# Automation of Soft Lithography

By

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Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Manufacturing

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# ABSTRACT

This dissertation is a final documentation of the project whose goal is demonstrating manufacturability of soft lithography. Specifically, our target is creating micron scale patterns of resists on a 3 square inch, relatively large area in case of soft lithography, flexible substrate using microcontact printing in order to forming electronic circuit patterns for flexible displays.

At first, the general principles and characteristics of soft lithography are reviewed in order to provide the snapshot of soft lithography technologies, and the key factors that affect the productivity and quality of microcontact printing are discussed because such factors should be understood in advanced to develop current lab-based microcontact printing science into plant manufacturing technology.

We proposed a prototype for automated of microcontact printing process adopting a continuous reel-to-reel design, ideal for mass production, as well as printing-side-up design in order to minimize the distortion of relief features of PDMS stamp. The machine we created not only demonstrated the manufacturability of microcontact printing, our initial project goal, but also high scalability for mass production. The machine can print micron scale patterns on a 7 square inch plastic sheet, four times bigger than initial target area, at once.

Thesis Supervisor: David E. Hardt
Title: Professor of Mechanical Engineering

## Acknowledgements

First, I would like to thank my God who provides me with the chance to study and guides me. He also gave the wisdom and the knowledge I needed.

I also recognize, with sincere thanks, two of my teammates in this project - Karan Chauhan & Arthur Cao Yuan (my colleagues in the M.Eng program). Karan has mainly contributed to software development for automation, and Arthur spent most of his time at the LMP shop, machining all the parts we needed.

I would like to express particular appreciation to my advisor, Professor David Hardt (MIT) not only for teaching us valuable knowledge in the class but also for his hidden efforts for coordinating and guiding the project. I am still impressed by his passion for manufacturing engineering.

I would like to thank all the members at Nano-Terra for helping us in every way while we develop the machine in the Nano-Terra lab. Brian James Wajji

I am also grateful for careful consideration from my colleagues and team leaders at POSCO. Jong-Hoon Lee, Dong-Sam Kim, Rim Seung-Wook, Sung Gee-Chan, Song Chi-Young, Won-Kook Cho, and Yeon Kyu-Sung. All of them were hidden support for me.

As a mechanical engineer, I am really fortunate to have an experience the entire design and manufacturing process, from the concept development and to the realization of the machine for state-of-the-art soft lithography technology. In some sense, this experience might be more valuable than any engineering knowledge I have learned at the class because it is very difficult to have such design experience in the real engineering world.

Finally, but not least, I would like to express special thanks to my lovely wife, Jin-Young, for her understanding and countless support during my study at MIT.

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# Chapter 1 Introduction

## 1.1 Introduction to Soft Lithography

Soft Lithography comprises a set of techniques that uses soft materials to enable replication and pattern transfer on a wide range of dimensional scales, ranging from nanometers to centimeters. These techniques follow a non-photolithographic strategy for pattern transfer based on self-assembly[1] of molecular layers and replica molding for carrying out micro and nanofabrication.

Most Soft Lithography techniques have been recently developed and have attracted significant attention from both academia and industry due their tremendous potential to support or even replace conventional means of micro manufacturing. The low capital costs and potential for high volume manufacturing with a variety of materials are significant attractions as well. Control over surface chemistry, required for some applications in medicine, is possible if using soft lithography. Other potential applications of soft lithography in the near future could include simple optical devices such as polarizers, filters, wire grids, and surface acoustic wave (SAW) devices (Zhao et al. 1996). Longer term goals include working toward optical data storage systems, flat panel displays, and quantum devices [1].

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[1] Self-assembly is the spontaneous aggregation and organization of subunits (molecules or meso-scale objects) into a stable, well defined structure via non covalent interactions. The information that guides the assembly is coded in the properties (e.g. topologies, shapes, and surface functionalities) of the subunits; the individual subunits will reach the final structure simply by equilibrating to the lowest energy form. Because the final self assembled structures are close to or at thermodynamic equilibrium, they tend to form spontaneously and to reject defects.

## 1.2 The Soft Lithography Taxonomy

Several different techniques are known collectively as soft lithography. Every soft lithography technique formally consists of three steps:

(1) Fabrication of a topographically patterned master, for example on a silicon wafer, using a conventional process like photolithography.

(2) Molding this master with a functional organic material (usually Polydimethyl siloxane or PDMS) to generate a patterned template.

(3) Generating a replica of the original template in a functional material or a 1:1 projection of the pattern on a surface by applying the stamp.

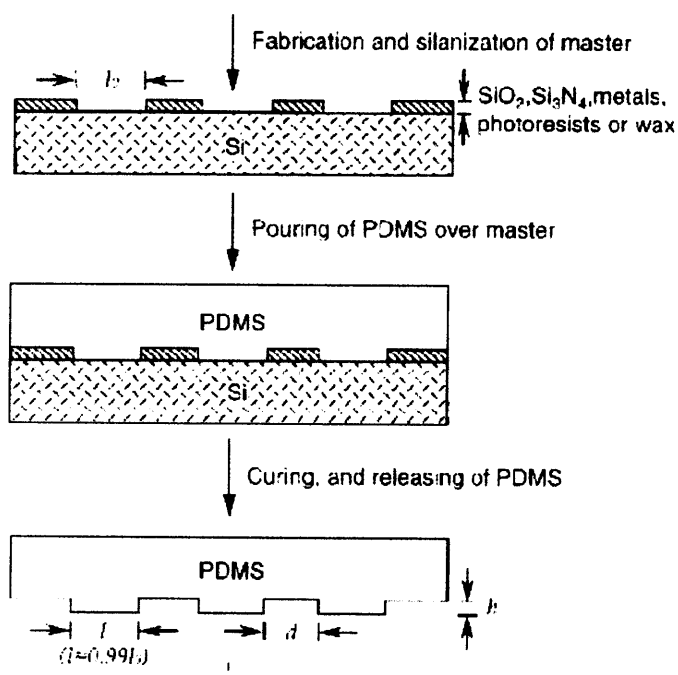



**Figure 1.1** Schematic illustration of the procedure for fabricating PDMS stamps from a master having relief structures on its surface [2].

The techniques which are collectively known as Soft Lithography techniques include:

## 1.2.1 Near Field Optical Lithography

A transparent PDMS mask with relief on its surface is placed in conformal contact with a layer of photo resist. Light, from a source, passing through the stamp is modulated in the near-field. If the relief on the surface of the stamp shifts the phase of light by an odd multiple of $\pi$, a null in the intensity is produced. Features with dimensions between 40 and 100 nm are produced in photo resist at each phase edge

## 1.2.2 Microcontact Printing (μCP)

A thin layer composed of an alkanethiol and ethanol, called "ink" is spread on a patterned PDMS stamp. The stamp is then brought into conformal contact with the substrate, which can range from coinage metals to oxide layers. The thiol ink is transferred to the substrate where it forms a self-assembled monolayer, or SAM, that can act as a resist against etching. Features on the substrate are revealed after etch treatment. Features as small as 300 nm have been made in this way [2]. This process shall be discussed in detail in Chapter 2.

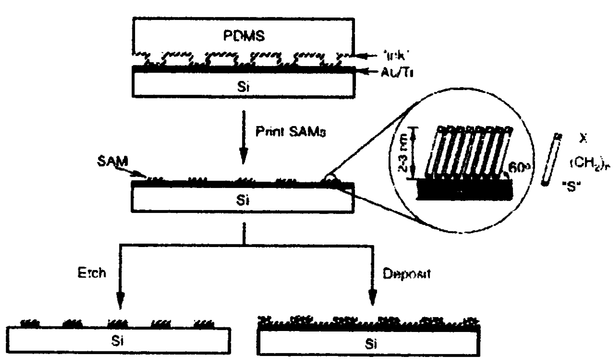



**Figure 1.2** Schematic procedures for $\mu$CP of hexadecanethiol (HDT) on the surface of gold: printing on a planar surface with a planar stamp [2].

## 1.2.3 Replica Molding

A PDMS stamp is cast against a conventionally patterned master. Polyurethane is then molded against the secondary PDMS master. In this way, multiple copies can be made without damaging the original master. Xia et al. demonstrated replica molding against elastomeric PDMS molds with resolution <10 nm. [3]

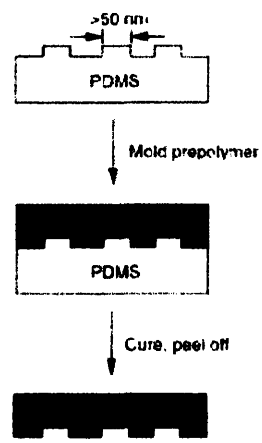



**Figure 1.3** Schematic of procedures for replica molding (REM) [4].

## 1.2.4 Micromolding in Capillaries (MIMIC).

Continuous channels are formed when a PDMS stamp is brought into conformal contact with a solid substrate [5]. Capillary action fills the channels with a polymer precursor. The polymer is cured and the stamp is removed. MIMIC is able to generate features down to 1 μm in size

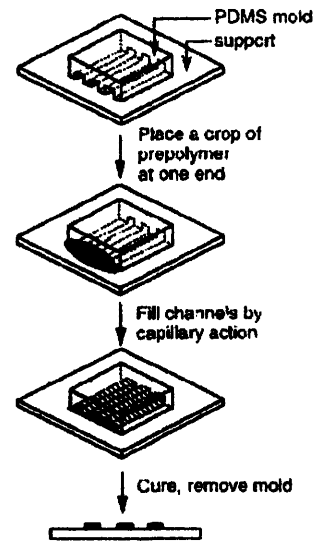



**Figure 1.4** Schematic of procedures for micro molding in capillaries ( MIMIC ) [4].

## 1.2.5 Microtransfer Molding (□TM)

A PDMS stamp is filled with a prepolymer or ceramic precursor and placed on a substrate. The material is cured and the stamp is removed. The technique generates features as small as 250 nm and is able to generate multilayer systems [6]

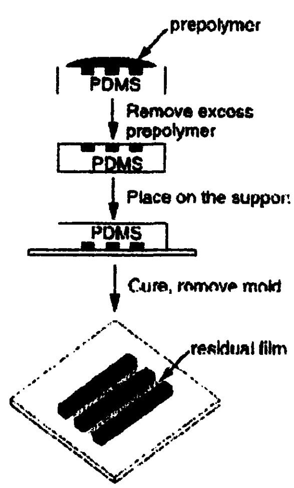



**Figure 1.5** Schematic illustration of procedure for microtransfer molding (μTM) [4].

### 1.2.6 Solvent-assisted Microcontact Molding (SAMIM).

SAMIM (Figure 1.7) forms relief features by spreading a small amount of solvent on a surface of a substrate such that the solvent can dissolve a thin layer of the substrate without affecting the PDMS mold [7]. After dissolving or swelling of a layer of the substrate by the solvent, the resulting fluid or gel is molded against the relief structures in the mold. SAMIM is similar to embossing in terms of operational principle, but it is different in that SAMIM uses a solvent instead of heat to soften a thin layer of substrate. Moreover, an elastomeric PDMS mold rather than a rigid master is used to imprint patterns on the surface of substrates [4].

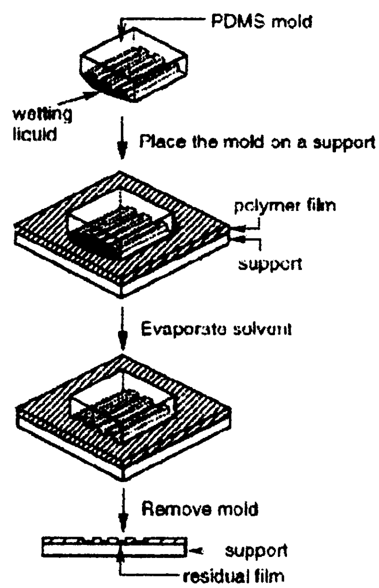



**Figure 1.6** Schematic illustration of procedure for solvent-assisted micromolding (SAMIM) [4].

## 1.3 Soft Lithography versus photolithography

Soft Lithography techniques not only promise a significantly cheaper alternative to the currently employed photolithography techniques, but also allow for more flexibility in product choices (for example, manufacturing structures on a non-planar surface, controlling chemistries of a surface etc), resolutions and feature sizes.

**Table 1.1** Tabular Comparison between Soft lithography and Photolithography [32].

| | Photolithography | Soft lithography |
|---|---|---|
| Definition of patterns | Rigid photomask (patterned Cr supported on a quartz plate) | Elastomeric stamp or mold (a PDMS block patterned with relief features) |
| Materials that can be patterned directly | Photoresists (polymers with photo-sensitive additives)<br>SAMs on Au and $SiO_2$ | Photoresists[a,e]<br>SAMs on Au, Ag, Cu, GaAs, Al, Pd, and $SiO_2$[a]<br>Unsensitized polymers[b–e] (epoxy, PU, PMMA, ABS, CA, PS, PE, PVC)<br>Precursor polymers[c,d] (to carbons and ceramics)<br>Polymer beads[d]<br>Conducting polymers[d]<br>Colloidal materials[a,d]<br>Sol-gel materials[c,d]<br>Organic and inorganic salts[d]<br>Biological macromolecules[d] |
| Surfaces and structures that can be patterned | Planar surfaces<br>2-D structures | Both planar and nonplanar<br>Both 2-D and 3-D structures |
| Current limits to resolution | ~250 nm (projection)<br>~100 nm (laboratory) | ~30 nm[a,b], ~60 nm[c], ~1 $\mu m$[d,e] (laboratory) |
| Minimum feature size | ~100 nm (?) | 10 (?) - 100 nm |

[a–e]Made by (a) $\mu$CP, (b) REM, (c) $\mu$TM, (d) MIMIC, (e) SAMIM. PU: polyurethane; PMMA: poly(methyl methacrylate), ABS: poly(acrylonitrile-butadiene-styrene); CA: cellulose acetate, PS: polystyrene; PE: polyethylene; and PVC: poly(vinyl chloride)

## 1.4 Overview of the Thesis

This thesis is a documentation of the thought process, its justification and the implementation details that went into prototyping an automated micro contact printing system for a nano technology based company in Cambridge MA during the summer of 2006. The objectives of this project were:

1. To understand and evaluate the capability for high volume production using soft lithography techniques based on the current state of knowledge about the processes and ongoing industrial and laboratory efforts. The techniques studied were near field soft optical lithography, replica molding and micro contact printing.
2. To conceptualize a manufacturing system built upon micro contact printing, to achieve economically viable production.
3. Based on a feasible manufacturing system design, implement a prototype that demonstrates automated inking, stamping and the tool/substrate transfer for micro contact printing.

Chapter 2 describes Near Field Phase Shifting Soft Optical Lithography- a soft lithography process- that was studied for feasible manufacturing. Chapter 3 describes the principles of micro contact printing, the current state of the art and critical factors for manufacturing including some feasible designs. Chapter 4 describes the overall design of the prototype that was developed. Chapter 5 provides details about the hardware and software integration to achieve automation in the prototype. Chapter 6 concludes this thesis with scope for future work.

## 1.5 Conclusion

The chapter introduced the reader to the scope and objectives of this project. A brief overview of the various soft lithography techniques was also presented. The next chapter will discuss one of the soft lithography techniques called microcontact printing in greater depth.

# Chapter 2 Background

## 2.1 Principles of Microcontact Printing

### 2.1.1. Definition & Characteristic

Microcontact printing (μCP) is a method for patterning Self-Assembled Monolayers (SAMs) on surfaces using elastomeric stamp. [8] The main distinguished feature in μCP is its use of SAMs to form micro patterns on a substrates. [4] SAMs are generated by contact between a topographically patterned elastomeric stamp, wetted with 'ink' consisting of molecules that form SAMs, and the surface of a substrate.

μCP can be used to form micron scale patterns of SAMs in a conventional chemical laboratory. It does not require photolithographic equipment or a clean room environment. Therefore, μCP can be an economically efficient alternative for patterning micron scale features when it is compared with photo-lithography.

