makes it suitable are highlighted below.

- The powder does not develop without the application of voltage
- The powder develops as a thick uniform coating on the photoconductor drum
- The size of the powder is small and it remains attached to the photoconductor surface without falling off
- There is no leakage of powder and so no spillage because the powder is small and can get into the pores of the developer roller surface very easily and transported without falling off
- When the voltage is switched off the powder gets cleaned off from the photoconductor drum and does not develop as the powder gets discharged by contact with the grounded doctor blade after the voltage is turned off.

In chapter 5, the charge and mass measurements for polymers were done on nylon – 12. In the flat photoconductor plate test bed the nylon – 12 is used to test the suitability of using polymers in the flat photoconductor plate test bed configuration of ESFF. Experiments were conducted on the development of nylon – 12 using the flat photoconductor plate test bed and study the variation of amount of powder development (powder mass) with respect to the voltage applied to the development roller and the doctor blade (development voltage). The results are presented in chapter 8.

CHAPTER 8 FLAT PHOTOCONDUCTOR PLATE TEST BED

The research work in the past on ESFF (Electrophotographic Solid Freeform Fabrication) was done on a test bed that used the modified laser printer to print toner powder on paper. The main objective of the past research works had been to determine the feasibility of printing parts in three dimension using electrophotography, which was satisfied by the test bed. Later in the research a need was felt to test powders other than toner powder for their ability to get printed in three dimension using electrophotography. Attempts have been made to replace the toner powder cartridge with powder developer designed to use with any powder. As the developer leaked powder, there was danger that it may damage the test bed by powder spillage. There was also attempt to print toner powder as a binder on a bed of other powder (Dutta 2002), which was not pursued due to the reason that this method also required uniform deposition of powders in thin uniform layers that requires powder developers to print the thin uniform layers. This again suffers with the problem of powder leakage on the test bed, which is not desirable.

The laser printer is a complicated piece of equipment and there are so many functionalities for user interface applications that are not required for the printer to be used to print toner powder by electrophotography. It has taken a considerable amount of time and effort to modify the printer and make it suitable to be used in the test bed (Zhang 2001). The maintenance of the printer is also equally difficult. Due to the fixed lifetime of a given model of printer it has to be replaced with another printer, which would take a considerable amount of time and effort to understand and modify for the

ESFF application, which is counter productive. So, this has to be replaced by some method by which there still can be electrophotographic printing without the additional work.

By analyzing the printer components and the electrophotography process it was inferred that only the laser imaging system has to be borrowed from the printer and the rest can be substituted by designing alternate mechanisms. It was also observed that in the printer the presence of a photoconductor drum mandates the presence of all the components that are a part of the electrophotography cycle in a circular fashion around the drum. The drum has to go through this cycle a number of times to produce an image, which can be generated in one step if a photoconductor plate is used.

The use of photoconductor plate also spreads the components for development and printing, in a linear fashion, making the design simpler and easier to build. By using a linear distribution we can make a modular design in which the components can be grouped together in a logical way so that each group performs one of the functions in the electrophotography cycle. Each of these modules can be debugged and repaired separately in case of any problem, which makes the troubleshooting and maintenance of this system easy to perform.

As mentioned in chapter 4, the laser imager system was extracted from the printer and it was tried to be controlled externally to produce images (Fay 2003). This chapter discusses the design and building of the rest of the test bed based on the movement of the flat photoconductor plate. The design includes the assembly of the charger, the imager and the developer assembly so that there is a uniform development of the powder on the charged image. The developer assembly consists of the developer roller, the doctor blade

and the powder box. Some results related to the development of powder using this test bed have also been discussed.

Electrophotography Cycle and Test Bed Design Concept

As explained in chapter 3, the electrophotography cycle consists of the events which help in the development and printing of image-wise uniform layers of powders. This includes charging of the photoconductor surface, imaging the charged surface, developing powder onto the image-wise charged surface, printing the developed powder on the build platform, fusing and consolidating the printed powder layer, cleaning the photoconductor surface and discharging it for the next cycle. These steps are shown in the schematic below to illustrate the events during the linear movement of the photoconductor plate.

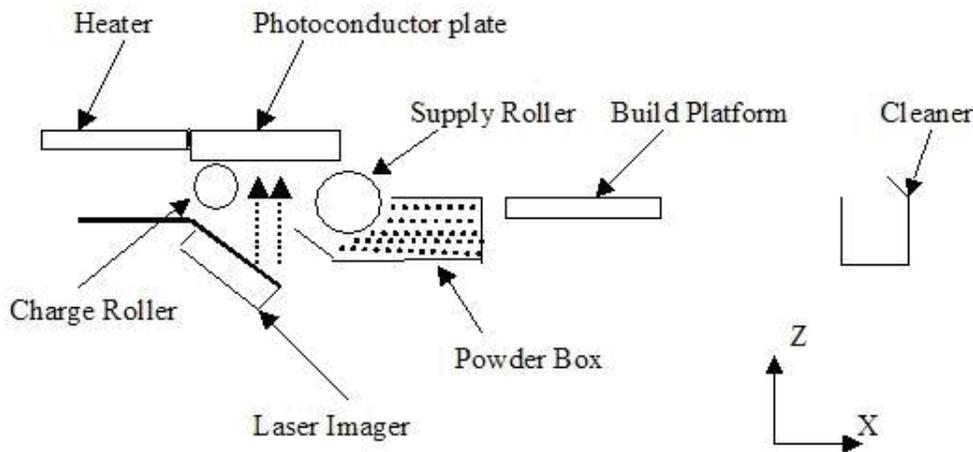


Figure 8-1. Schematic of the Concept of Flat Photoconductor Plate Test Bed Assembly

The individual components that can be used for the test bed are discussed below.

Charging

The different types of charging methods and their properties were explained in chapter 3. The corona charger is very bulky and difficult to assemble in the test bed setup. It requires the use of high voltage for better performance and there is a chance of the charger damaging the photoconductor surface by sparking. Due to these reasons a charge roller is used for charging the photoconductor surface. The charge roller is supported on either of its ends by spring loaded holders, which are fixed to a common side plate which also holds the developer assembly. When the photoconductor plate passes over the charge roller by rubbing against the roller surface to get charged, the springs get pressed and orient the axis of the roller parallel to the photoconductor surface for uniform charging.

Imaging

The laser imager in the printer is reused for imaging the photoconductor plate. The organic photoconductor surface is sensitive to ultraviolet light which can be supplied by the laser imager used in the laserjet4 printer. The controls of the imager were identified and modified for it to work independent of the printer (Fay 2003). In the test bed the opening for the laser imager is placed just after the charge roller and before the developer. The schematic below explains different parts of the laser imaging system and the control sensors and actuators.

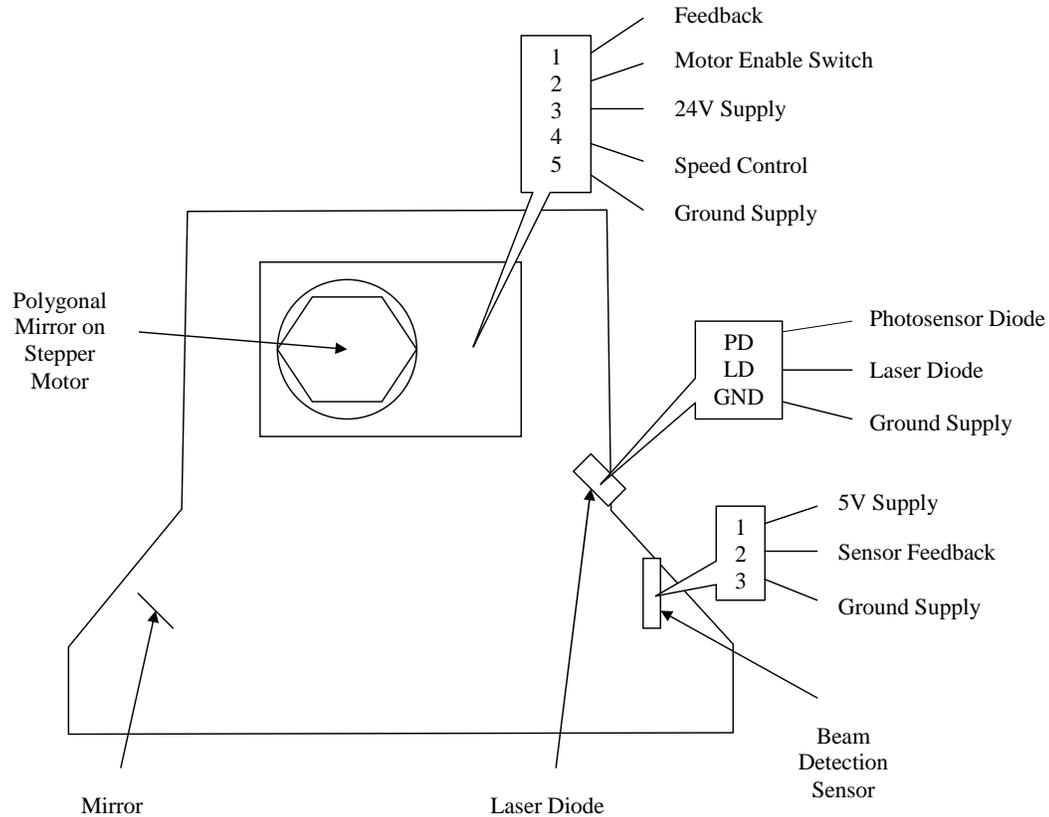


Figure 8-2. Schematic of Laser Imager (Fay 2003)

The laser has to be turned on or off depending on the image and scan the image line by line using the existing rotating mirror system. The imager modification for independent operation is yet to be perfected so that it can replicate the images sent from computer. The laser imaging system is fixed facing upwards, so that it can discharge the downward facing photoconductor plate.