Another characteristic of μCP is conformability. Because the microcontact printing uses rubber-like stamps, the stamps are able to conform to substrate with little force, compensating roughness of the surface of substrate. This is important for transporting molecular level SAMs

### 2.1.2 SAMs

Self-Assembled Monolayers (SAMs) are layers formed on a solid surface ( e.g. substrate )by spontaneous organization of molecules. Kumar and Whitesides discovered that a polymer inked with an alkanethiol and brought into contact with a gold-coated surface can form a monolayer of these molecules in the areas of contact in 1993 [2], [9].

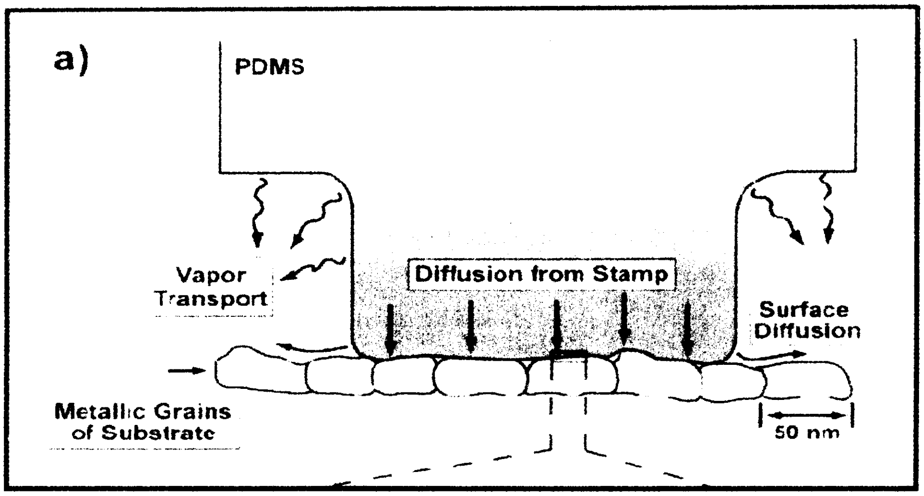



**Figure 2.1** Schematic illustration depicting the application of a PDMS stamp containing thiols to a polycrystalline metal film. The primary mechanisms of mass transport from the stamp to the surface are shown [8].

Thiols that form SAMs are mainly transported by diffusion from the bulk of stamp to the interface between the stamp and the surface of the substrate contacted by stamp. Diffusion from the edges of the stamp and vapor transport are other mechanisms that form SAMs. These two transport mechanisms – diffusion from edges and vapor transport – need to be taken into consideration [8]. When feature sizes are smaller than 500 nm, these non contact transport become significant enough to compromise the final pattern resolution [10].

The physical objects on which SAMs form are referred to as the "substrate." Substrates are prepared by common physical vapor deposition (PVD) methods (thermal or electron beam evaporation). Among a wide range of materials used for substrates, gold is commonly used because it is easy to obtain as a thin film and to pattern by a combination of lithographic tools (photolithography, micromachining) and chemical etchants. In addition, gold is a reasonably inert material, so it does not oxidize at temperatures below its melting point; it does not react with atmospheric $O_2$ [8]. Silver [11] and copper [12] also have been used as a substrate for forming SAMs

### 2.1.3 Stamp Fabrication Procedure

As shown in Figure 1.1., the fabrication of a stamp for microcontact printing begins by pouring degassed liquid polydimethylsiloxane (PDMS) on a patterned master. PDMS is the most common material used for stamps in μCP because it is a nontoxic, commercially available silicone rubber [8]. In addition, PDMS has a low surface energy ($\gamma$=21.6 dyn/$cm^2$), which makes it easy to remove the stamp from most surfaces [13]. Generally, a mixture of SYLGARD silicone elastomer 184 and SYLGARD silicone elastomer curing agent ( Dow Corning Corporation ) is used and cured at temperatures between 20~80 ℃, up to 48 hours.

Masters are fabricated by standard photolithography, or micromachining etc. Once a master is fabricated, patterned stamps can be easily replicated by the same process or replica molding as discussed in Chapter 1. After pouring, PDMS is cured in an oven for several hours. Curing time and temperature are main factors determines the Young's modulus of PDMS, critical to possible printing resolution.

### 2.1.4 Printing Procedure

Microcontact printing starts with applying ink solution, composed of thiols (e.g. alkanethiols ) and solvent ( e.g. ethanol ), on the PDMS stamp. The stamp is commonly inked by dropping ink solution on the patterned surface for 30 ~ 60 seconds, and the ink solution is dried in the air, leaving thiols on the stamp. A steam of nitrogen gas helps to reduce time to dry the solution.

Patterned SAMs on a stamp is formed by contacting inked stamp with a substrate for a few seconds. And the relief patterns of a PDMS stamp transports ink on the substrates by contact to form micro patterns on the surface of substrates.

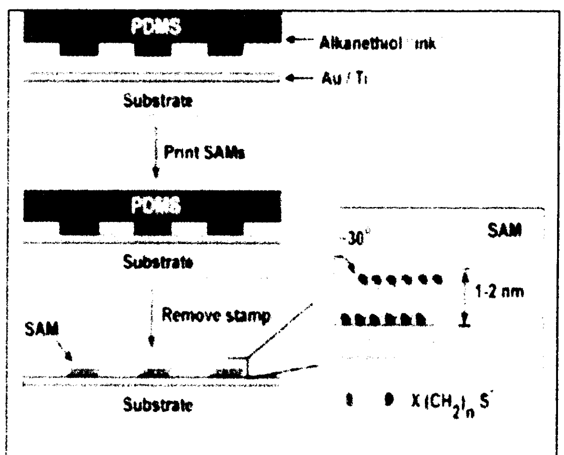



**Figure 2.2** Schematic procedures of microcontact printing procedure [2].

## 2.2 Previous works related to μCP automation

It has been reported that there are three promising areas of applying soft lithography as a tool for high-volume manufacturing: systems for microfludics, large-area electronics, and drug discovery [15]. Among these three areas, large-area electronics is well suited to μCP because the μCP has an ability to pattern large areas in relatively few processing steps and offers high potential for high production rate with low cost. Therefore, efforts for μCP automation have focused on its capability to pattern large areas.

For example, μCP using a cylindrical rolling stamp was suggested by Xia et al. [16] Instead of flat stamp, cylindrical stamp (Figure 2.3) was used to prevent air bubbles between stamp and substrate.

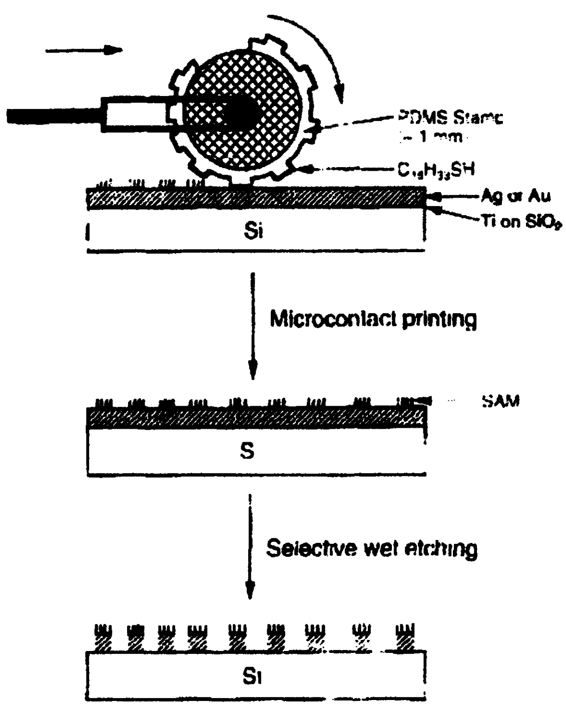



**Figure 2.3** Schematic procedures for conducting μCP with a rolling PDMS stamp [16].

The rolling process took 15 seconds and was performed manually. 300 nm features were printed over a 3 inch substrates (areas of ~50 $cm^2$). Although the rolling was not automated, it demonstrated continuous microcontact printing over large area substrate, which is indispensable for mass production. One problem with this design is that the stamp is deformed in accordance with curvature of the rod diameter used as a rigid core for PDMS stamp, and it is highly possible that the deformation of a tool (stamp) can cause inconsistency between printed patterns and relief features.

The concept of wave printing [17] was proposed in order to minimize the deformation and distortion of patterned SAMs printed by the stamp which has both large and small feature and space in a single stamp. Slender posts (height to width ration h/w 2.5) can be easily buckled and sagging will occur if the height of posts is relatively small to space between relief features by a small normal force. In wave printing, a glass backplane as a flexible glass mount is attached to elastomeric stamp to prevent distortion of relief features and this stamp-backplane creates wave by the pressured air mechanism, generating line contact between stamp and backplane. It took twenty minutes for inking, one hour for drying, and 15 seconds for printing as small as 0.75 μm, with hpost =2.3 μm. Micro contact wave printing demonstrated single layer capabilities with very low distortions.

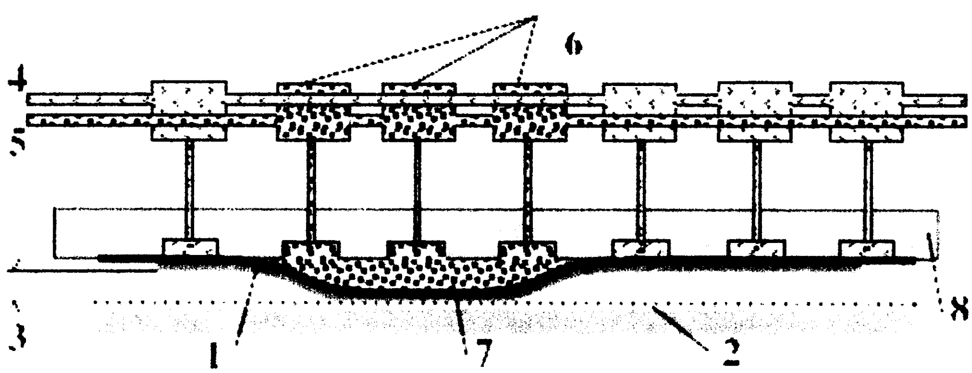



**Figure 2.4** A vertical Cross-section of the wave printing prototype [17].

1: Stamp-backplane assembly; 2: Substrate; 3: Working gap ( ≈ 100μm); 4:Vaccum supply; 5:Pressure supply (≈2kPa); 6:Valves switched to pressure supply, thereby creating the wave. 7, 8: Grooves-plate [17].

The IBM group uses a thin composite stamp that creates gradual propagation of contact region as shown in Figure 2.5. Using this machine, they patterned large-area thin film transistor backplane circuits for liquid crystal displays [18]. The Lucent group has also successfully patterned 6" X 6" organic electronic backplane circuits for flexible electronic paper displays [19].

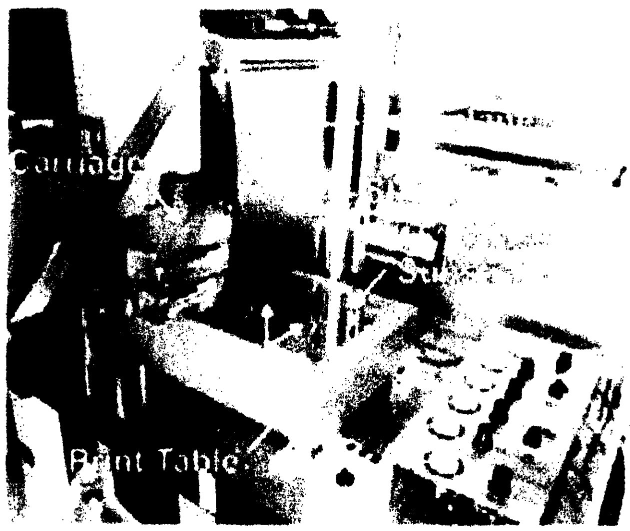


**Figure 2.5** The IBM printing system designed for fabricating 15" active matrix backplane circuits for displays [15].

# Chapter 3 Manufacturing Consideration

## 3.1 Process Breakdown

The breakdown of microcontact printing is the first step to bring lab science to a manufacturing process for a factory. In terms of manufacturing, microcontact printing comprises two steps; Inking and stamping. Inking is applying ink on the stamp and waiting until the ink dries, and stamping includes initial contact with the substrate and propagation to prevent air bubbles, full contact, and then peeling off. Table 3.1 shows required time, failure modes, and main control factors of each step.

**Table 3.1** Microcontact printing process

| Process | Inking | | Stamping | | |
|---|---|---|---|---|---|
| Step | Deposition | Drying | Initial Contact& Propagation | Full Contact | Peeling Off |
| Time (Typical) | 30 ~ 60 sec | 10 ~ 60 sec | ~ 5 sec | 10 ~ 30 sec | ~ 5 sec |
| Failure Modes | Swelling | Distortion (by Capillary Force) | Air trapping | Diffusion Deformation | Deformation |
| Control Factors | Concentration of ink solution | Drying Time Drying Methods | Propagation methods | Contact time Pressure Temperature | Velocity |

Assuming that PDMS stamp is already fabricated, the microcontact printing process starts with the deposition of ink on the stamp. Dropping thiol-containing solution onto the stamp or immersing the stamp in a solution of thiol is a common method for applying ink. Before printing, the excess solvent should be evaporated to keep the ink solution from dropping on the substrates. A stream of nitrogen gas will reduce time required to dry the stamp. Creating initial contact and propagation is critical especially for patterning SAMs over a large area in order to prevent trapped air between the stamp and substrate. After accomplishing full contact, the stamp must remain on the substrate until SAMs form completely. Generally, it requires a sufficient amount of contact time (30~60 seconds) to form SAMs without defects, but non-contact printing can occur by surface diffusion from the edge of the feature or vapor transport if contact time is too long. The stamp should be peeled gently after forming the SAMs.

## 3.2 Critical factors in microcontact printing.

### 3.2.1 Young's Modulus

Young's Modulus of the stamp is one of factors that determines the minimum pattern size. Young's Modulus of the Stamp is determined by the mixing ratios between prepolymer precursor and curing agent, and the curing time and temperature [20]. Stamps that have low young's modulus (1~3 MPa) are widely used because it provides conformability, a distinguishing feature of microcontact printing. However, soft stamps can be easily deformed if aspect ratio are >>1 or <<1, so it is recommended to use harder stamps to print submicron scale patterns. For example, a feature size of ~20nm was patterned using hard PDMS, whose Young's modulus was 9.7MPa [21]. Therefore, Young's modulus should be carefully determined in accordance with the feature size of the product and the need for substrate conformance

### 3.2.2 Contact Time

Some hydrophobic SAMs can be used as resists for etching[22], and SAMs should be thick enough to protect metal films from corrosion by aqueous wet-chemical etchants. Figure 3.1 represents that thickness of printed SAMs is proportional to contact time during printing. For example, it takes 10s to form 10nm thickness SAMs and 1000 seconds to reach 2.5nm thickness. Moreover, as shown in Figure 3.2, longer contact time reduces the defect ratio under the same concentration of ink. There is a 50 % rate of defects when contact time is 1 second, but approximately 2% defects rates were reported when contact time is longer than 70 seconds. Therefore, when SAMs are used as resists for etching, contact time should be long enough to transport all thiols to the surface of substrate so that desired thickness can be formed.