Developing

The requirement for the developer is to deliver the powder for upward development. The gravitational force acts in the opposite direction to the powder movement direction during powder development. This system also has to be independent of powder property. This is a challenging task as cascade development cannot work without gravity. The details of the design are explained later in the chapter.

Printing

There is no elaborate arrangement designed for the build platform in the test bed setup. Current setup only contains an insulator plate (sometimes replaced by conductor plate for insulator powders) on which the photoconductor plate prints powder by various powder transfer methods. More details on the printing method used were discussed in chapter 6.

Fusing and Compacting

The fusing and compacting system has not been designed and built, but in the illustration in figure 8-1, a conceptual arrangement is presented in which a flat plate heater is attached to the trailing edge of the photoconductor plate at a higher Z-level than the photoconductor surface. This flat plate heater can be borrowed from the old test bed configuration in which a flat plate contact heater was used to fuse and compact the toner powder. After printing the powder, the photoconductor moves ahead and then lowers itself so that the flat plate heater can come in contact with the printed powder surface and apply heat and pressure to fuse and compact the freshly printed powder layer. This gives green strength to the part for post processing operations.

Cleaning and Discharging

After fusion and compaction the photoconductor plate proceeds to the next station where the powder that was not printed on to the build platform is cleaned off the plate surface. The surface is then discharged by a charge roller supplied with ac voltage, which removes any charge left on the surface by the charged powders. The cleaning and discharging system is also in the stage of concept as shown in the illustration. The concept cleaning system consists of a box with a flexible polymer blade attached to it at an angle. To clean the photoconductor plate surface the plate is pressed lightly on the

cleaner blade and passed over it so that the surface get rubbed against the blade and get cleaned. Along with the cleaning of the plate it is discharged when it passes over a charge roller present after the cleaner.

Photoconductor Plate Motion

The available motions on the test bed, horizontal linear motion the x direction and vertical linear motion in the z direction were used to move the photoconductor plate around the linear test bed setup. While the x direction motion helps in moving from one functional module to another, the z direction helps in positioning the plate surface with respect to the charge roller, developer roller, build platform and the cleaner and discharge roller. These two axes of motion were performed by servomotors, which were controlled by signals given from the computer commands through the Galil Motion controller.

Photoconductor Plate

It is important to discuss photoconductor plate assembly before going into the details about the other components of the test bed as it determines the design and distribution of rest of the test bed.

As discussed in chapter 3, organic photoconductor and amorphous selenium are the two popular commercial materials available for photoconductivity applications. Organic photoconductor material is widely used in printers compared to amorphous selenium because they are cheap to produce and sensitive to a narrow spectrum of ultraviolet light reducing the chance of any discharge of the image due to ordinary light falling on it. This makes the design and production of organic photoconductors convenient and economical. Organic photoconductor has a very short dark decay time (time taken for decay of half of charge without exposure to light), which has to be taken into consideration while designing the test bed assembly. This is not much of a concern in the case of organic

photoconductor drum as it will be spinning in high velocity giving enough time to develop and print. This is a problem when the whole photoconductor plate is charged, imaged and developed at the same time that requires a longer time comparable to the dark decay time.

On other hand, amorphous selenium can retain charged image for a longer time, which makes it a suitable choice for the photoconductor plate. In addition to that the photoconductor surface made of amorphous selenium is more resistant to abrasions than the softer organic photoconductor, which makes it suitable material for the photoconductor plate to be used on various powders (including abrasive metals). It is the price of the amorphous selenium material which offsets all its favorable characteristics. Due to its high cost it is used in very limited applications like the xero-radiography and digital offset printing and has less availability than the organic photoconductor. This is the reason for using organic photoconductor material for making photoconductor plate. Moreover amorphous selenium is sensitive to a wide range of light wavelengths and requires a more complicated design of the test bed with enclosures protecting the photoconductor surface from ambient light. Another advantage of using the organic photoconductor plate is that the laser imaging system from the Laserjet4 printer is proven to be effective on organic photoconductor and can be used directly in the assembly.

Due to the unavailability of a plate coated with organic photoconductor material suited for experimental applications, a flat photoconductor surface was created out of organic photoconductor belt taken from one of the laser printers. The belt assembly is shown below.

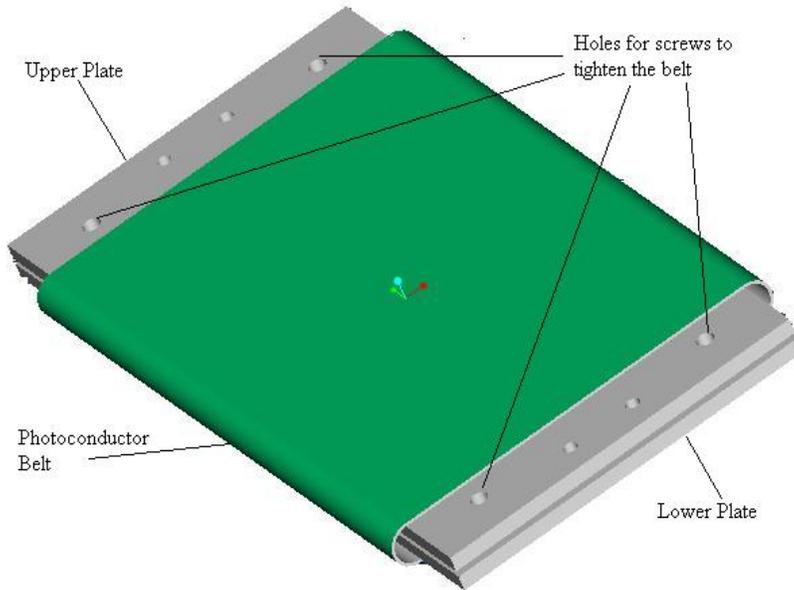


Figure 8-3. Solid Model of Photoconductor Belt Assembly

In the design for creating a flat photoconductor surface the available belt is wrapped around two rectangular insulator plates with smoothed edges. There are four screws at the corners of the plates, which are tightened to increase the gap between the plates, which in turn put tension in the belt and create a flat surface. The screws are attached to the top plate and push against the lower plate, which moves the lower plate outwards and stretches the belt. This flat surface approximately simulates the photoconductor plate. This photoconductor plate is attached to the moving platform through a cantilever beam. The belt is not as flat as a plate, but it is a good approximation for testing purposes.

Design and Building of Charger-Imager-Developer Assembly

The initial goal of building the flat photoconductor plate test bed was to determine the possibility of developing powder and printing in uniform layers. The next goal is to print an image using the laser imager. The final stage is to complete electrophotographic

cycle by building the test bed setup with a design for the build platform and a cleaning and discharging assembly.

The focus of this thesis is to build an assembly consisting of charge roller, the laser imager and the developer assembly, which can be used to develop uniform layers of powder. The discussion about powder properties, development and transfer theories with quantitative experimental results are presented in the next two chapters. This chapter is mainly concerned with discussion about the design of the charger-imager-developer assembly and some qualitative results from the experiments.

Developer Design

In the design of the test bed setup, the photoconductor plate is moved around with its photoconductive surface facing downwards. This requires the development of the powders against gravity from the developer placed below. For organic photoconductors, the dark decay time is very small and so the development has to be done immediately after the charging process. This requires that the developer powder bed should be placed adjacent to the imager so that the photoconductor plate passes over powder bed as it gets charged and imaged. This demands that a fresh uniform layer of powder should be available immediately after the laser imaging for the whole travel of the photoconductor plate.

The developer discussed in last chapter is modified to build a developer to be used for flat photoconductor plate test bed configuration. As said earlier cascade development is required to develop powders with different properties. For cascade development to work the powder should be at a higher level than the developer roller as can be seen in the developer designs in chapter 5. In the present case the flat photoconductor plate needs vertical access to the developer roller surface and a clear path to travel during the

development process. These requirements are met when the powder box is at a lower level than the horizontal tangential plane through the top of the developer roller. This does not have powder supply through gravity and the powder has to be pushed against the developer roller by mechanical force so that when the roller rotates the powder would come out sticking to the developer surface by friction.

Developer Design

The developer is divided into two parts, the nib assembly (to supply powder) and powder box assembly (to store powder). The nib assembly design is borrowed from the developer used for charge and mass measurement device (chapter 5) and modified to suit the requirements. The solid model and the cross sectional view of the developer assembly is shown as illustration.