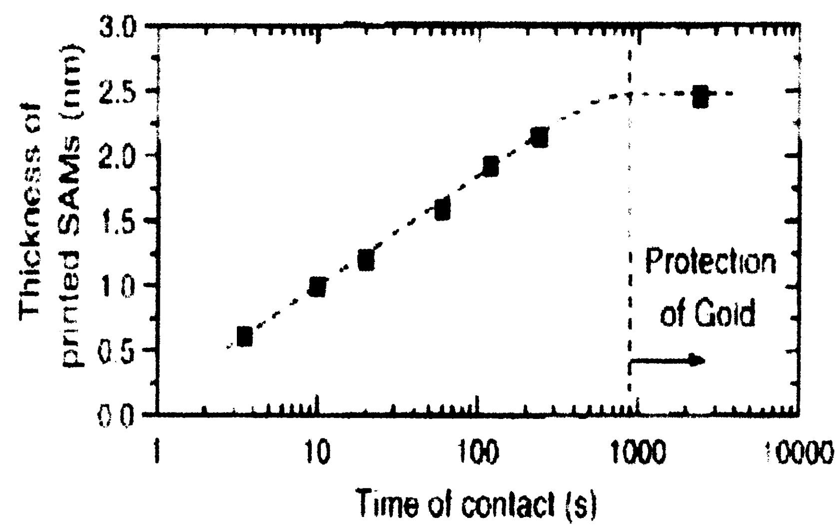



**Figure3.1** Relationship between thickness printed with 0.2mM solution of ECT ink [23].

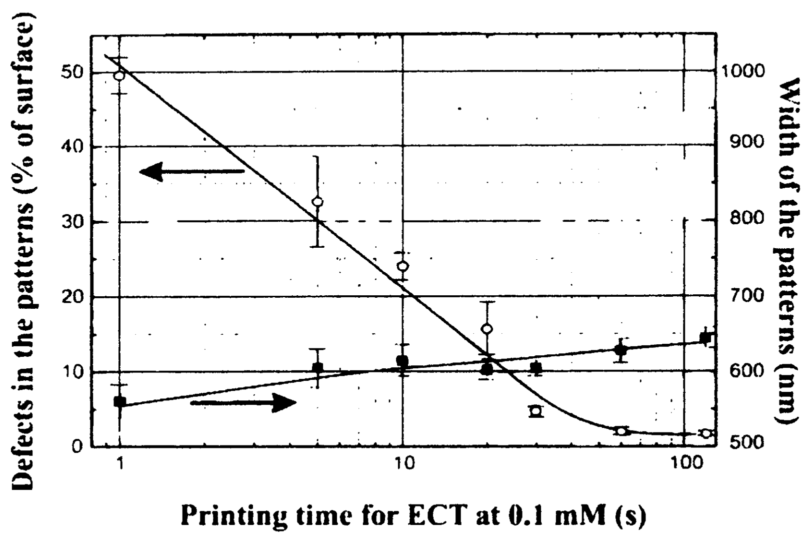



**Figure 3.2** Relationship between printing time and defects in the pattern [24].

## 3.2.3 Concentration of ink solution

Concentration and printing time are also inversely related. Figure 7 shows the result of microcontact printing using different concentration of ink for a constant contact time(30 seconds). High concentrations of thiols take less printing time and the number of defects are decreased when concentrations of ECT becomes higher. However, it should be noted that high ink concentration also provides the opportunity for thiols to diffuse.

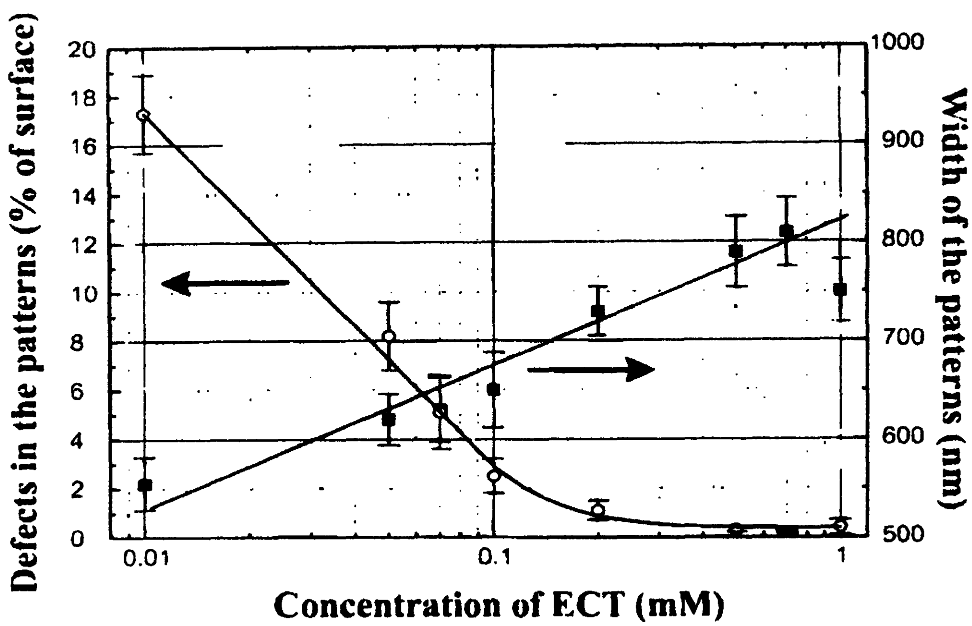



**Figure 3.3** Quality of microcontact printed gold structures performed in the case of an ECT contact-inked stamp [24].

### 3.2.4 External Force

The required pressure is based on the magnitude that can initiate and control conformal contact without causing patterns to collapse. In order to prevent unwanted printing caused by excessive pressure, we need to examine the basic deformation mechanisms. Figure 3.4 shows the basic geometry of a stamp that consists of periodic relief line features with height of $h$, feature width of $2w$, and trench width of $2a$. When pressure is applied to the stamp, several types of deformation occur. These include in-plane lateral expansion and "sagging" of the trench and relief features from compression by the external stress [25].

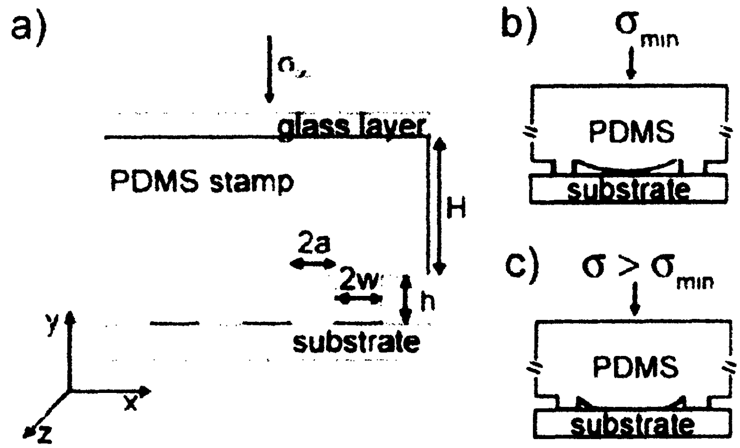



**Figure 3.4** Illustrations of (a) basic geometry of a PDMS stamp and stamps deformed into contact with substrates under (b) required minimum and (c) excess pressures [25].

Delamarche et al. [26] showed that the height-to-width ratios, the aspect ratios, of the relief structures on PDMS stamps need to be between about 0.2 and 2 to obtain defect-free printing. If the aspect ratio of the PDMS feature is too high, the roof of the feature may come into contact with a substrate under its own weight or under an external pressure. When the aspect ratios are too low, the relief structures are not able to withstand the stamp weight.

Specifically, the model for promoted contact between roof and substrates under external stress is suggested by Hui as follows [27].

$$V_{\max} = \frac{4\sigma_{\min}}{\pi E^*}(w+a)\cosh^{-1}\left[\sec\left(\frac{w\pi}{2(w+a)}\right)\right] \qquad (3.1)$$

where $V_{max}$ is the maximum displacement of the roof by an applied minimum external stress, and the conformability [i.e. the ratio of Young's modulus divided by the work of adhesion ( E/w ) of the material ] was found to be a measure of the spontaneous occurrence of conformal contact as well as of spreading collapse [28].

### 3.2.5 The Choice of Inking Method

Inking can be carried out in three different ways – Immersion inking, Pen-Type inking, and Contact inking. Three inking methods are explored and discussed in the academia [24].

1. **Wet Inking** - Ink is uniformly applied to the PDMS stamp to cover the entire exposed surface area. This is done by fully submerging the patterned surface of the stamp in an ink tub.
2. **Pen Stamp** - Ink is stored in an ink tank behind the PDMS stamp and diffuses onto the surface of the stamp for stamping. The method derives its name due of its functional similarity to a writing ink pen.
3. **Contact Inking** - Ink is only applied only to the relief features of the stamp. This is achieved by bringing the stamp's relief feature in contact with a pad soaked with ink.

Table 3.1 gives a functional comparison for each method.

**Table 3.1** Comparison of Three Methods of Inking Stamps for μCP [24]

| | **Wet Inking** | **Pen Stamp** | **Contact Inking** |
|---|---|---|---|
| **Distortion of stamps** | Capillary effects, slight swelling | Strong swelling | No distortion |
| **Adversary diffusion of the ink (HDT)** | Strong | NA | Strongly minimized |
| **Geometric effects** | Some | NA | Strongly minimized |
| **Surface crystallization** | Strong (>=0.5mM) | Strong (>=0.01mM) | Strong (>=0.5mM) |
| **Ease for repeated inking/printing** | Bad | Very good | Fair |
| **Scalability** | Unknown | NA | Plausible |
| **Economy of reagent** | Bad | Very Good | Fair |

Stamp distortion is important to us since a single stamp may have to go through multiple rounds of printing in the industrial production. Even slight distortion would be dramatically reduces the productivity and product quality collectively.

The scalability is also important to us as the goal is to design a machine good for large scale production. For output quality of the printed patterns, it is important that adversary diffusion (due to vapor transport) is minimized. With the factors above and Table 4.2, contact inking was chosen be the most appropriate inking method for this project.

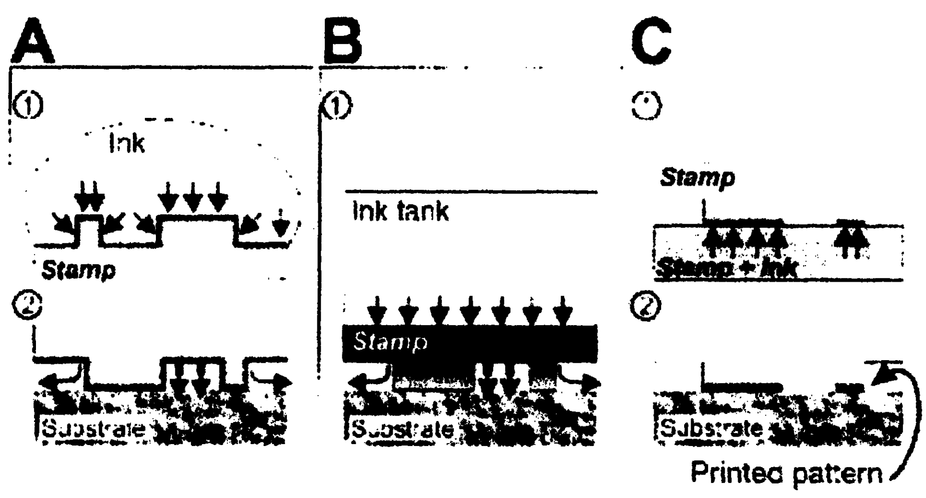



**Figure 3.5** Three different types of inking for Micro contact printing. The patterned stamp is consequently inked only via the contact zones where molecules will be needed in step 2. Concentration and immersion time are inversely related: low concentrations of thiols in solution require long immersion times. (A) A liquid inking technique allows impregnation of the entire surface of the patterned stamp with a drop a dilute solution of thiols in ethanol. The possible consequence of this inking method is the interference during printing of thiols on the stamp adjacent to the regions of contact. (B) Inking a stamp by transferring thiols from a liquid reserve of alkanethiols in ethanol through the PDMS allows the stamp to be inked permanently and reused readily, but does not localize this stamp impregnation only where needed (C) Direct inking of the patterned stamp follows its contact with a flat inker pad previously impregnated by immersion in a dilute solution of thiols. [24].

### 3.2.6 Propagation Methods

Air bubbles trapped between the stamp and substrate easily occur when large areas are printed. Several methods, such as Microcontact printing under the low pressure environment [23] and forcing air out using flexible backings have been studied, but contact initiation and propagation is simple and generally used method.

The contact propagation can be categorized into three methods: radial contact propagation, linear contact propagation, and rolling contact propagation [30].

a)

b)

c)

**Figure 3.6** Three contact propagation methods (a) Radial contact propagation (b) Linear contact propagation (c) Rolling contact propagation [30].

Radial contact propagation is done by making a stamp convex. The contact initiation starts from the center, and convexity is decreased gradually along with spreading contact region [16]. Linear contact propagation starts from line contact instead of point contact. The end of a bent stamp creates line contact initiation and contact area gradually increases by dropping the stamp gently. A thin bendable layer of metal or polymer can be used for backing the soft stamp. Third contact propagation method is rolling contact, using cylindrical stamp. In terms of automation, rolling propagation has benefits in that it does not require another mechanism or process for separation of stamps after printing. Moreover, rolling propagation can simply scalable to mass production process of Micro contact printing such as reel to reel process. However, the deformation of stamp is difficult to expect during preparing cylindrical stamp and printing.

### 3.2.7 Temperature

It has been known that forming SAMs at temperatures above 25℃ can improve the kinetics of formation and reduce the number of defects in them [9]. Also, the effect of temperature is particularly relevant during the first few minutes of the formation of a SAM when most of the adsorption and reorganization of the SAM is taking place.

## 3.3 Summary of manufacturing considerations

Rate, quality, cost, and flexibility of manufacturing process provide systematic and analytical view not only in evaluation but also in designing the process. Therefore, critical factors related to physics and automation of the process should be considered based on the four factors.

**Rate:**

In designing an automated microcontact printing process, it is important to decouple the printing and inking processes such that two processes operate independently or individual processing times.

Different inking methods require different inking time, and printing time mainly depends on two factors, concentration of ink solution and target thickness of SAMs. Because micro contact printing is a serial process involving inking and stamping, the time to complete inking and printing needs to be simulated by deciding key factors such as inking method and concentration of ink before designing a production line.

**Quality:**

There are a lot of factors that affect printing quality, but the fundamental problems of Micro contact printing relate to the properties of the stamp material. Xia et al [22] proposed three main concerns when microcontact printing is implemented as one of the micro fabrication process.

1. The shrinkage of PDMS during curing and the swelling of PDMS by a number of nonpolar organic solvents such as toluene and hexane.
2. The elasticity and thermal expansion of PDMS makes it difficult to get high accuracy in registration across a large area.
3. The softness of an elastomer limits the aspect ratio *(height of feature / length of feature)* of microstructures in PDMS. When the aspect ratio is too high, two posts

can easily stick together (pairing). If the aspect ration is too low, space between two posts will collapse (sagging)

**Cost:**

The expected cost of tool, ink solution, change over time should be considered in designing & evaluating Micro contact equipment. Usually, tool cost depends on wear of the tool (PDMS stamp) but wear has not been reported so far, so it is very difficult to predict the total tooling cost. However, we can minimize the tool cost by minimizing the number of tools in the buffer between inking and printing station.

**Flexibility:**

In a high volume manufacturing process, flexibility of tooling and tool change - over time are important, so Micro contact printing machine should be designed such that it provides a fast tool changing mechanism. In addition, if Micro contact printing machine is used for multilayer micro fabrication, the tool changing mechanism should also provide accurate registration capability.

# Chapter 4 Concept Development

## 4.1 Introduction

The objectives of this project included designing a manufacturing system for micro contact printing and prototyping an automated system for inking and stamping that could achieve economically viable process. To achieve these goals, a thorough understanding of the process physics involved in micro contact printing was required besides identifying the critical factors that could contribute to output quality and production rate. The final manufacturing system design and the prototype design were derived after several design iterations. The key breakthrough in the design process was achieved on the realization that the target substrate was a flexible sheet of gold coated plastic film which allowed keeping the stamp stationary (to avoid stamp deformation) and apply the substrate onto the stamp while achieving linear propagation (to avoid air bubbles).

This chapter takes the reader through some of the most important design iterations towards the final design. We discuss designs for both the inking and stamping steps. Though some of the designs do not involve the use of a flexible substrate, not only are they are significant milestones in this project but also and can be considered for hard substrates. Finally, we propose a complete manufacturing system for high volume production.

## 4.2 The Inking Process

### 4.2.1 Possible Designs for Inking

Having decided upon contact inking for the reasons outlined in section 4.2, several mechanisms to achieve it were considered. The most important ones are described next.