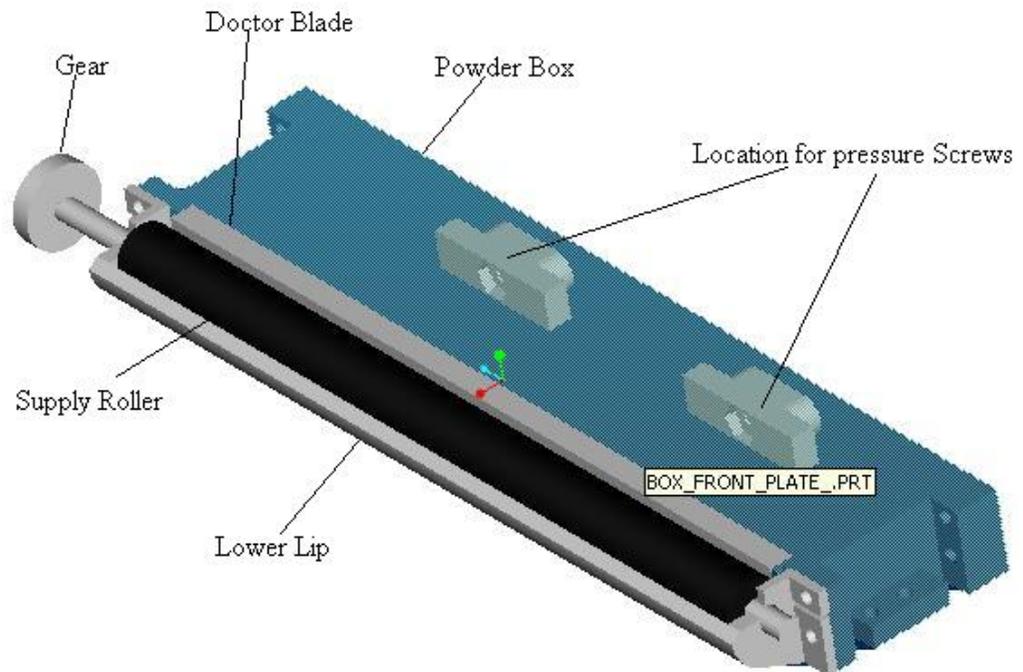


Figure 8-4. Solid Model of the Powder Developer Assembly

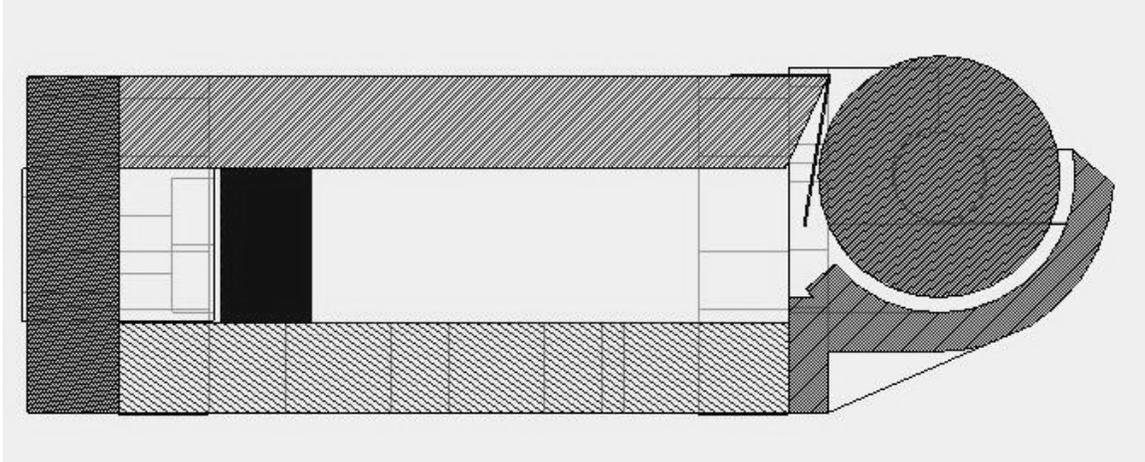


Figure 8-5. Cross-sectional view of the Powder Developer Assembly

The pivoting blade was removed and replaced with a bent brass sheet fixed to the powder box and extends into the powder-box opening to act as doctor blade and also charge the powder. Some top portion of the nib was removed to expose the developer roller above the surface of the nib top. This nib has flanges with screw holes provided to fix it to the flanges of the powder box. The nib attaches with the powder box with some packing of soft polymer sheet in between them that prevents any powder leak at the joint.

The powder box is a rectangular box with an opening on one of its sides, where the nib is attached. Opposite to this, the powder box has a cap that can be opened to pour powder inside the box. After the powder is filled a rectangular plate is placed on the top of the powder level to act as a piston to push the powder out of the box and the box is closed by fixing the cap. This plate (acting like a piston) is called pressure plate as it is used to apply pressure on the powder to be pressed against the developer roller and transported to the development region by friction. The pressure plate is pushed by two screws using the screw threads on the cap. As the powder gets used up the powder pressure on the developer roller drops that can be brought back to the normal level by

tightening the screws. The height of the box is lower than that of the developer roller to allow for the horizontal motion of the photoconductor plate during development.

The developer roller is the same that was used in the charge and mass measurement test setup. It is conductive and has a high frictional porous surface that helps in bringing the powder out of the box for development. The powder box is made of transparent acrylic sheet, which helps in observing the level of powder and the piston position inside the powder box. The developer roller is driven by a gear mechanism attached to a stepper motor.

Charger-Imager-Developer Assembly

The solid model and cross-sectional view are shown in the following figures.

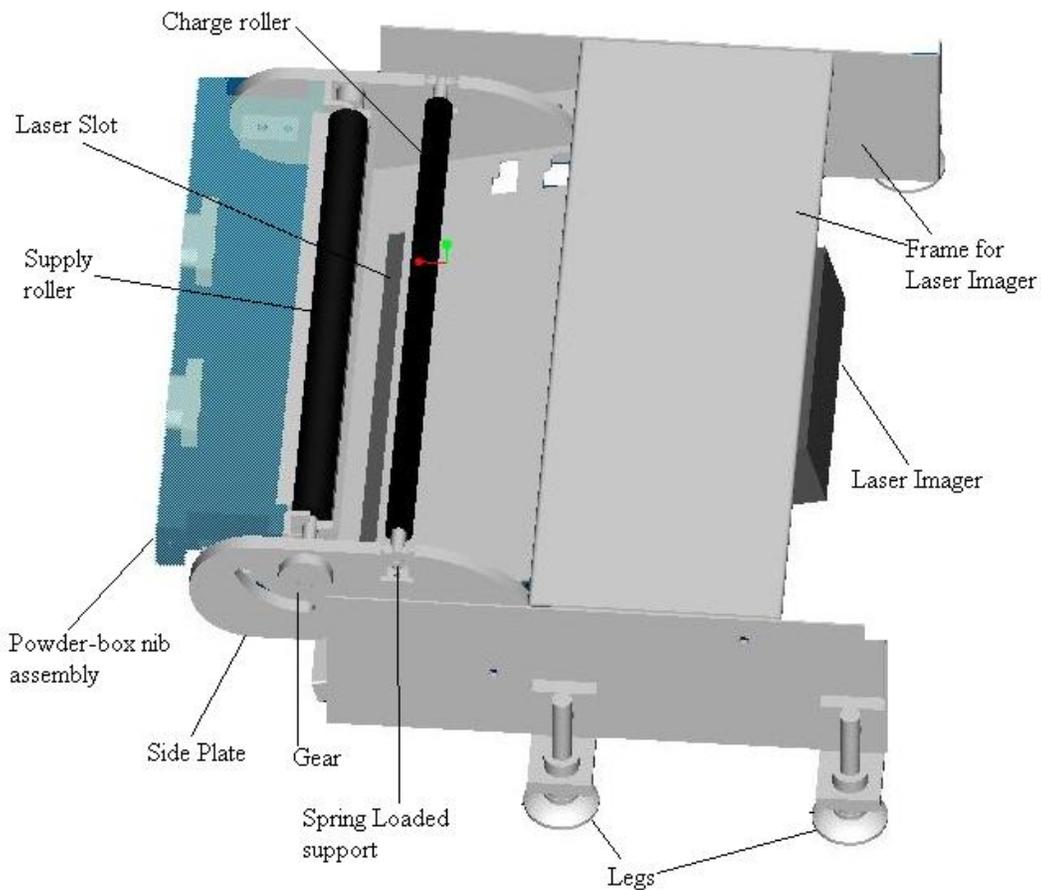


Figure 8-6. Solid Model of Charger-Imager-Developer Assembly

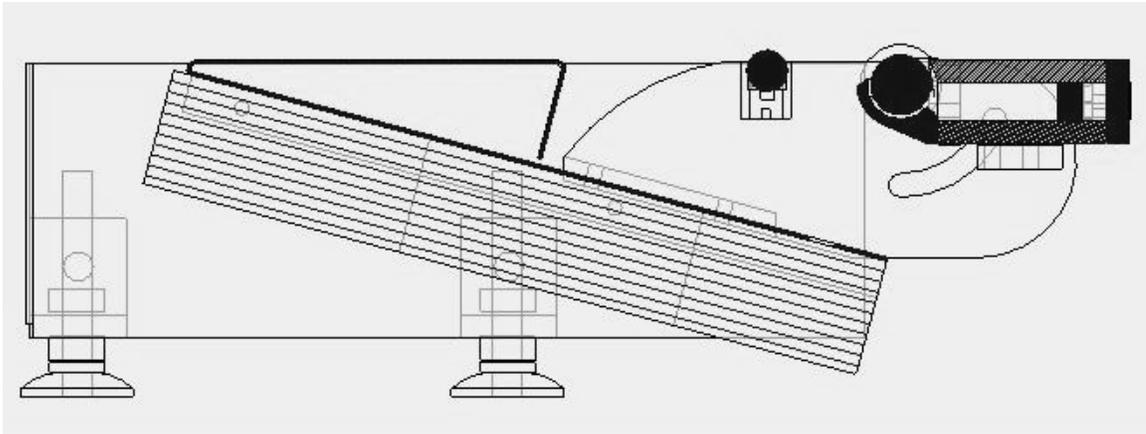


Figure 8-7. Cross-section of Charger-Imager-Developer Assembly

The charger and developer are assembled together by side plates on either side with a gap in between to allow the ultraviolet laser to pass through. The charge roller is supported on both sides by spring-loaded holders. As mentioned earlier, these allow the roller to orient according to the photoconductor surface to charge the surface uniformly. The charge roller is assembled at a higher level than the developer roller because when the photoconductor plate passes over them it should touch the charge roller to get charged and at the same time have a small gap with the developer roller. A gap is required between the photoconductor plate and the developer roller as they move in opposite directions at the development region. This opposite direction of motion of photoconductor plate and the surface velocity of the developer roller is due to functional and geometric constraints. Any contact between them will wipe away the developed powder from the photoconductor surface. This gap should not be larger than a threshold, as the electric field for powder development decreases with increase in gap.