### (a) Roll Inking

A hard roller is inked by rolling it over an ink-soaked pad (contact inking) or by having an ink tank inside (Pen Inking). Then the roller rolls over a fresh stamp to transfer the ink. The advantage of this design is that it could generate linear propagation (to the ink) during the inking process to apply the ink uniformly over the stamp. Also the inking time between the roller and the stamp could be well controlled by the forward motion of the roller. Thirdly, it's convenient to shift between the stamping inking stage and the inking roller inking stage.

However, there are also several challenges with this design.

1. The vertical position of the inking roller determines the applied pressure. Excessively high pressure may deform the stamp while insufficient pressure may lead to insufficient ink transfer or worse, slippage causing some relief features to miss ink application completely.
2. The weight balance of the roller. As the weight of the roller itself is big enough to cause the deformation of the stamp, the weight must be well balanced with the external mechanism.
3. If applying the wet ink to the stamp, it takes longer to dry the ink. After the stamp is inked, it has to wait for another 10-60 seconds before it can be shifted to the printing. This could be the bottleneck for the process.

### (b) Polygonal Inking

Instead of a cylindrical inking roller, a regular polygonal rolling tool could be used. We consider the case using a hexagonal tool. The design is easily understood with the help of Figure 4.1. A major advantage is that the inking and stamping steps are readily integrated.

However, the challenge is that the inking pad and stamp have to be lifted up or down each time the hexagonal tool rotates. As Figure 4.1 shows, when the hexagonal tool rotates, the ink pad and the stamping stage have to be moved vertically by ½ of the edge length to allow the pinnacles of the hexagon rolling through. This requires high precision position control system, particularly given that the stamps will have to be changed regularly.

The other disadvantage, which is more critical than merely the mechanical inconvenience, is air trapping. As the hexagon surface rests over the stamps, there will be no linear contact propagation.

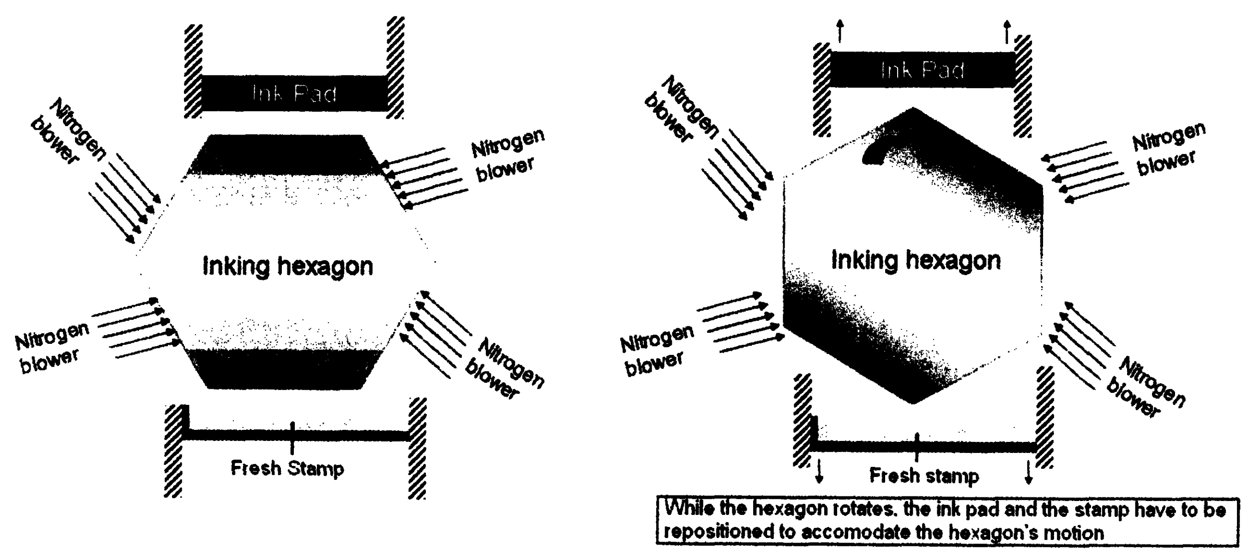



**Figure 4.1** The basic concept of polygonal inking.

## 4.2.2. The Finalized Inking Design

The final inking design is shown step by step in Figure 4.2. This design is based on the inking roller idea and takes into consideration the need for weight balance, pressure adjustment and vertical position control.

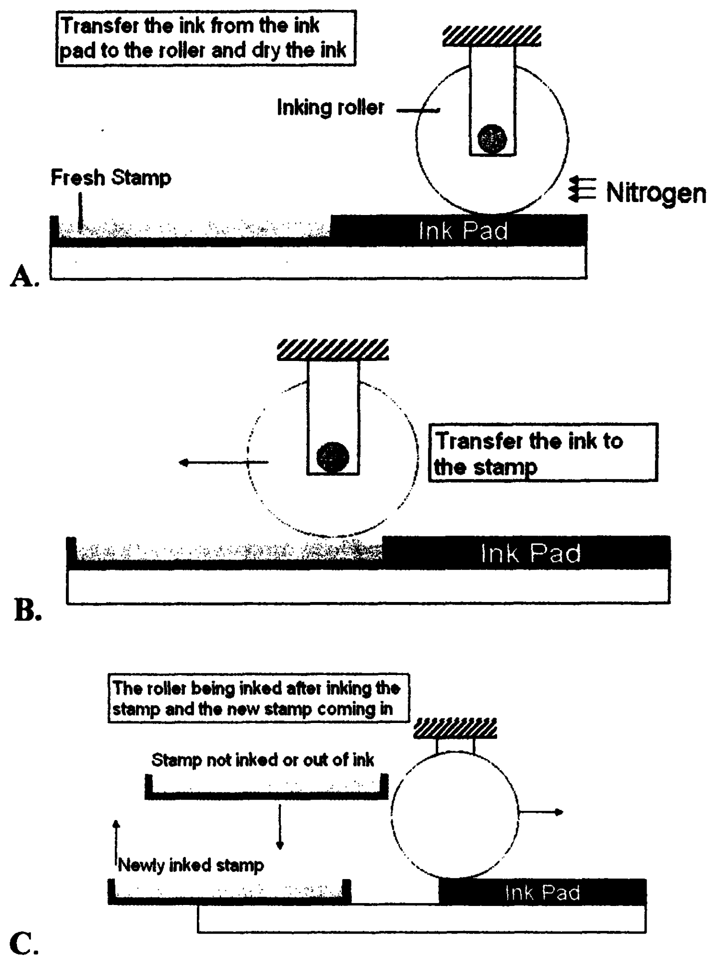



**Figure 4.2** The finalized inking design. (A) The inking roller runs over an ink pad to collect ink while a stream of Nitrogen gas dries the ink solution. (B) The inked roller transfers the dried ink onto a fresh PDMS stamp (C) The inked stamp is transferred onto the stamping station and is replaced by a new stamp [33].

The inking roller is supported by two arms and an arm connector that is driven by a lead screw actuator. The roller is rigidly fixed to a steel shaft that is connected to the arms.

The roller is supported on either end by timing belt pulleys which run on a urethane timing belt track. This ensures smooth and slip free motion. The ink pad is set up under the rails. The junction between the roller shaft and the arms is slotted to allow free vertical motion of the roller.

A nitrogen stream will be applied to the roller to dry the ink while the roller moves on the rails. The ink will then be almost dry before being transferred to the stamp. With this dry inking design, the actual drying and inking time to the stamp will be dramatically shortened and yet the quality will be assured.

A fresh stamp will be positioned on the other side of the inking stage. After ink has been collected from the ink pad and dried by the nitrogen stream, the roller will start transferring the ink onto the stamp. After the inking completed, the newly inked stamp will be transferred to the stamping station through two sequential transfer mechanisms- transfer of the stamp from the inking station to the stamping station and transfer of the stamp onto the stamping stage for stamping.

With this design, the two challenges to the previous roller design have been overcome. The weight of the roller will be supported by the rail together with the frame system. The vertical position can be adjusted along the slots on the two roller arms. More importantly, with the dry inking design, the inking and dry time for the PDMS stamp will be shortened, which will greatly improve the production rate.

At the same time, the advantages of the roller design remains. The linear propagation effect will reduce the air trapping during inking and automating the shift between the inking pad and stamps is straightforward.

## 4.3 The Stamping Process

In our design a flexible sheet of PEN is used as the substrate, which is applied onto a stationary PDMS stamp, and this played a dominant role in finalizing the design for the stamping process. However, several designs for stamping with hard substrates were also considered, which helped us in arriving at the finalized design. Regardless, the following are the key considerations for achieving good stamping outcome:

1. The ability to bring the stamp and the substrate in contact at an appropriate contact pressure.
2. Spreading of the substrate onto the stamp or vice versa in a way such that there is no air trapping.
3. The ability to peel off with force just enough to overcome the adhesion force. Excessive force might damage the printed features due to excess strain induced.

### 4.3.1 Possible Designs for Stamping

In this section, we will discuss the most important stamping designs which led us to the final design. We shall first describe a couple of designs for hard substrates and then present the final design applicable to flexible substrates.

## (a) Roll Stamping

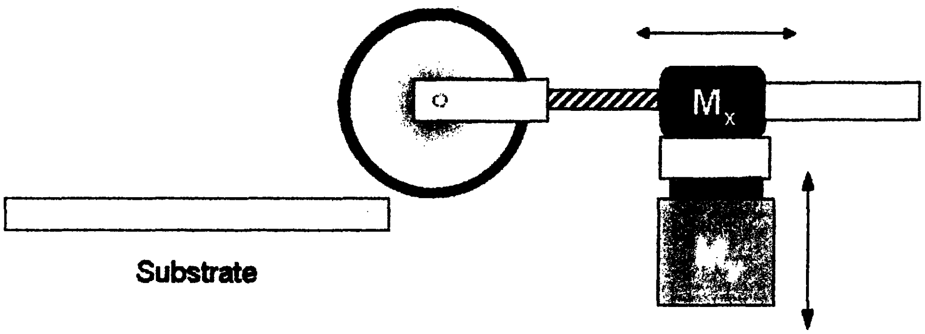



**Figure 4.3** Roll Stamping. The motor $M_x$ moves the roll forward and the motor $M_y$ can control the vertical position of the roll and hence the contact pressure either actively or in open loop.

In this design a hard roller wrapped with a PDMS stamp with the desired patterns is run over an ink pad. The ink solution is dried with a stream of nitrogen and transferred onto a fresh PDMS stamp. While the process is extremely simple and involves only a horizontal motion, it has the following drawbacks:

1. Wrapping of the stamp over a roller can cause deformation of the features on the stamp (figure 4.4). It can be easily shown that the strain in the stamp will be a function of the diameter of the roll. This will severely affect the resolution achievable with this process.
2. The vertical position of the roller will have to be very accurately controlled in real time to achieve the right contact pressure.
3. Any slippage due to mismatch between the angular and linear motions would be detrimental to output quality.
4. It would have been hard to control the contact time.

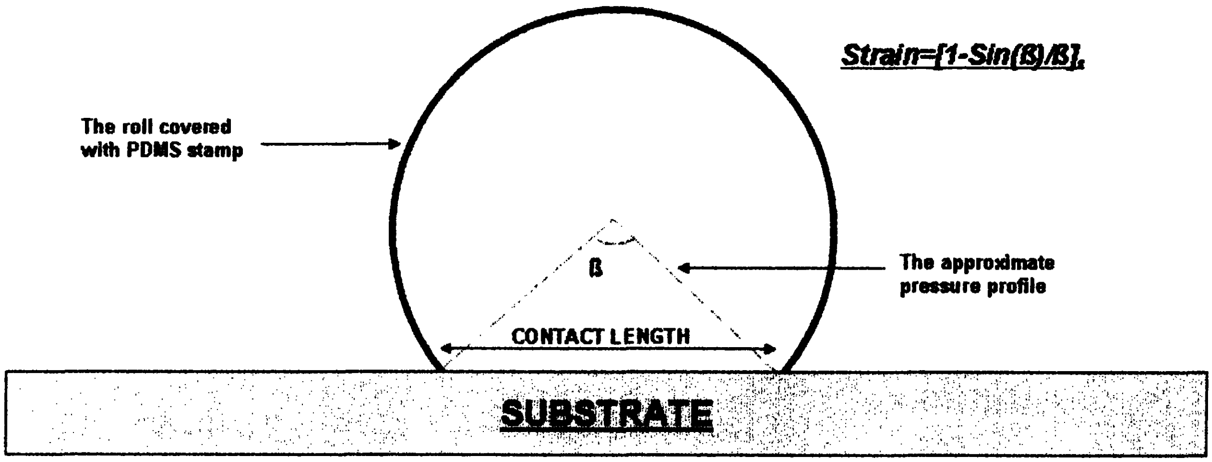



**Figure 4.4** Elastic strain induced in the stamp with Roll Stamping. The strain is [1-Sin(ß)/ß], So, as contact length becomes large, we have greater strain which would severely distort the stamp given the high feature-size/resolution ratio. However, if the radius of the roll is large, the angle could still be small.

## (b) Polygonal Stamping

An improved variation to roll stamping, polygonal stamping overcomes the stamp deformation due to wrapping of the stamp on a roller. Each face of the polygonal tool is covered by a PDMS stamp (but not rigidly attached). The tool can rotate about a hinge (the instantaneous edge of the polygonal tool in contact with the substrate. See Figure 4.3.1.4) and applies the stamp onto the substrate. Linear propagation is achieved without wrapping the stamp onto a cylindrical roller and thus stamp deformation is avoided. The design is explained step by step through Figure 4.5.