The laser imager is assembled to the same frame where it used to be fixed to in the printer. The frame is modified to fit into the whole new test bed assembly. It has the correct angular orientation to shine laser in the vertical direction through the slot provided on the frame. The side plates containing the developer and the charger are

assembled to this frame in such a way that all the components are centered and the gap between the charger and the developer roller is positioned over the opening for the laser and is suitable for imaging by laser.

The image below shows the position of the photoconductor plate with charging imaging and developing happening at the same time. Note the relative positioning of the charge roller, imager opening and the developer roller. The other thing to note is the gap between the developer roller and the photoconductor surface while it is getting charged.

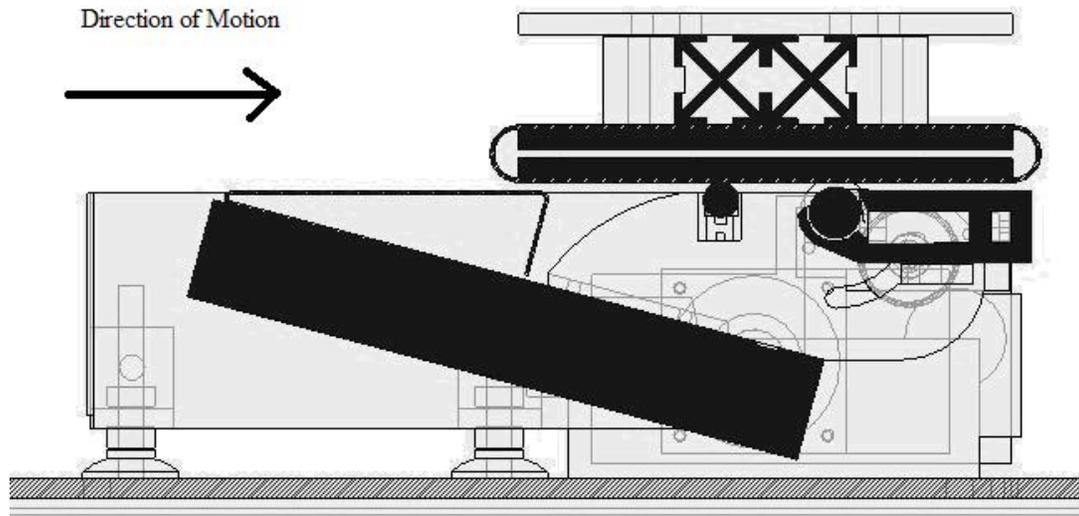


Figure 8-8. Cross-sectional Image of Charger-Imager-Developer Assembly with Photoconductor Belt Assembly on top, Illustrating the Passing of Photoconductor Plate over the Charger, Imager and Developer Simultaneously during Development

The four legs attached to the side plates of the laser imager frame by angle brackets give the whole assembly a steady support during development. The legs have set screws to adjust the height and orientation of the charger-imager-developer assembly. The whole assembly standing on the four adjustable legs is placed on a flat plate attached to the test bed frame. After the height and orientation of the assembly are adjusted it is fixed by screwing one of the legs to the base plate. A close up of the assembly on the test bed is

shown in the following solid model to illustrate the relative position of the various components discussed above.

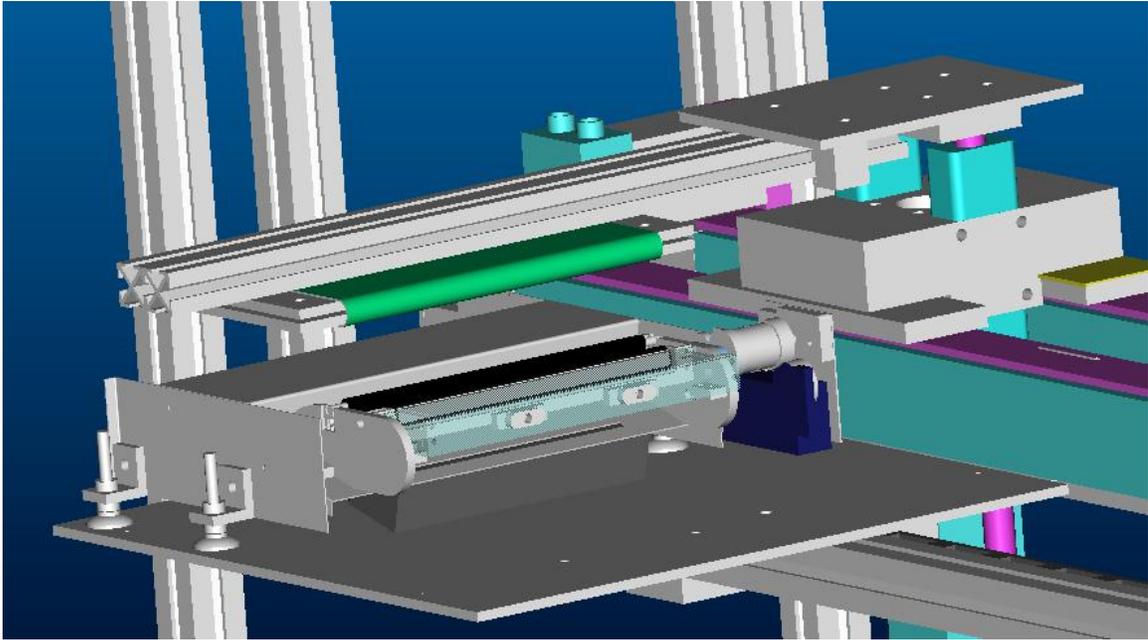


Figure 8-9. Close-up of Solid Model of Test Bed Showing the Flat Photoconductor Plate Developer Assembly

Experiments and Results

A number of experiments were conducted on this test bed involving the development and printing issues of metal and polymer powders. The results are discussed in the following subsections. Some of the pictures taken of the developed and printed nylon powder are also presented.

Metal Powder Development using Flat Photoconductor Plate Test Bed

The powder was developed using the three methods of development (discussed in chapter 6) and for each method voltage applied for development was varied to note the change in developed powder mass due to this. The other parameters tested are the charge that flows through ground connection of one of the electrodes during development, which gives an approximate measure of charge on the total iron powder developed and the

surface voltage of the photoconductor plate after development of powder. The respective tables and graphs are shown below.

Table 8-1. Development of iron powder by providing voltage to the development roller and grounding the photoconductor plate (Data 1)

Voltage	Charge Q (nC)	Surface Voltage	M ₁	M ₂	M ₂ – M ₁ (M)	Q/M
500	7	92	8.772	8.775	0.003	2.333
1000	16	104	8.775	8.782	0.007	2.286
1500	95	280	8.782	8.800	0.018	5.278
2000	522	318	8.800	8.870	0.070	7.457
-2000	-397	-328	8.870	8.938	0.068	-5.838
-1500	-122	-264	8.938	8.983	0.045	-2.711
-1000	-20	-65	8.983	8.997	0.014	-1.429
-500	-8	-3	8.997	9.005	0.008	-1

Table 8-2. Development of iron powder by providing voltage to the photoconductor plate and grounding the developer roller (Data 2)

Voltage	Charge Q (nC)	Surface Voltage	M ₁	M ₂	M ₂ – M ₁ (M)	Q/M
500	5	430	9.005	9.009	0.004	1.25
1000	13	886	9.009	9.014	0.005	2.6
1500	86	1156	9.014	9.040	0.026	3.308
2000	298	1538	9.040	9.101	0.061	4.885
-2000	-322	-1736	9.101	9.169	0.068	-4.735
-1500	-92	-1270	9.169	9.193	0.024	-3.833
-1000	-12	-980	9.193	9.195	0.002	-6
-500	-4	-483	9.195	9.196	0.001	-4

Table 8-3. Development of iron powder by charging the photoconductor surface and grounding both photoconductor and developer roller (Data 3)

Voltage	Charge Q (nC)	Surface Voltage	M ₁	M ₂	M ₂ – M ₁ (M)	Q/M
500	5	243	9.199	9.201	0.002	2.5
1000	15	126	9.201	9.209	0.008	1.875
1500	23	485	9.209	9.223	0.014	1.643
2000	150	224	9.223	9.260	0.037	4.054
-2000	-70	-553	9.260	9.295	0.035	-2
-1500	-26	-457	9.295	9.312	0.017	-1.529
-1000	-15	-501	9.312	9.325	0.013	-1.154
-500	-2	-314	9.325	9.326	0.001	-2

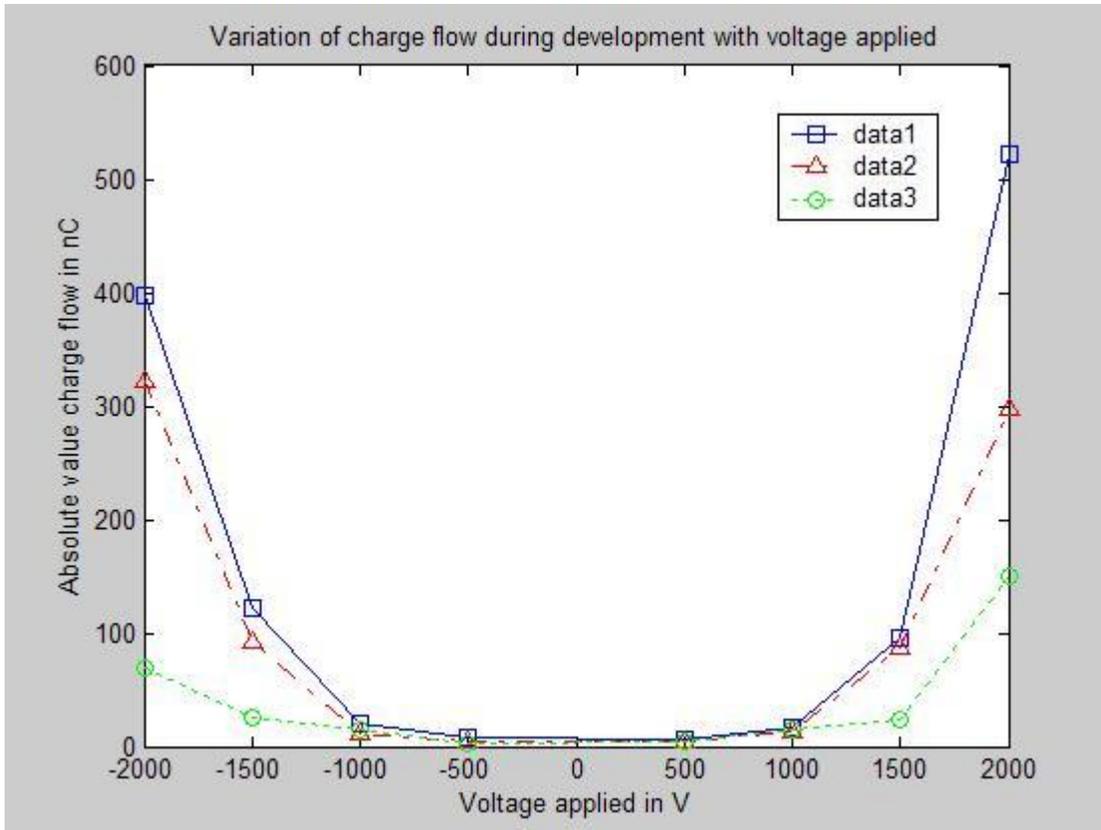


Figure 8-10. Charge Flow through the Ground during Development, where Data 1 is when Voltage is Provided to the Development Roller, Data 2 is when Voltage is Provided to Photoconductor Plate and Data 3 is when Photoconductor Plate is Charged by Charge Roller

It can be seen from the graph in figure 8-10 that the case where voltage is applied to the developer roller the charge of total powder developed is marginally more than the case where voltage is applied to photoconductor plate. The case where the photoconductor plate surface is charged the charge of the developed powder is the least. This amount of charge is the charge of the collective developed powder, which may mean more powder got developed or powder with more charge got developed. Both of these give the same charge flow reading.

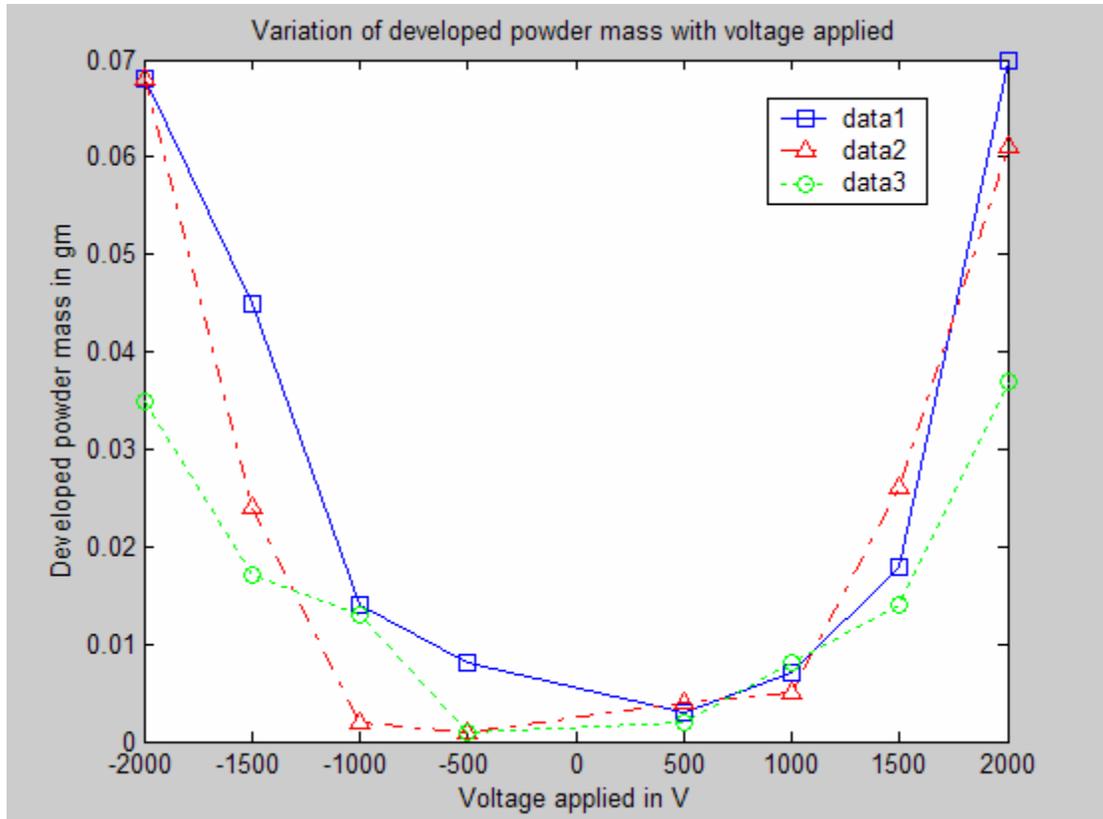


Figure 8-11. Variation of Amount of Powder Developed with Change in Voltage, where Data 1 is when Voltage is Provided to the Development Roller, Data 2 is when Voltage is Provided to Photoconductor Plate and Data 3 is when Photoconductor Plate is Charged by Charge Roller

The graph displayed in figure 8-11 shows that in the case of development when the voltage is applied to the charge roller the powder development is more compared to other methods. The next best development method is the case when voltage is applied to the photoconductor plate. The least productive method of development is when the photoconductor surface is charged.

By these results it can be concluded that the most productive way of developing metal powder is to apply voltage to the developer roller and ground the photoconductor plate.

Polymer Powder Development using Flat Photoconductor Plate Test Bed

The powder development experiment is done using nylon – 12 to observe the development pattern of nylon powder with change in voltage. The experiment is done for both positive and negative set of voltages. In each set of voltages the magnitude of voltage varies from 1000 to 5000 in steps of 1000. The results of these experiments are presented below.

Table 8-4. Amount of powder developed with change of voltage in the positive range

Development voltage (V)	Mass before Development (M_1) gm	Mass after Development (M_2) gm	Mass of developed powder (M) gm
1000	8.5158	8.5167	0.0009
	8.5167	8.5219	0.0052
2000	8.5219	8.5232	0.0013
	8.5232	8.5251	0.0019
3000	8.5251	8.5363	0.0112
	8.5363	8.5426	0.0063
4000	8.5426	8.5483	0.0057
	8.5483	8.5565	0.0082
5000	8.5565	8.5635	0.0070
	8.5635	8.5683	0.0048

Table 8-5. Amount of powder developed with change of voltage in the negative range

Development voltage (V)	Mass before Development (M_1) gm	Mass after Development (M_2) gm	Mass of developed powder (M) gm
-1000	8.5683	8.5692	0.0009
	8.5692	8.5712	0.0020
-2000	8.5841	8.5846	0.0005
	8.5846	8.5851	0.0005
-3000	8.5851	8.5910	0.0059
	8.5910	8.5943	0.0033
-4000	8.5943	8.5993	0.0050
	8.5993	8.6043	0.0050
-5000	8.6043	8.6102	0.0059
	8.6102	8.6156	0.0054

Table 8-4 shows the variation in the amount of nylon powder developed using flat photoconductor plate test bed setup, with the variation in applied positive voltage in the

development zone. Two readings are reported for each voltage to decrease the chance of experimental error. The next table shows the results from similar experiment but using negative voltage.

From these two set of experiments it is noted that the amount of powder developed does not depend on whether the voltage is positive or negative. Although it seems like the amount of development is marginally higher with positive voltage, it may be neglected due to the chance of influence of experimental errors. It can also be noticed that, it is only at 3000V (both positive and negative), that we see a significant increase in the amount of powder developed. It may be concluded from this observation that to develop nylon powder, a voltage greater than 3000V should be applied to the developer roller.

Printing of Polymer using Flat Photoconductor Plate Test Bed

The last section described the experimental results of polymer powder development with respect to its response to the change in voltage. In this section some sample prints of Nylon – 12 are presented.

The control of laser imager to produce image patterns on the photoconductor surface is beyond the scope of the presented thesis work. As it was necessary to prove the effectiveness of the designed test bed with the new developer and flat plate photoconductor, specially designed electrodes were used to develop powder from the developer roller. These electrodes were cut in the shape of different patterns and assembled on a common back plate to replicate the latent image of photoconductor due to imaging. The surfaces of the electrodes were made sure to be aligned along the same horizontal plane for uniform development due to equal development gap between all the electrodes and the developer roller.



Figure 8-12. Electrodes Shaped in Different Patterns

Development of Nylon – 12 powder was done by providing voltage to the developing roller and grounding the patterned electrodes. Copper sheets are cut in pattern shapes and glued to the top surfaces of the patterns and grounded. These sheets are covered with PET sheets which are also cut to size according to the patterns. The PET cover is provided to avoid any sparking that may occur during the powder development process. Using result from the last experiments on Nylon – 12 development characteristics, a voltage of 3000V was supplied to the developer roller for better powder development.