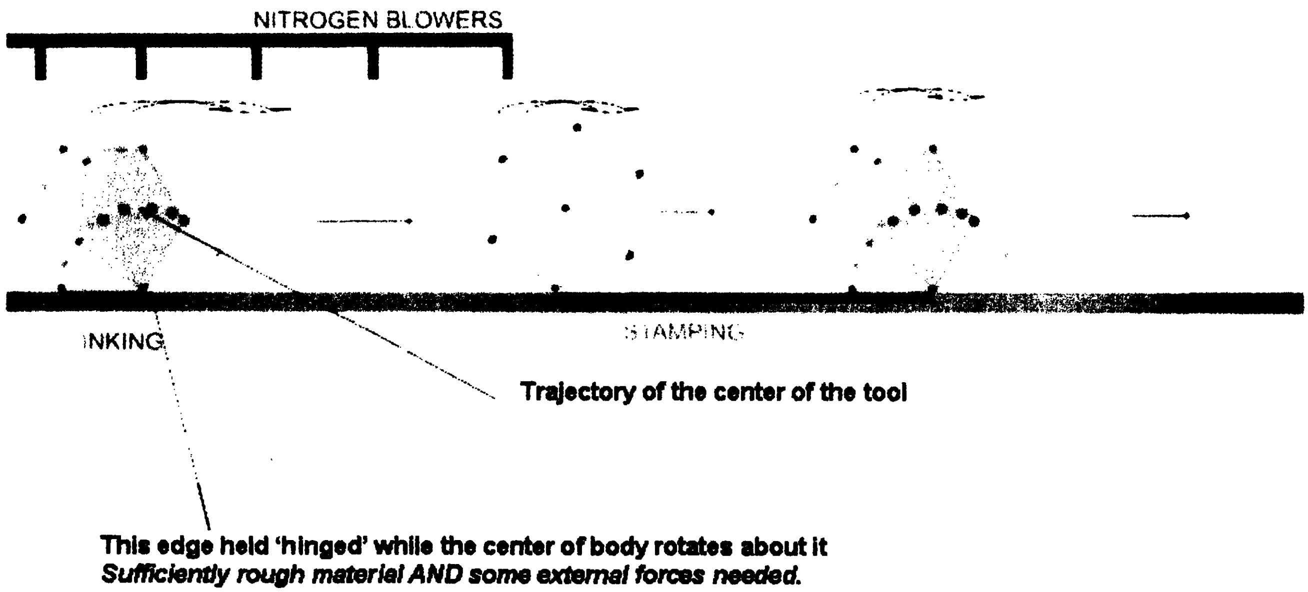



**Figure 4.5A** The basic concept of polygonal stamping.

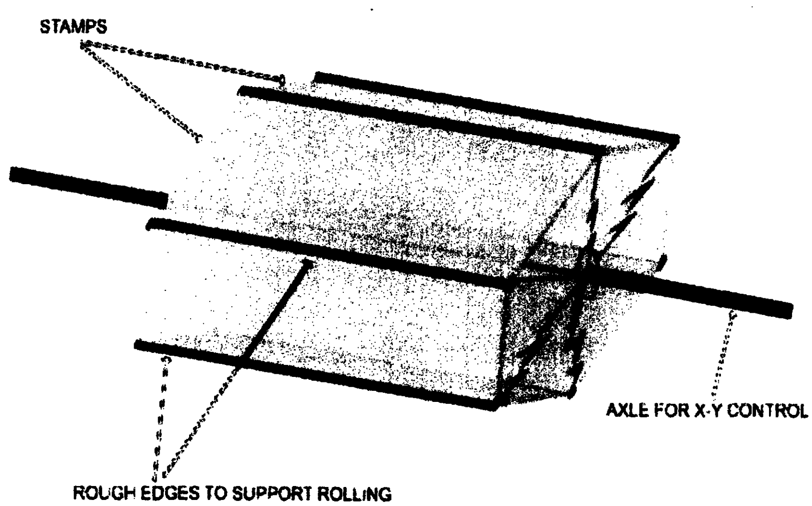



**Figure 4.5B** The stamping tool proposed for Polygonal Stamping.

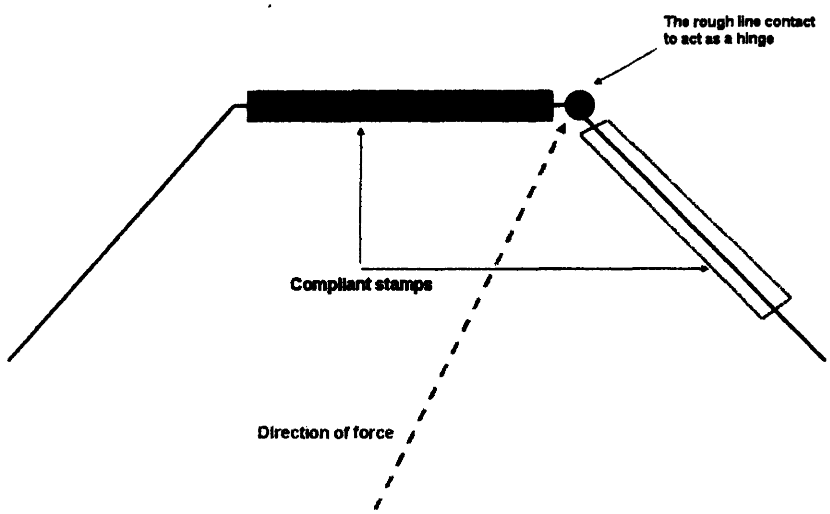
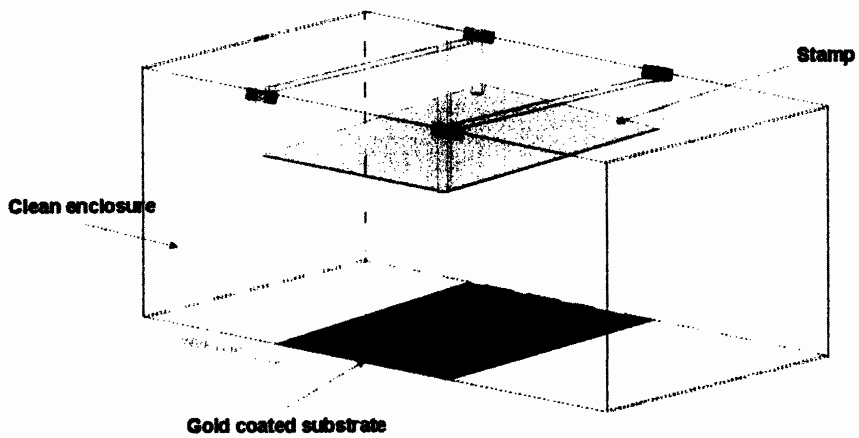



**Figure 4.5C** The hinge effect of the polygonal stamping tool.

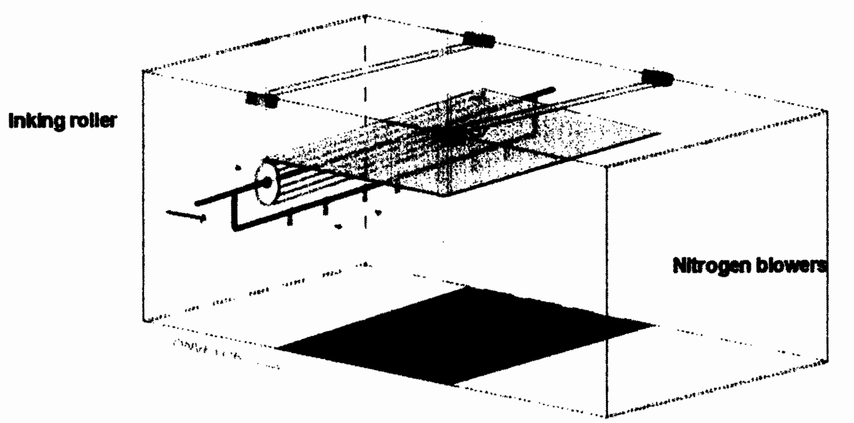
In this design, it is important that the PDMS stamps are not attached to the faces of the tool as then no linear propagation could be achieved when the stamp is applied to the substrate. If they are indeed made to hang freely between the two fixed edges, some deformation of the stamp (near the second edge) might take place while the stamp face is parallel to the ground.

### (c) Pseudo Roll Stamping

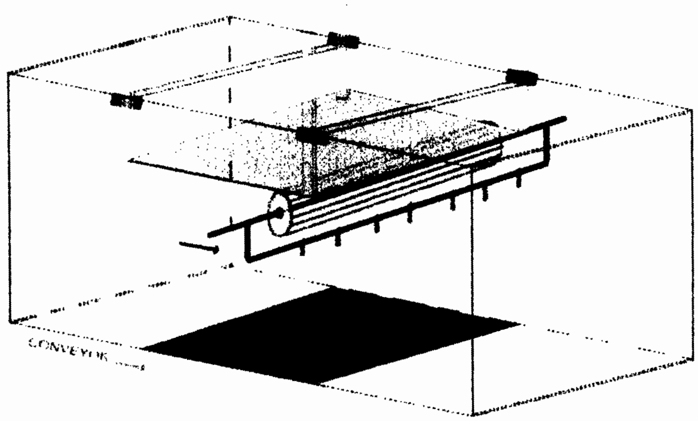
The design derives it name from its similarity in concept to roll stamping. The stamp is applied to the substrate through a mechanism that resembles roll stamping with a roll of infinite diameter (which gives almost no deformation). The process is explained through Figure 4.6.


Stamp
Clean enclosure
Gold coated substrate

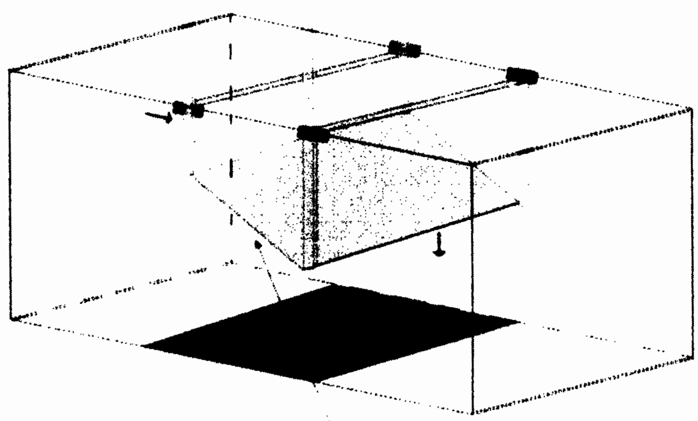
**A.**


Inking roller
Nitrogen blowers

**B.**

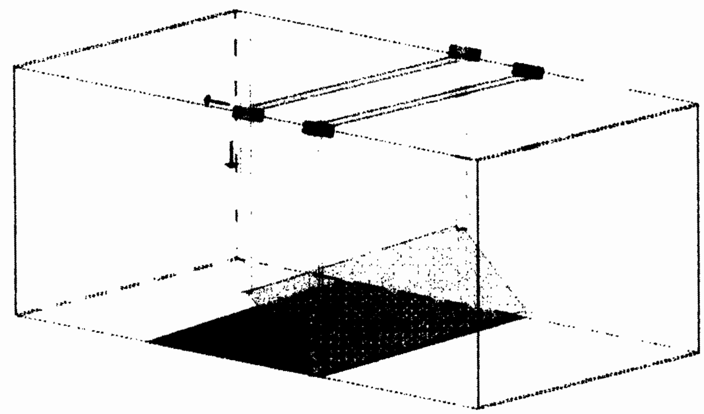



**C.**

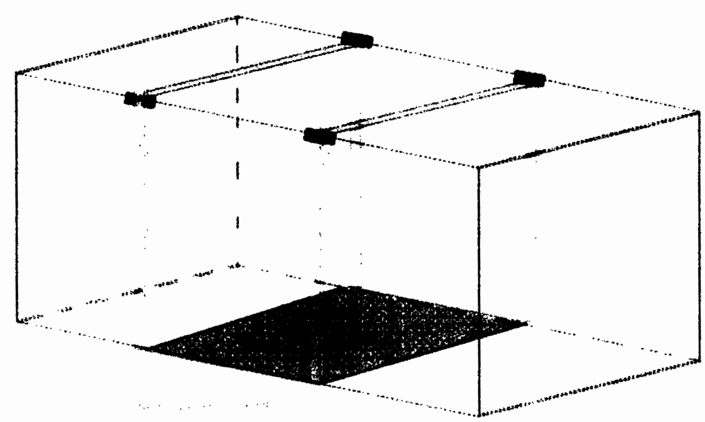


*The stamp will be kept at near zero tension*

**D.**



E.



F.

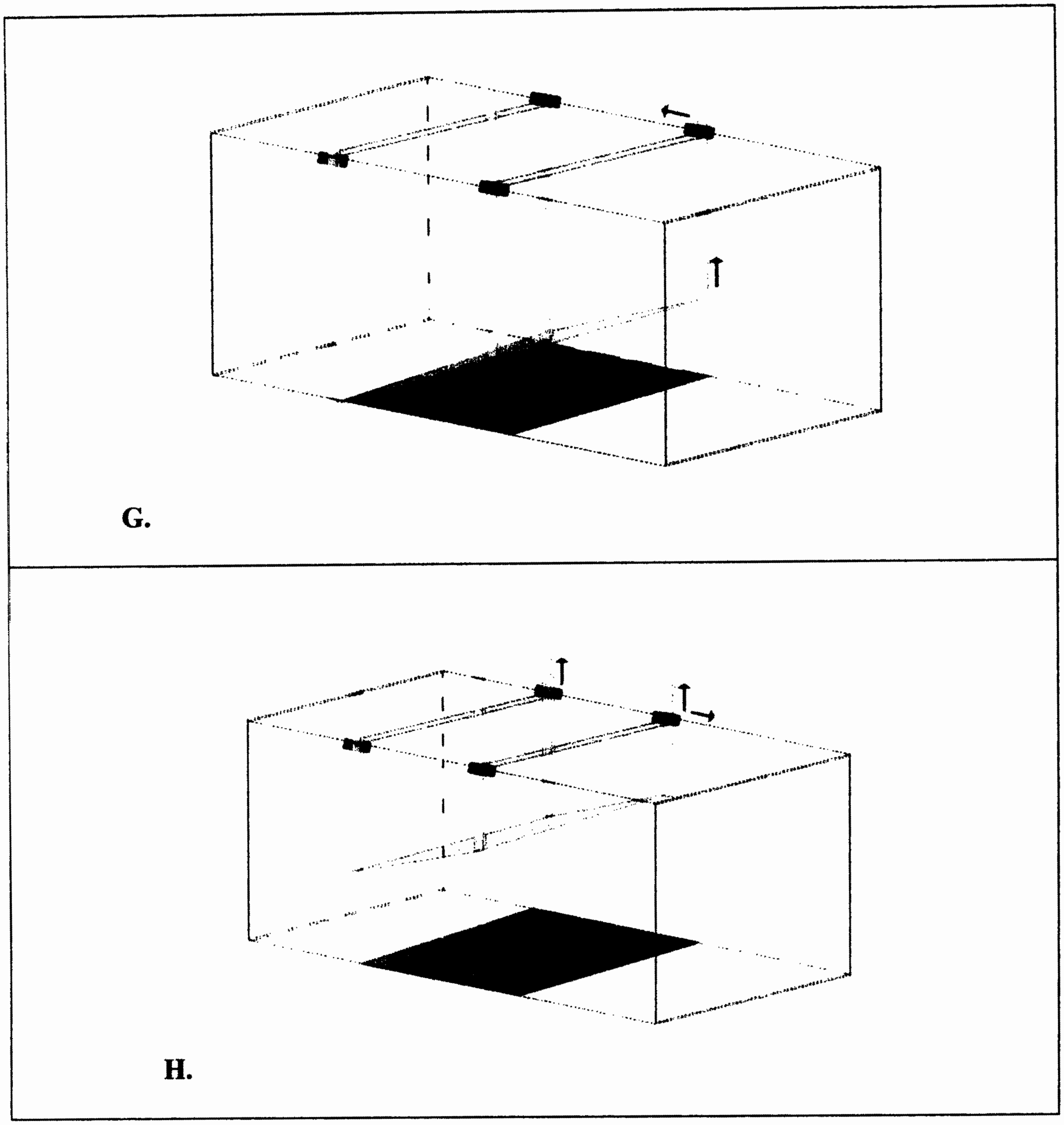


**Figure 4.6** Illustrations of the steps in Pseudo Roll Stamping.

The process discussed does not address any contact pressure adjustment means. In roll stamping this could be achieved by balancing the weight of the roller with counter-weights. In this design, this could be achieved by either using a thicker stamp or through a uniform stream of air.

## 4.3.2 Automation concept for manufacturing process

We developed the reel to reel printing process with two wipers that generate line contact propagation as well as peeling off. The schematic of the machine is shown in Figure 4.7. The pay-off reel supplies fresh gold-coated substrates and the take-up reel collects the printed substrates. The tension meter is placed in the center and two fixed guide rolls are located between two reels. The no. 1 fixed guide roll, between the take-up reel and tension meter, keeps the wrap angle constant regardless of the diameter increase at the pay-off reel. The no.2 fixed guide roll provides two functions: one is to maintain the wrap angle constant just as the no.1 fixed guide roll and the other guides the peeling direction of substrate.

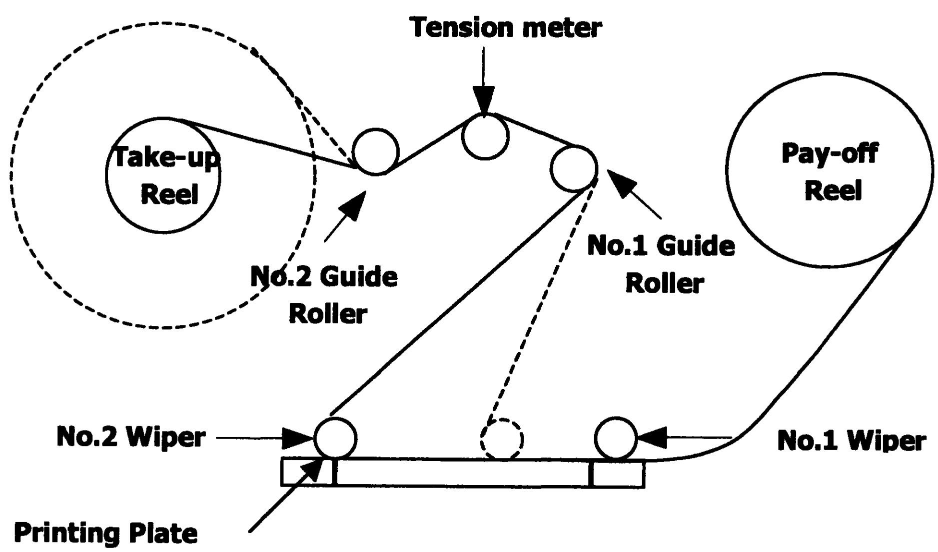



**Figure 4.7** Schematic of main components of μCP machine

The printing steps are shown in the following Figure 4.8

**Step 1: Creating initial contact (Figure 4.8A)**

At home position of two wipers, no.1 wiper is slightly higher than no.2 wiper the supply spool and printed substrate sheet is hanging on two wipers. Once the printing operation starts, both wipers move down until the no.2 wiper reaches the printing plate. In the mean time, the pay-off reel rotates clockwise in order to feed fresh substrates, maintaining low tension between the two wipers and the pay-off reel.

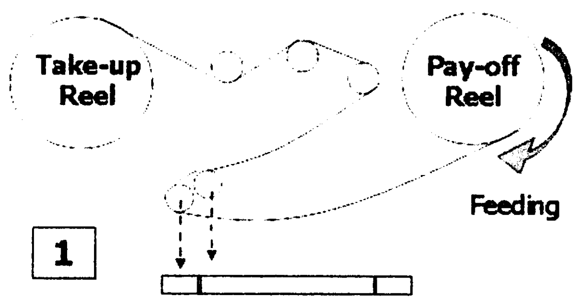



**Figure 4.8A** Schematic of creating initial contact

**Step 2: Propagating contact region (Figure 4.8B)**

The no.1 wiper travels forward in order to create linear propagation of the contact region between the substrate and the stamp while one end of the substrate is fixed by no.2 wiper. The pay-off reel is kept rotating clockwise to prevent high tension between the no.1 wiper and pay-off reel during propagation

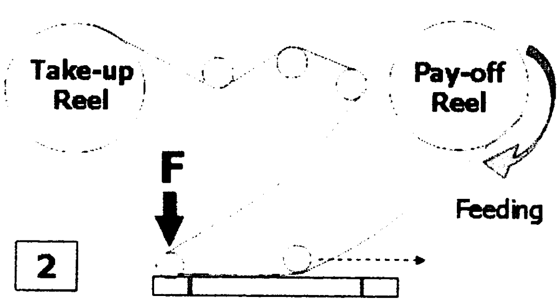



**Figure 4.8B** Schematic of propagating contact region

**Step 3: Printing SAMs (Figure 4.8C)**

Once the no.1 wiper reaches the other end of the substrate, it moves slightly down to create the force required to fix the substrate. Meanwhile, the thiols will diffuse through the contact region of the substrate and the stamp and SAMs are generated.

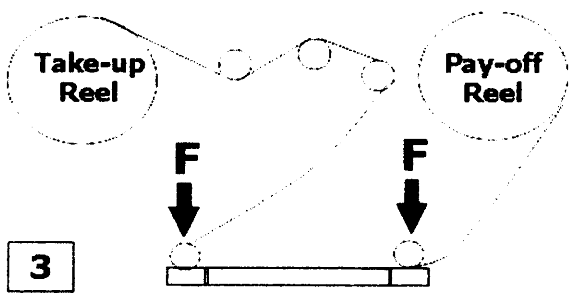



**Figure 4.8C** Schematic of printing SAMs

**Step 4: Preparing peeling off (Figure 4.8D)**

The take-up reel starts to rotate clockwise to tighten the substrate between the no.2 wiper and take-up reel. The tension meter measures the tension along the substrate to make sure the tension will not cause any elongation or deformation of the sheet.

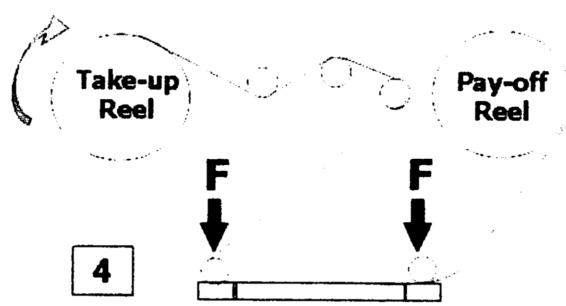



**Figure 4.8D** Schematic of preparing peeling off

**Step 5: Peeling printed substrate off (Figure 4.8E)**

The peeling off process takes place by moving the no.2 wiper forward as the drive rotates continuously to maintain appropriate tension. No. 2 wiper needs to travel until it complete peeling off. The no. 1 wiper holds the end of the substrate by keeping a constant normal force to prevent possible slip caused by tension for peeling.

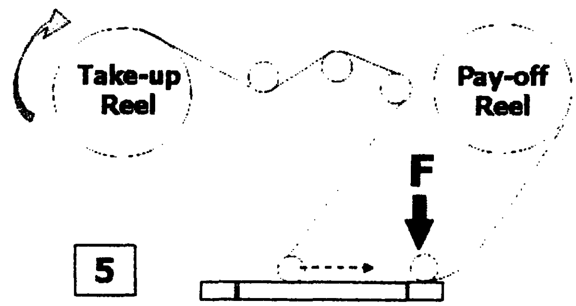



**Figure 4.8E** Schematic of peeling printed substrate off

**Step 6: Taking entire substrate off (Figure 4.8F)**

After completing the peeling off process, the two wipers should move up to take the entire substrate off. The take-up motor should remains rotating clockwise in this step in order to create tension for taking the substrate off.

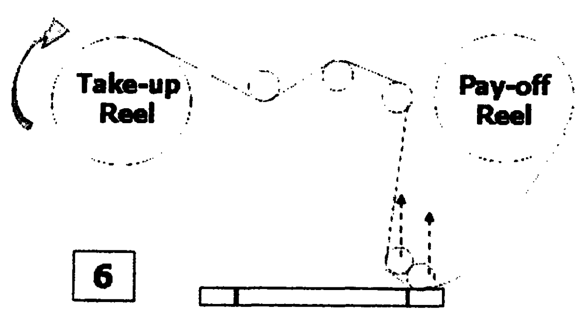



**Figure 4.8F** Schematic of preparing peeling off

**Step 7: Supplying fresh substrate (Figure 4.8G)**

Fresh gold substrate is fed by two wiper's travel to home position. Two motors for take-up reel and pay-off reel should rotate appropriately for exact indexing, which depends on either the roll diameter of take-up reel or that of pay-off reel.

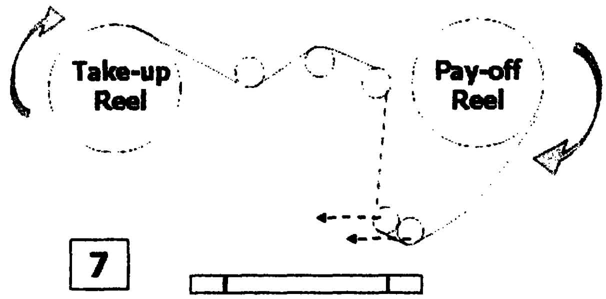



**Figure 4.8G** Supplying fresh substrates

**Step 8: Home position (Figure 4.8H)**

The two wipers return to the home position and are ready for next printing cycle.

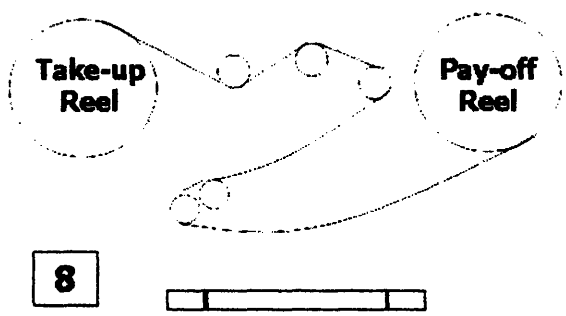



**Figure 4.8H** Home position

## 4.4. Manufacturing System for High Volume Production

For microcontact printing to succeed commercially, it is very important that the process be capable of producing products at production rates which cost less than the existing pattern transfer techniques. The most important goal while designing a manufacturing system for micro contact printing was to achieve the highest possible quality at a rate which was limited only by the chemistry of the process.

An integrated design of the inking and stamping processes above could be considered as the miniature model of the high-volume production machine without the etching step. We will show later that inking station could be integrated with the stamping station so that the production throughput from the inking-stamping steps depends only on the ink transfer time in the stamping station. After being stamped, the substrate would be etched in an etch-bath as shown in Figure 4.9 Because etching time is considerably larger than the inking or stamping times, the length of the substrate inside the etch-tub could be several miles long to allow continuously fast production. The process resembles hot rolling in the way the individual processing times are decoupled.

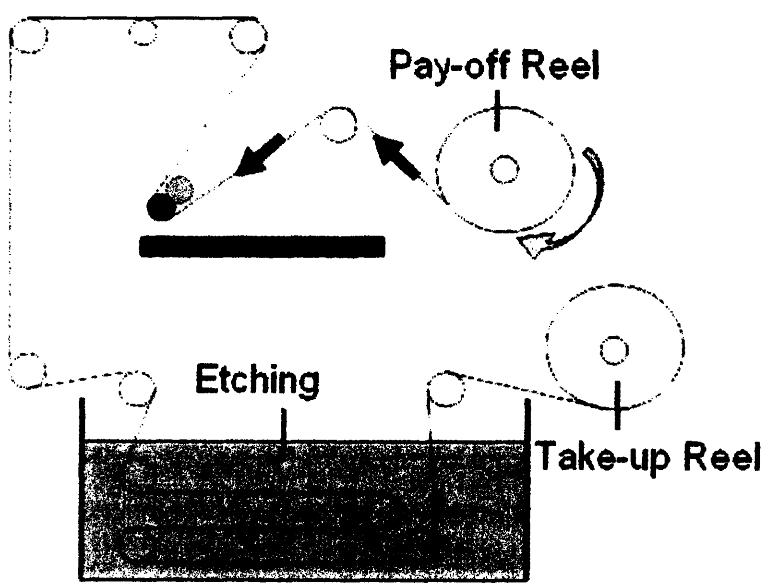



**Figure 4.9** A schematic illustration of a process centric manufacturing system showing the integration between the inking-stamping steps and etching.

Another version of the manufacturing system showing higher level detail is shown in Figure 4.10. Here, ink is applied to the stamp by applying an ink pad onto the stamp and leaving it for an appropriate period of time. A stamp with an ink pad residing on its top can still move on the conveyor. This decouples the stamping time and inking time from the production rate. The decoupling of the etching time from the production rate has already been discussed.

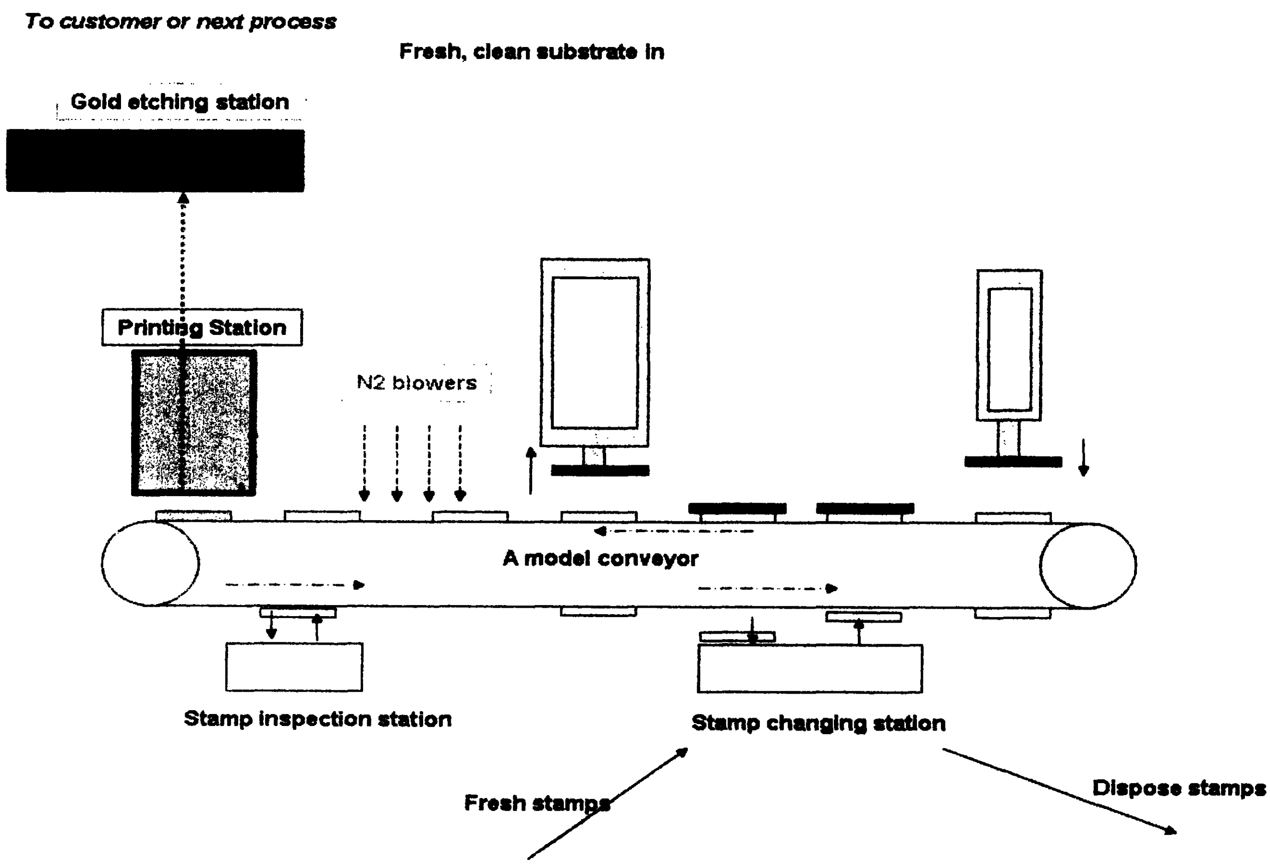



**Figure 4.10** Another version of the manufacturing system discussed before. Note that here, the inking step is shown is different than the one we finalized. Note that the number of stamps on the belt between the 4 stations can be adjusted based on the time for inking, printing, removing etc.

## 4.5 Conclusion

In this chapter, we described development of our design to achieve inking and stamping. We also discussed how the three steps for micro contact printing – inking, stamping and etching could be integrated for high volume production such that the production rate depends only on the chemistry of stamping. We hope that scientific advancements with a better process optimization or discovery of new materials could reduce this time further.

In the next chapter, we shall discuss the mechanical design of the printing station prototype in detail.