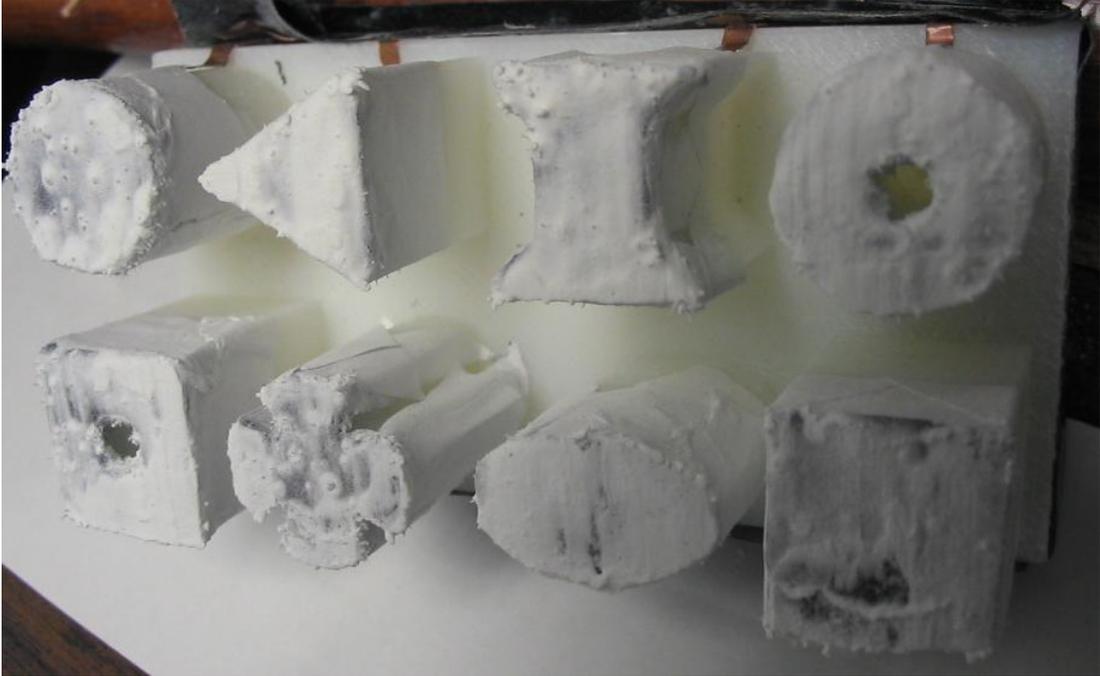


Figure 8-13. Patterned Electrodes after Developed with Nylon – 12 Powder

The build platform was borrowed from the old test bed configuration, which is an aluminum plate supported by four springs at its corners. The platform adjusts itself, due to the springs, to the plane of the electrodes when the electrodes are pressed against it. A sponge is placed on the aluminum plate to help in finer adjustments of the surface orientation of the patterned transfer electrodes and the build platform electrode. A schematic of the build platform is presented below.

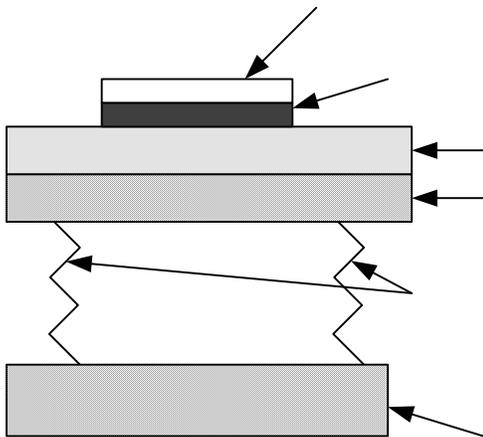


Figure 8-14. Build Platform for Printing Nylon – 12

The printing is done on paper rather than PET on the build platform electrode is due to the fact that after each print the PET surface retains charge of the printed layer of powder which distorts the transfer of powder for printing purpose on the build platform. The pictures of intended assembly of patterns and actual printed patterns are shown below.

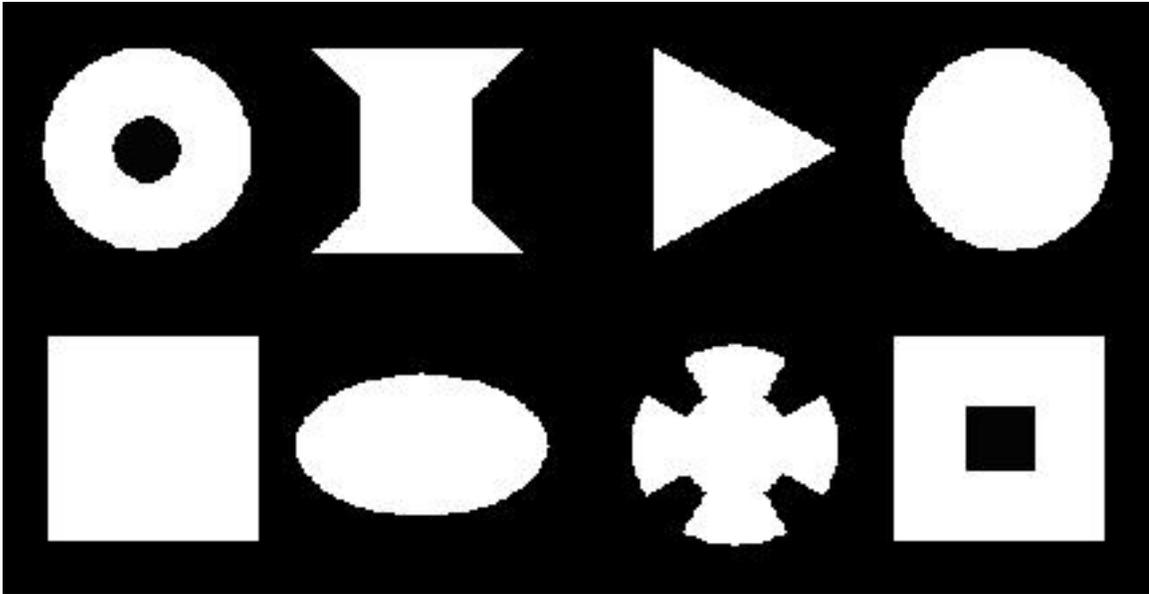


Figure 8-15. Intended Assembly of Patterns



Figure 8-16. Actual Printing of Assembly of Patterns using Nylon – 12

The difference in the intended print of assembly of patterns and the actual print can be due to various reasons. Some of the reasons are:

- The surface of the patterned transfer electrodes may not be at the same level during powder development. This may result in differential powder development due to the differential electric field experienced for each of the electrodes, as electric field decreases with increase in distance when voltage is given to be constant.
- There may be localized surface undulations which make the development non-uniform. These undulations also affect the transfer pattern due to the non-uniform gaps between the electrodes during transfer.
- The PET surface may retain some charge on its surface and affect the development and transfer patterns due to the influence of electric field produced by these charged areas.
- Powder may not come out uniformly from all the regions along the length of the developer roller, which may cause differential development. There may be the case of less powder coming out of the developer that is not enough to develop all the patterned transfer electrodes.
- Less charged powder may get developed due to high electrostatic field and may get transferred as a lump during printing on to the build platform. There may be the possibility of powder getting developed as agglomerated mass (due to cohesive forces) and during printing get transferred as a thick layer due to self weight.

All these possibilities present for us a lot of variables to control and analyze. There need to be done a series of experiments to isolate the parameters which have major influence on the development and transfer of powder, which was not pursued due to the limitation in time and resources. These issues can be dealt in the future to get better prints. One of the major improvements was done to the print quality by replacing the PET sheet on the build platform copper electrode with a sheet of paper. This can be clearly visualized by comparing the print in figure 8-14 (printed on paper) with figure 8-17 (printed on PET).



Figure 8-17. Print of Assembly of Patterns on PET Sheet Surface.

Comparing the two figures we see that in case of printing on PET surface there is a lot of background printing and diffused printing. This may be due to the possibility that PET surface may retain some surface charge which have their own electric field lines. These may distort the field pattern during powder transfer and cause the developed powder to scatter and result in a diffused background print. This was avoided by the use of paper, which is not a good insulator and so cannot retain surface charge. The paper has enough insulating capability to avoid any spark during the close contact of the two electrodes for transfer of powder. The transfer of powder was done at 1500V for the paper and 5000V for PET. Printing on paper also improved the visibility of the print as it has a contrasting black color with the white colored nylon – 12 powder.

CHAPTER 9 CONCLUDING DISCUSSION AND FUTURE WORK

Throughout this thesis there has been an attempt to understand the behavior of metal and polymer powders and their suitability to be printed as a structural material using Electrophotographic Solid Freeform Fabrication (ESFF).

A series of experiments were done with five polymer powders, namely, Polyvinyl Alcohol, Nylon – 6, Nylon – 12, ABS and PVC. Their physical properties including volume resistivity, permittivity and mass density were found out by using a test cell. The qualitative nature of development of these powders was observed and it was concluded that Nylon – 12 is the suitable polymer for ESFF test applications.

Charge per unit mass (Q/M) and mass per unit area (M/A) are two important properties of materials which are essential for quality of development and print. The old charge and mass measurement test setup was modified and improved so that it can be used to test developers designed to develop any powder. The developers were improved by solving problems of powder leakage and better flow and charge control of the powders. In the charge and mass measurement setup there was a need of discharging the surface of the drum before it goes for another cycle, which was incorporated in the new design. In the new design the method of powder mass measurement was simplified by wiping the powder off the drum surface using a cleaning blade and collecting them in an attached cleaner box and then weighing the box. Tests were conducted on this setup to estimate the Q/M values of iron and nylon – 12 powders. It was also concluded that the Q/M value of metals is directly proportional to the applied voltage and can be controlled

by it. In contrast to conductive metal powders, it was found that the Q/M value of nylon – 12 decreased with increase in voltage. This is attributed to large number of low charged powder particles getting developed at higher fields created by increase in voltage.