# 5. Design of microcontact printing machine

## 5.1. Design overview

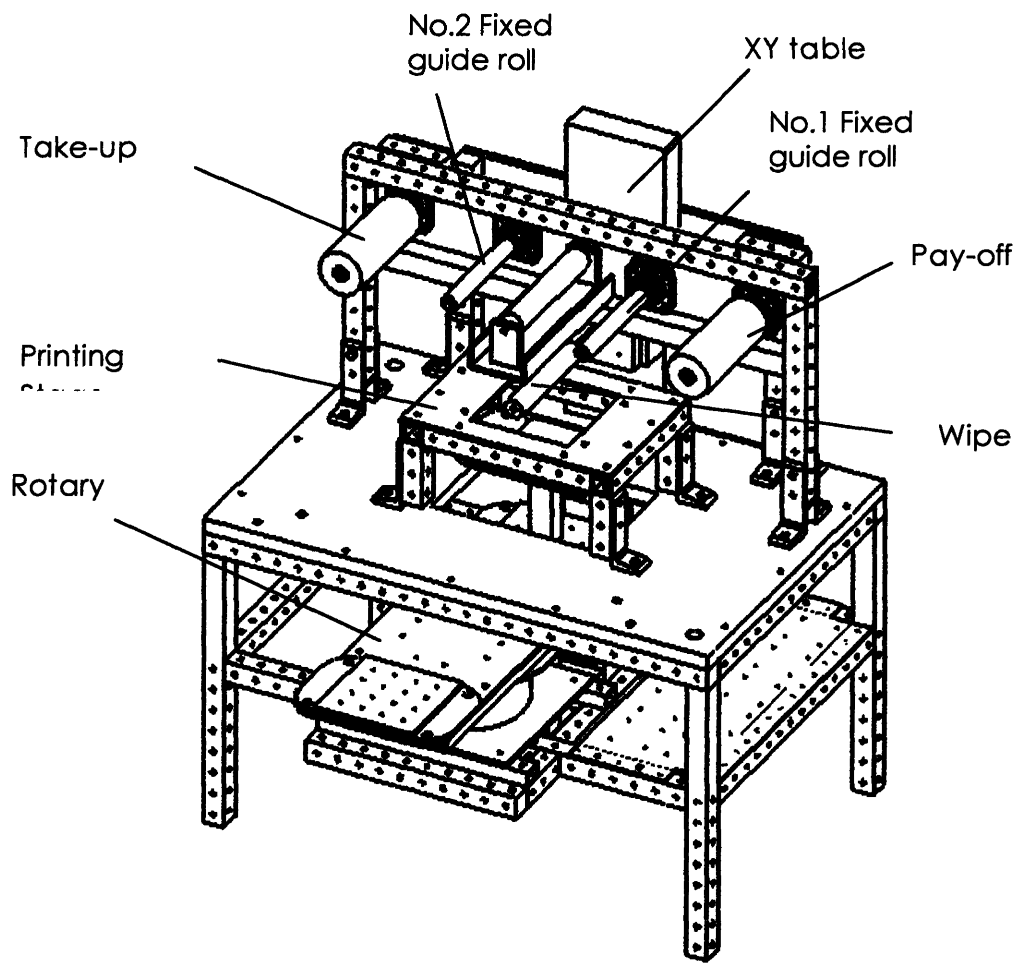



**Figure 5.1** CAD model of the printing station of microcontact machine.

Our design for microcontact printing is the combination of reel to reel process, suitable for mass production with print-side-up stamp mounting. This is appropriate for high quality, high volume production. As shown in Figure 5.1, the microcontact printing machine consists of two XY positioning tables, a wall assembly, and printing stage.

XY positioning tables are fixed at the both edge of the floor to create movements for stamping, and the wall assembly between XY tables provides reel to reel function. The printing station is mounted at the center of floor, consisting of top printing plate and frames. There is a 7 X 7" square hole in the middle of top printing plate so that a maximum size of X 7" PDMS stamps can be lifted through the square hole. The floor has another hole in the middle for allowing stamp retainer, on which PDMS stamp is mounted, to travel through the hole by Z positioning leadscrew under the floor.

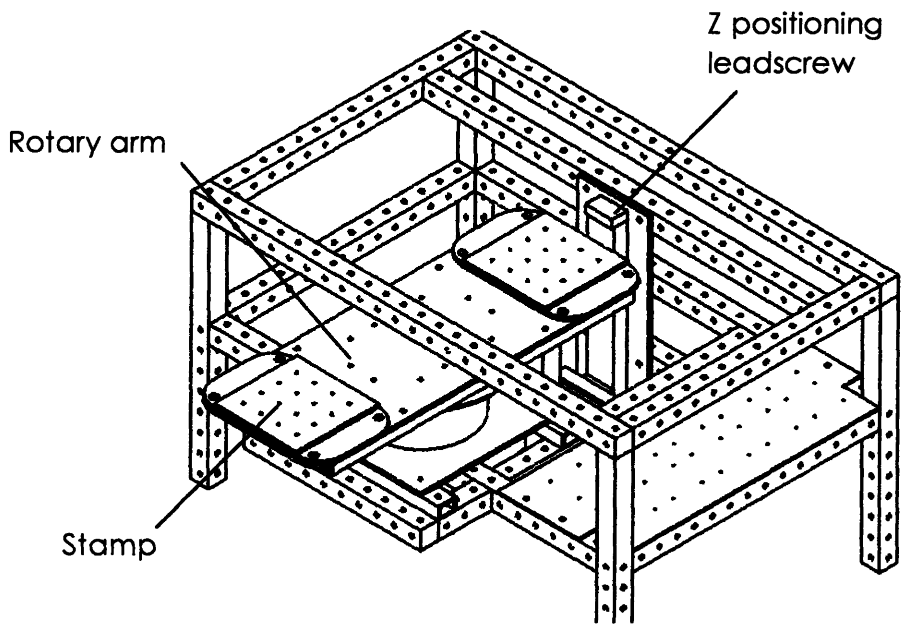



**Figure 5.2** CAD model of rotary table and Z positioning leadscrew

The rotary table has a function of transporting an inked stamp retainer from inking station to printing station as well as returning the retainer back to inking station for re-inking. Two stamp retainers are placed on the both end of rotary table arm. After finishing inking at inking station, the rotary arm rotates 180 degrees such that inked stamp retainer can be placed in the middle of frame and be ready for lifting up to the printing station by Z positioning leadscrew.

## 5.2. Design of propagation mechanism

### 5.2.1. Design of wiper

The key functions of two wipers are to generate contact initiation, propagation of contact region, and peeling flexible substrates off after completing printing as shown in Figure 5.3. Each wiper is fixed on the mounting head of XY positioning table and, therefore, each wiper can create any 2 XY motion by a XY table. Figure 5.3 shows CAD model of the wiper assembly, consisting of plastic hollow rod, threaded shaft, and soft foam.

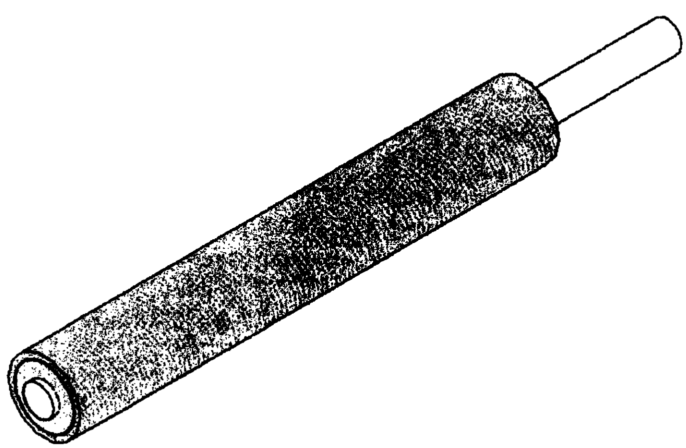
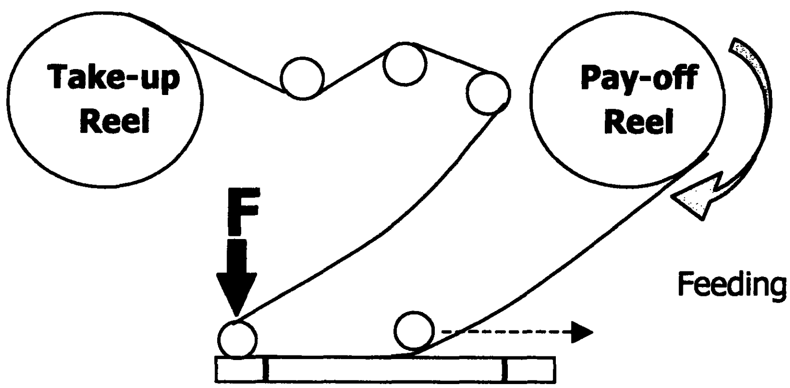


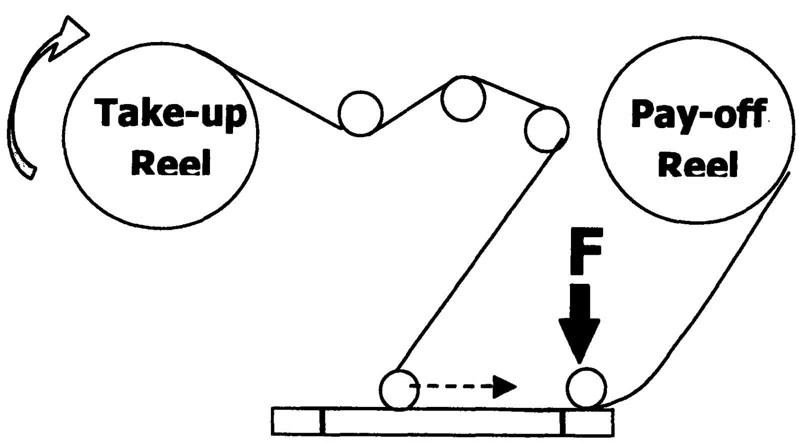
**Figure 5.3** CAD view of wiper assembly

Designing the wiper assembly, we considered three main mechanical factors: friction between wiper surface and flexible substrate, stiffness of wiper surface material, and bending of threaded shaft caused by cantilever effects.

The surface of wiper should provide enough friction so that one of wipers can fix the substrate during propagation or peeling off step. (**Figure 5.4**)




(a) Propagation of contact region step




(b) Peeling off step

**Figure 5.4** Schematics of propagation and peeling steps

However, if the friction ratio of wiper surface is too high, the tension of substrates between take up reels and No.2 wiper becomes high during peeling off step, which can cause vibration of machine or deformation of printed pattern. It is very difficult to find the material whose friction ratio satisfies both conflicting requirements: sticky enough to fix one end of the substrate during peeling off or propagation step and slippery enough to send the substrate to No.1 fixed roll during peeling off. We chose the assembly of hollow plastic rod, shaft, and foam in order to satisfy both conflict friction requirements. As shown in Figure 5.3, the hollow plastic rod is inserted into steel shaft, and friction ratio between two materials is small such that hollow rod easily rotates with small torque, generated by the tension of substrates, regardless of the friction ratio of wiper surface.

The minimum curvature for preventing any deformation or defects in substrate has not been studied so far, so we determine the diameter of hollow rod and shaft not based on the properties of gold-coated substrate but based on of the wiper shaft bending, which will be discussed later in this chapter.

Stiffness of wiper surface is another critical factor that taken into consideration because printing pressure is generated by not only self-weight of substrate material but also compression of wiper surface. Specifically, the printing pressure generated by wiper surface compression is determined by the stiffness of wiper surface material as well as the distance between the center of wiper and the substrate. The closer the distance between substrate and wiper becomes, the higher pressure generates by the wiper surface. This relationship can be represented by a simple spring model (Equation 5.1)

$$F = k(r - d) \qquad (5.1)$$

Where *k* is the stiffness of wiper, *r* is the outer radius of wiper surface, and *d* is the distance between the center of wiper and the top surface of printing station. i.e., $r - d$ represents compressed distance of the foam. (Figure 5.5)

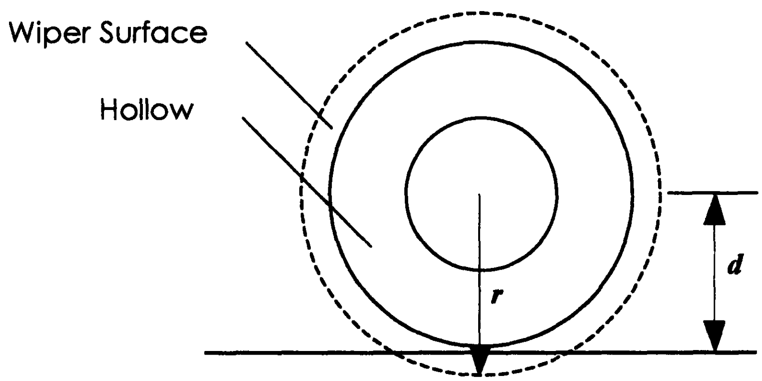



**Figure 5.5** Schematic of wiper shaft (Front View)

It is very difficult to model the required normal force theoretically because two driving forces – mechanical force (normal force), and chemical force (adhesion force) affect microcontact printing quality. The required external normal pressure is generally small because the adhesion force is known as the main driving force that forms conformal contact [33] In addition, if the stiffness of surface material is higher than that of stamp, the relief feature of PDMS can easily be deformed. Therefore, the surface material should be compliant enough to create minimal force.

The surface of the wiper is wrapped with soft foam whose stiffness, *k*, is 0.99N/mm, measured by pressing the form on the scale using vertical positioning device. Stiffness can be changed by wrapping more layers of forms and the overall stiffness, K, is calculated by equation (5.2)

$$\frac{1}{K} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \qquad (5.2)$$

Ideally, two wipers should be parallel to the surface of stamp such that uniformly distributed, but only one end of the wipers are mounted on the rigid body like a cantilever and, therefore, bending occurs across the wiper. Maximum displacement of beam under uniform load can be calculated from Equation (5.3)

$$W_{max} = \frac{pL^4}{8EI} \qquad (5.3)$$

where $I = \frac{\pi r^4}{4}$ for a circular cross section.

Given that the radius of inner shaft, *r*, is 0.5 in, the second moment inertia, *I*, is 0.05 $in^4$, distributed load, *p*, is 0.584 lb/in (assuming that the compressed distance of the foam is 0.1 in), Young's modulus of carbon steel is approximately $29 \times 10^6$ psi (200 GPa), the maximum displacement of shaft is $-1.93 \times 10^{-7}$ in and the maximum and given the fact that k = 5.64 lb/in (0.99 N/mm)

## 5.2.2 XY positioning table

An XY positioning table (Figure 5.6) was chosen for the wiping motion generator because it provides high flexibility of motion; Any 2-dimensional motion can be generated by controlling two motors. Two XY positioning tables are installed vertically (Figure 5.7), and two wipers are fixed on the mounting head of XY positioning table such that they can create 2-dimensional motion for the propagation of the substrate and peeling off.

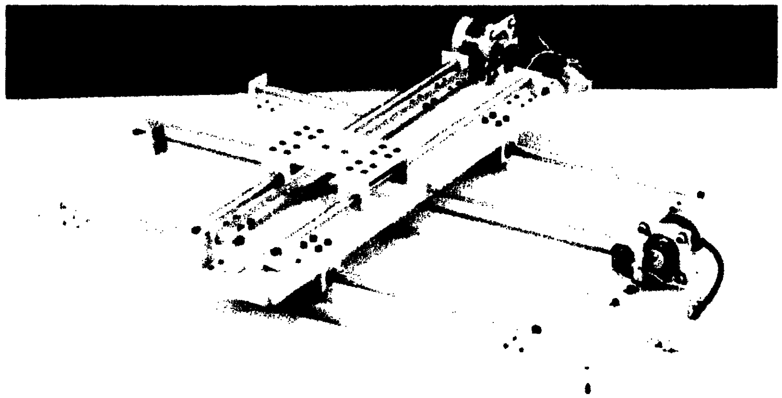


**Figure 5.6** Picture of an XY positioning table for the wiper.

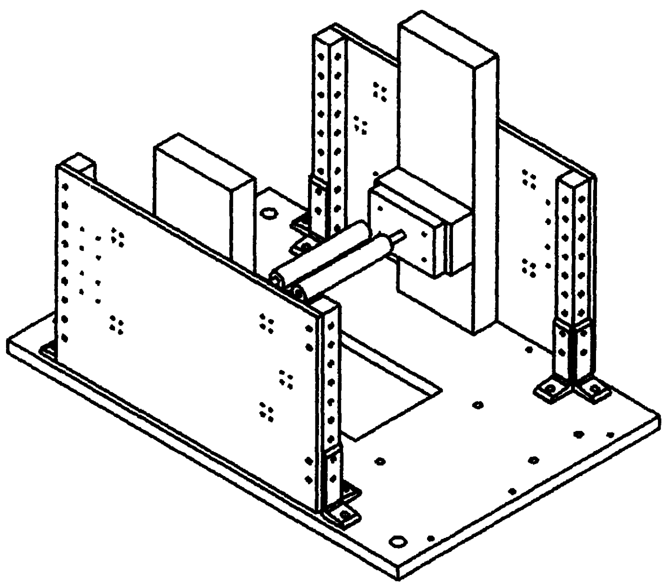


**Figure 5.7** CAD model of two XY tables (wall assembly is hidden)

Table 5.1 shows the general specification of XY positioning table. XY movements are operated by stepper motor through timing belt mechanism. Belt systems have been used for transferring mechanical power. The advantages of belt system are low noise, low weight, and low cost. It is important to keep the appropriate belt tension because high tension will prevent the pulley from rotating smoothly and low tension will decrease positioning accuracy and repeatability. There are slots in the idler pulley bracket for the purpose of tension adjustment.