The problems associated with the test bed design based on commercial laser printer using toner as the print medium were discussed and a need for a test bed independent of any commercial printer was realized. A conceptual design based on a flat photoconductor plate was proposed and discussed. A developer was designed and fabricated, which could develop powder vertically upwards. This developer was assembled with the charge roller and the laser imaging system to make a complete powder development system.

Iron and nylon –12 powders were developed and tested using this new test bed concept. The three methods to develop iron were compared and it was concluded that the method in which the developer roller is supplied voltage is the most suitable development technique. Although the method of charging the photoconductor drum is the only way to image iron powder, this method is mostly unreliable and it can only be used for charged area development.

It was also concluded during the discussions that to make metal parts there has to be alternating layers of metal and insulator. This is due to the fact that metal cannot be transferred on to another metallic surface. Powder development in alternate layers solves the problem of imaging, as imaging can be done using the insulator powder layer. This also solves the problem of holding metal powders together during development, as the polymer powders can be fused to hold the metal powders together.

The only configuration to develop polymer powders is by providing voltage to the charge roller and grounding the photoconductor drum. This is due to the fact that the

polymer powders are insulator powders and they can only be charged triboelectrically and by injection charging. Triboelectric charging is material dependent and it is difficult to design a system which can effectively charge any polymer powder triboelectrically. The only option left for charging is by injection and for that the powder has to be in contact with a conductor connected to voltage source. This makes it necessary that the charge roller and the doctor blade should be connected to voltage source. The polymer powder can develop in both charge area development (CAD) and discharge area development (DAD). The development of polymer powder was tested and the results presented. Attempt was made to print Nylon – 12 powder in patterns using patterned electrodes. The prints of patterns on paper and PET surfaces were shown. It was seen that print on paper is better than PET surface, as PET retains surface charge and distorts the print to create diffused background printing. There are other parameters which could be controlled to improve the print can be explored in future.

By theoretical calculations on metal powder development using flat photoconductor plate test bed setup it was concluded that the minimum Q/M on a particle is independent of powder size and is equal to 3.27nC/gm for development in air. The electrostatic force available for development is found out to be more than the gravitational pull on an iron powder particle of 60 microns diameter. The maximum diameter that a particle can have to develop in air is 3.1mm.

The four methods of transferring powder were discussed and it was found out that the most suitable method of transferring powder, which does not depend on the field created by potential difference across the transfer zone, is the method of repelling powder from the photoconductor plate. A method which uses a capacitor to store charge and then

use this charge to repel the developed powders is proposed. The experimental analysis of this method is a very sensitive process and a new setup has to be designed to test this concept, which was not possible during the duration of research presented in this thesis. This can be done in the future and the effectiveness of the method can be verified.

In the future, the imaging capability of the laser imager has to be improved to be able to create image of the cross-sectional figure of the solid model from PC. The print quality of nylon – 12 printing can be improved by careful experimentation and identification of critical parameters controlling it. The rest of the flat photoconductor plate test bed, including the build platform and the cleaning and discharging assembly has to be designed and implemented. The method of fusing the powder has to be chosen and assembled into the test bed. As mentioned earlier, the concept of powder transfer for printing on build platform by repelling powder from the photoconductor surface by creating high electric field using a capacitor arrangement at the backside of the photoconductor plate has to be tested for feasibility using improved experimental setup to handle such sensitive experiment.

APPENDIX
MEASUREMENT WITH KEITHLEY ELECTROMETER

Resistivity Measurement using Keithley 6517A Electrometer and Test-point Software

The electrometer has to be set from the factory default values to user defined values of the parameters which are measurement cell specific. This is done by accessing the ohms configuration menu. This is done, by pressing CONFIG and then R.

In the menu, scroll to the MEAS-TYPE option. This is used to select and configure the measurement type for the ohms function.

RESISTANCE: Use this menu item to configure the ohms function to make normal resistance measurements.

RESISTIVITY: Use this menu item to configure the ohms function to make surface or volume resistivity measurements.

After selecting **RESISTIVITY** there will be two options **SURFACE** and **VOLUME**, for configuring parameters for surface and volume resistivity measurements respectively.

In both the options there is **MODEL-8009** which is used when using the model 8009 Resistivity Test Fixture, and **USER** option in which user can define his own text fixture.

For **SURFACE** enter the value of K_s and for **VOLUME** enter the value of K_v . The values are defined below.

$$K_s = P/g$$

Where: P = The effective perimeter of the guarded electrode (mm)

g = Distance between the electrodes (mm).

$$K_v = \pi \left(\frac{D}{2} + B \frac{g}{2} \right)^2$$

Where, D is the outside diameter of the circular electrode

g is the gap between the guarded electrode and the ring electrode

B is the effective area coefficient, which is found by comparing the readings from the designed test cell and the one that is already calibrated.

B is typically near to zero for electrodes with relatively small gap, d. It is thus approximated as zero.

For measuring volume resistivity thickness has to be specified. Use THICKNESS to specify (in mm) the thickness of the sample.

Use EXIT to come out of the menu at all times.

The figure below explains the connections and the cross section of the test cell. The voltage source is a part of Kiethley. The HI terminal of the electrode is connected to the top electrode and the HI terminal of the voltage source is connected to the bottom electrode. The low terminals of the voltage source and the electrometer are connected internally and one of the terminals is connected to the metal foil acting as the guard ring. Another metal foil is wrapped around the test cell to protect it from errors induced by external fields. The guard ring is connected to the terminals through this shield. The guard ring with the LO terminals are grounded.

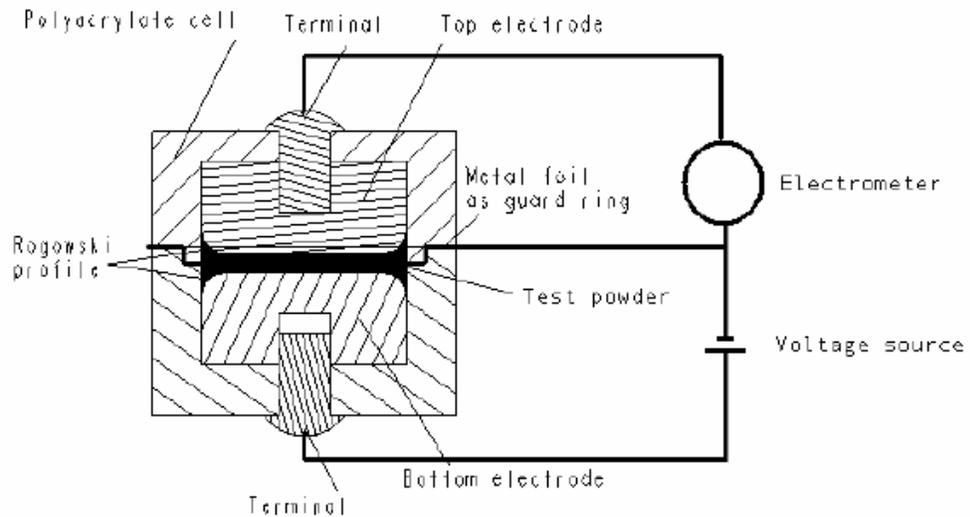


Figure A-1. Parallel Plate Powder Resistivity Test Cell

Note: The interlock cable with the Model 8009 resistivity test cell **MUST** be connected to Kiethley to allow the voltage source to apply the voltage.

Then open the 6517 Hi-R Test terminal.

It will display a window as shown in the figure. From the menus select the autorange “on” and measurement type “Volume (ohm-cm)”. Then press the run button to start the experiment. At the end of the experiment the window will display the resistivity value.

We can also do surface resistivity and resistance measurements with this setup.

The window display is shown in the figure below

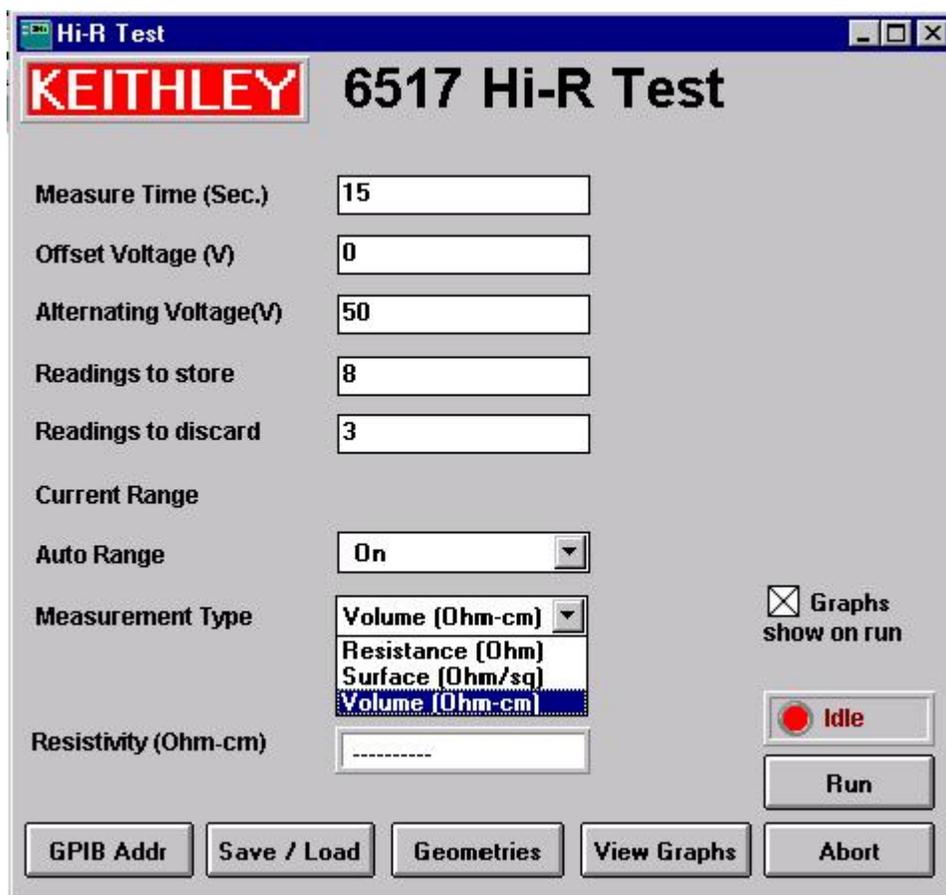


Figure A-2. Test Window for Resistivity Measurements.

Permittivity Measurement Using Keithley 6517A Electrometer and Test-point Software

For this test the metal foil acting as the guard ring is removed from the test cell.

The circuit setup is shown in the figure below.

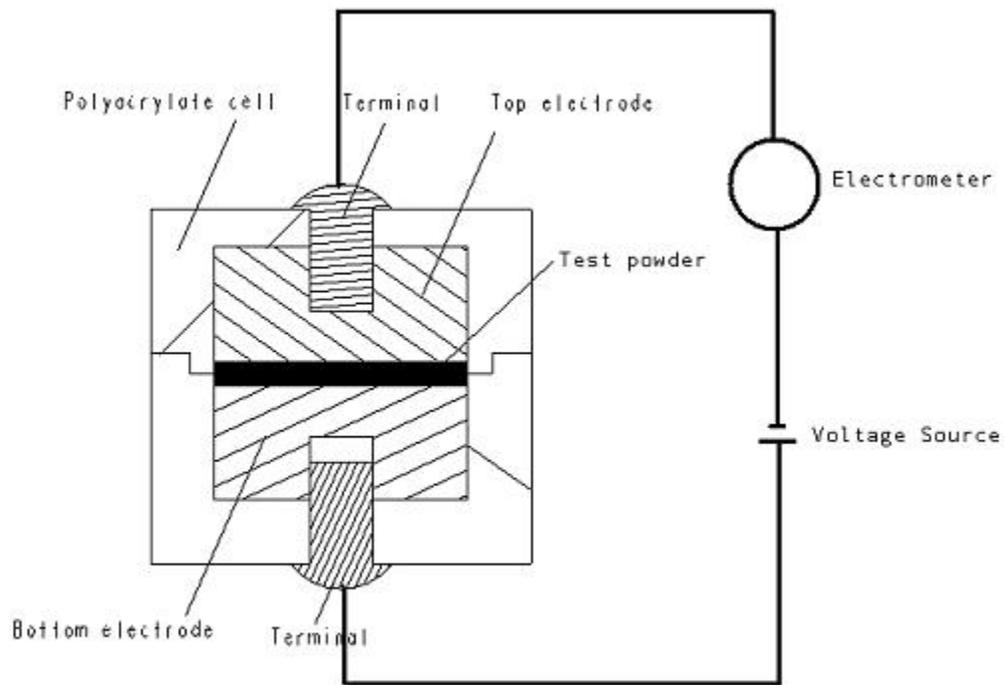


Figure A-3. Parallel Plate Powder Capacitance Test Cell.

The HI terminals of both electrometer and Voltage source are connected to top and bottom electrode respectively. The LO terminals are connected internally and one of the LO terminals is connected to the outer metal foil shield.

The 6517 Hi-R Step Response window is opened. It looks like the figure below.

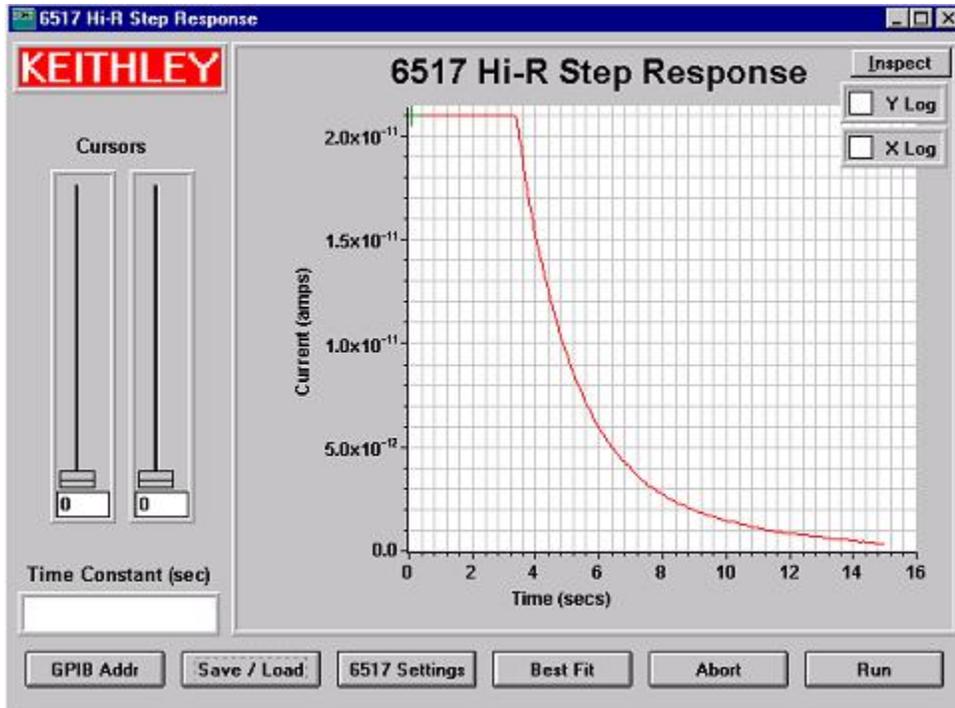


Figure A-4. Hi-R Step Response Window

Figure A-5. Step Response Settings

Then the software is run which interfaces with Keithley and runs the test. During the test a step voltage is applied and the capacitor is allowed to discharge. The capacitor

leakage current through the electrometer is used to plot the exponential graph. The two cursors which are at 0,0 are moved so that they have the exponentially decreasing curve between them. Then a best fit curve is plotted and the time period of this curve is displayed. This time period is equal to R multiplied by C . So, the capacitance is found by dividing the time period by the resistance. Resistance is measured by changing the wire connections and connecting them in the same way as it was done for resistivity measurement. Now we do not have the guard ring and the resistance option selected from Hi – R test menu. The value of capacitance is then used to calculate the permittivity of the packed powder in the test cell.

Step by Step Procedure for Performing the Tests:

Common Steps for All Tests

- Connect the power cable to the main.
- Connect the cable with the terminals for measurement to the electrometer, the cable has three wires (red for HI, black for LO, and green for GND).
- Connect the wires acting as the terminals for the voltage source, (red for HI, black for LO).
- Connect the electrometer to the computer by connecting to the IEEE-488 bus and RS-232 interface.
- Connect the interlock cable provided with the Model 8009 Resistivity test fixture.
- Connect a terminal to ground

Steps for Resistivity Test

Connections

- Turn on the electrometer
- Fill powder inside the cavity on the top of the lower electrode of the test cell.
- Place a guard ring on the top of the powder in the interface between top and bottom electrodes.

- Slide the cylindrical metallic foil on the outside of the test cell to be in contact with the guard ring coming out of the cell through the gap between the top and bottom electrode.
- Connect one of the electrodes of the test cell to the HI of the electrometer and another to the HI of the voltage source.
- Connect one of the LO, either of the electrometer or the Voltage source, to the outer metallic shield. (The LO of the electrometer is internally connected to the LO of the voltage source.)
- Connect the ground terminal to the outer shield.

Software

- Open the Hi-R Test window.
- Click on the Auto Range ON.
- Click on the measurement type – Volume (ohm-cm), Surface (ohm/sq), and Resistance (ohm)
- For measuring resistivity the dimensions of the test cell has to be provided. This has to be done every time the Hi-R Test window is opened. This is done, by clicking the Geometries button. This will pop up a window, where entries about the surface area and the thickness can be provided.
- The test is started, by clicking on the run button.
- Other parameters that can be changed are measurement time, offset voltage, Alternating voltage, readings to store and readings to discard. Normally all these are provided with default value for each.
- Once the test run is complete, the value of resistivity or resistance is displayed on the main window accordingly.

Steps for Permittivity Test

Finding Time Constant

The connections for this test are similar to that of the resistivity test except the following changes.

- The guard ring is removed while preparing the test cell with powder.
- The ground wire terminal is removed.

To use the software for the experiment we use the following steps

- Open the Hi-R Step Response Test window.
- Click on 6517 settings to set the values of Measure time and Step Voltage. It is initially provided with the default Values.
- Click on the Auto Range ON.
- Click Run to start the test.
- After the test is complete, a discharge graph is displayed. Move the cursors on the graph and position them suitably on the graph. The cursor controllers are on the left side of the main window.
- Then an exponential decay curve is fitted on the graph by clicking on the Best Fit button. If the exponential curve does not cover the range of reading (visual inspection), then move the cursors around to get a better fit.
- The window below the “cursor controllers” displays the Time Constant of the exponential curve.

Finding Resistance

The resistance of the test cell is found out by going through the steps of the resistance measurement as explained under resistivity measurement steps. This is done without connecting the guard ring, but connecting the ground terminal. The only difference from the Step Response Test is that the ground terminal is clipped on the outer shield.

Finding Permittivity

Calculate capacitance by using formula $C = T/R$

Calculate relative permittivity by using the Value of Capacitance and the Geometry of the test cell.

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BIOGRAPHICAL SKETCH

The author was born in March 1980, in Bhubaneswar, India. In 2001, he graduated with a Bachelor of Technology degree in mechanical engineering from Indian Institute of Technology, Madras, India. He entered the Master of Science program in mechanical engineering at University of Florida in Fall, 2001.