**Table 5.1** Specification of XY positioning table.

| Maximum Payload | 10 pounds | Comments |
|---|---|---|
| Accuracy | +/-.010" per foot | |
| Resolution | .005" per .9 degree step | Decreased to be 0.0005" by micro-stepping |
| Repeatability | .005" | |
| Maximum Speed | 6" per second | |

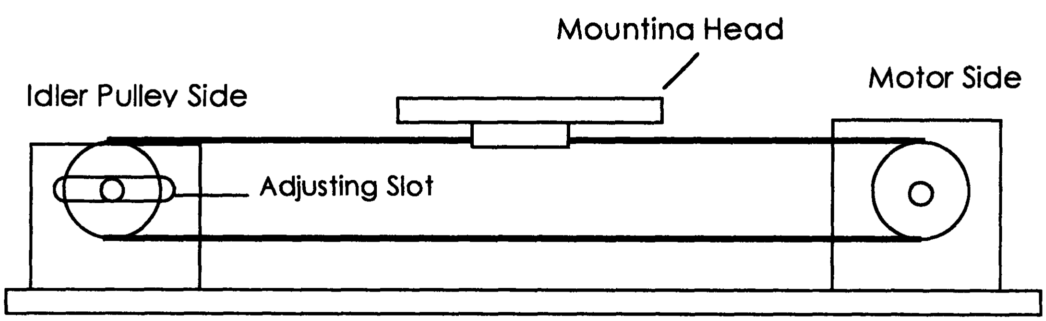



**Figure 5.8** Schematic view of XY positioning table

Two parallel guide shafts guide the direction of X or Y motion of the mounting plate. The alignment of two shafts is critical for smooth movement of mounting head, but, in reality, it is very difficult to make two guide shafts perfectly parallel with this XY positioning table. It is required to test alignment of a shaft by sliding the mounting head back and forth repeatedly while tightening the screws at both ends of the shaft. Helical spring washers are inserted between tightening screws and frames in order to prevent loosening under shock or vibration.

## 5.2.3 Stepper Motors

Stepper motors were used as actuators for XY positioning tables and reels because they are simple and suitable for most open-loop motion control applications. A stepper motor is an AC motor whose shaft is indexed through part of a revolution or step angle for each DC pulse sent to it. Trains of pulses provide input current to the motor in increments that can "step" the motor through 360 degrees, and the actual angular rotation of the shaft is directly related to the number of pulses introduced.

**Table 5.2** MS23 Stepper motor specifications. [40]

| Parameter | Value |
|---|---|
| NEMA size | 23 |
| Full step angle | 1.8 degrees |
| Full step accuracy | +-5% |
| Full Step Current | 3.00 Amp |
| Micro Step Current | 4.20 Amp |
| CD Resistance | 0.85 ohms |
| Inductance | 1.73 mH |
| Power Total | 15.3 Watts |
| Holding Torque (static torque) | 140 oz-in |
| Running Torque | 110 oz-in |

If the diameter of the pulley is D inches, then one full revolution of the "X Motor" will result in a horizontal motion of $\pi$D inches. Most stepper motors rotate 1.8 degree per full step, that is 200 steps per revolution. If M is the microstepping index used, then one revolution of the motor is achieved with 200M steps or counts. Thus, it can be easily shown that to move by 'x' inches along the x direction, $\frac{200Mx}{\pi D}$ steps have to be given to the "X motor". Thus, to move from (x1,y1) to (x2,y2) is achieved by giving the "X Motor

$\frac{200M(x_2 - x_1)}{\pi D}$ steps and electronically gearing the "Y Motor" as the slave to the "X Motor", with a constant gear ratio of $\frac{(y_2 - y_1)}{(x_2 - x_1)}$ [39]. The step rate to achieve the desired travel velocity can be easily calculated using the above relation.

When using stepper motors to drive the table at high speeds with large payloads, lost steps can occur. The torque of a stepper motor will decrease as the speed is increased and cause lost steps. We mounted the XY positioning table in a vertical direction, which requires motors to move against gravity, so accuracy and repeatability of position should be tested before increasing the operation speed. Counter-balance of the payload with weights or springs is helpful to reduce motor torque requirements.

### 5.2.4 Alternative Design

A ballscrew-driven system is recommended for a high precision control. Because the normal force to ensure the conformal contact between substrates and stamp is controlled by position of wipers, highly precise position control can be required if the size and pattern of relief features on stamp is nanometer scale. The main advantage of a ballscrew-driven system is that it offers high position accuracy, repeatability by reducing backlash of leadscrew close to zero. A ballscrew system is commercially available as a module, and create multi-axis by combining two linear guide systems. (Figure 5.9) Typically, an accuracy of 5 to 10 μm per 300 mm can be accomplished by ballscrew-driven system with position feedback sensor [35].

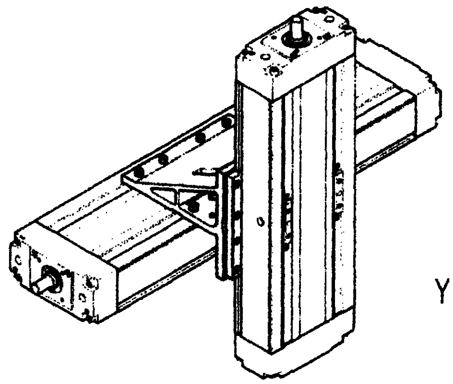



**Figure 5.9** Example of 2-axis system using ballscrew-driven module [36]

## 5.3 Design of Reel Mechanism

### 5.3.1 Design of reel assembly

The main functions of the reel assembly are to supply flexible substrates to printing station and to collect the flexible substrates after printing under specific tension. The reel assembly is composed of a pay-off reel, take-up reel, two guide rolls, and a tension roll between two guide rolls as illustrated in Figure 5.10.

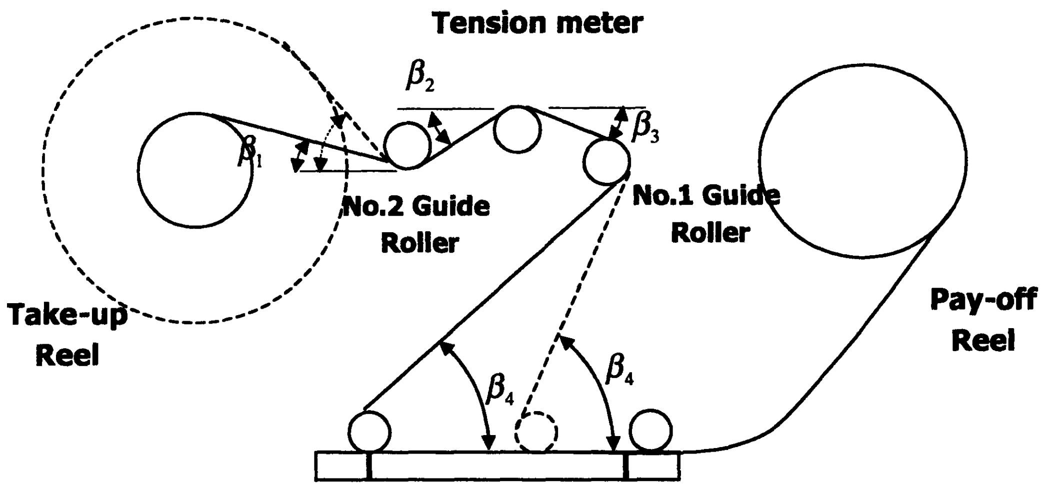



**Figure 5.10** Schematics of wall assembly

The take-up reel collects the printed substrates. The pay-off reel supplies fresh gold-coated flexible substrates by rotating during contact initiation and propagation step and take-up reel winds the patterned substrates after finishing printing. No. 1 guide roll not only makes peeling off easy by guiding the travel direction of substrates but also maintains the angle, $\beta_3$ ,constant for tension meter regardless of angle between printing station and substrates, $\beta_4$. No. 2 guide roll also makes the other wrap angle, $\beta_2$, independent on the diameter change of collected substrates such that tension meter can always sense the tension under the same wrap angle.

Theoretically, web tension between two rigid materials is different at each location; Local tension is increased by the friction when the substrates are passing contact area of rollers as shown in Figure 5.11.

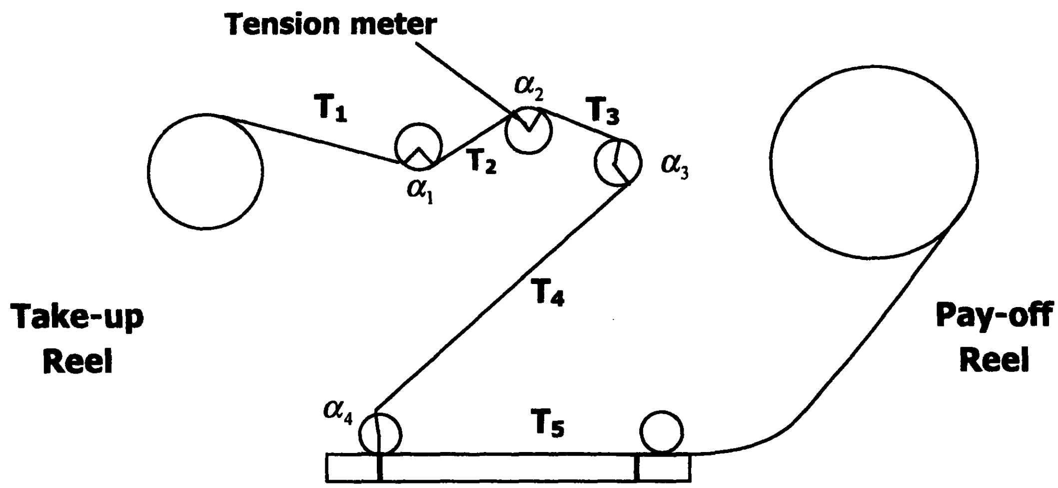



**Figure 5.11** Schematics of local tension map.

Basically, two tensile forces of a flexible bend, wrapping around a cylindrical drum, is [37]

$$T_{take-up} = e^{\mu\alpha} T_{pay-off} \qquad (5.4)$$

Where μ = frication ratio and α = wrap angle

Therefore, the tensile force relationships between each location are as follows

$$T_1 = e^{\mu_1\alpha_1} T_2 \qquad (5.5)$$

$$T_2 = e^{\mu_2\alpha_2} T_3 \qquad (5.6)$$

$$T_3 = e^{\mu_3\alpha_3} T_4 \qquad (5.7)$$

$$T_4 = e^{\mu_4\alpha_4} T_5 \qquad (5.8)$$

Substituting Equation (5.8) into Equation (5.7), tensile force $T_3$ becomes

$$T_3 = e^{(\mu_3\alpha_3+\mu_4\alpha_4)}T_5 \qquad (5.9)$$

In the same way, substituting Equation (5.9) into Equation (5.6)

$$T_2 = e^{(\mu_2\alpha_2+\mu_3\alpha_3+\mu_4\alpha_4)}T_5 \qquad (5.10)$$

The tensile force required to take up the substrate is

$$T_1 = e^{(\mu_1\alpha_1+\mu_2\alpha_2+\mu_3\alpha_3+\mu_4\alpha_4)}T_5 \qquad (5.11)$$

Equation (5.5) can be simplified by the assumption that $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu$. The tensile force for collecting the substrate can expressed as follows:

$$T_1 = e^{\mu(\alpha_1+\alpha_2+\alpha_3+\alpha_4)}T_5 \qquad (5.12)$$

However, in stead of using Equation (5.11) or (5.12), we measured the local tension $T_2$ directly using tension meter, which measures normal force from two load cells at both ends of the roller shaft. If we assume that the coefficient of friction at the tension meter is 0, then $T_2$ equals to $T_3$. The relationship between tension of substrates and the normal force can be represented by Equation (5.13)

$$F = T_2 \sin\alpha_2 + T_3 \sin\alpha_3 \qquad (5.13)$$

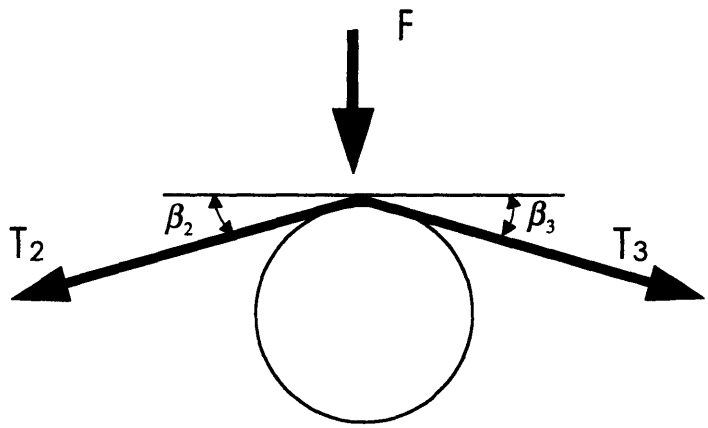



**Figure 5.12** Relationship between of normal force and web tension

The value of $\beta_2$ and $\beta_3$ are 15.866° and maximum weight measured from the tension meter is approximately 1.76 lbs (7.8N), and calculated substrate tension $T_2$ is 1.1 N. The wrap angle of no.2 guide roller, $\alpha_1$, is 35.11°.

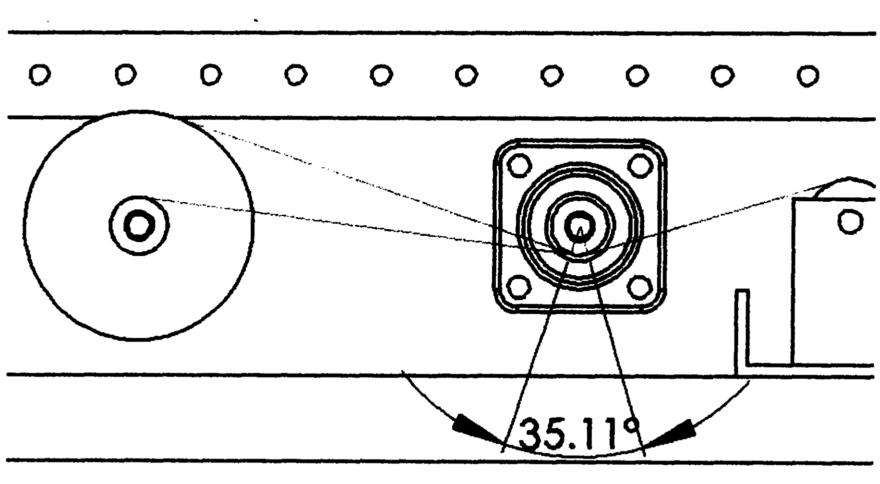



**Figure 5.13** Detailed view of no.2 guide roll and take-up reel [40]

Assuming that friction ratio is 0.03, general value of rolling bearing, we can estimate the tension between the take up reel and the no.2 guide roller, $T_1$. Substituting

$\mu_1 = 0.03$, $\alpha_1 = 35.11°$, and $T_2 = 0.247$ lb (1.1 N) into Equation (5.2), $T_1$ becomes 0.721 lb (3.2 N).

Therefore, required torque for the take-up motor, $T_{motor}$, can be derived from equation (5.14)

$$T_{motor} \geq T_1 \times R_{\max} \tag{5.14}$$

where $T_1$ is tension between motor and no.2 guide roll and $R_{max}$ is maximum radius of a substrate coil.

Given that $T_1 =$ 11.52 oz (3.2N), $R_{max} = 2$ in, the required torque for the take-up reel is 23.04 oz-in (0.11 N-m). MS23 series stepper motors from the USdigital are used for the take-up reel and the torque of motor is always greater than 23.04 oz-in as long as the speed of the motor is less than approximately 2,000 RPM as shown in Figure 5.14.

The maximum required speed of the motor is always less than 500 RPM, so actual torque of the motor is always greater than 80 oz-in, sufficient for collecting the flexible substrate. The detailed analysis of motor speed is explained in Chapter 5 (Automation Hardware and Software) of Karan's Thesis [39].

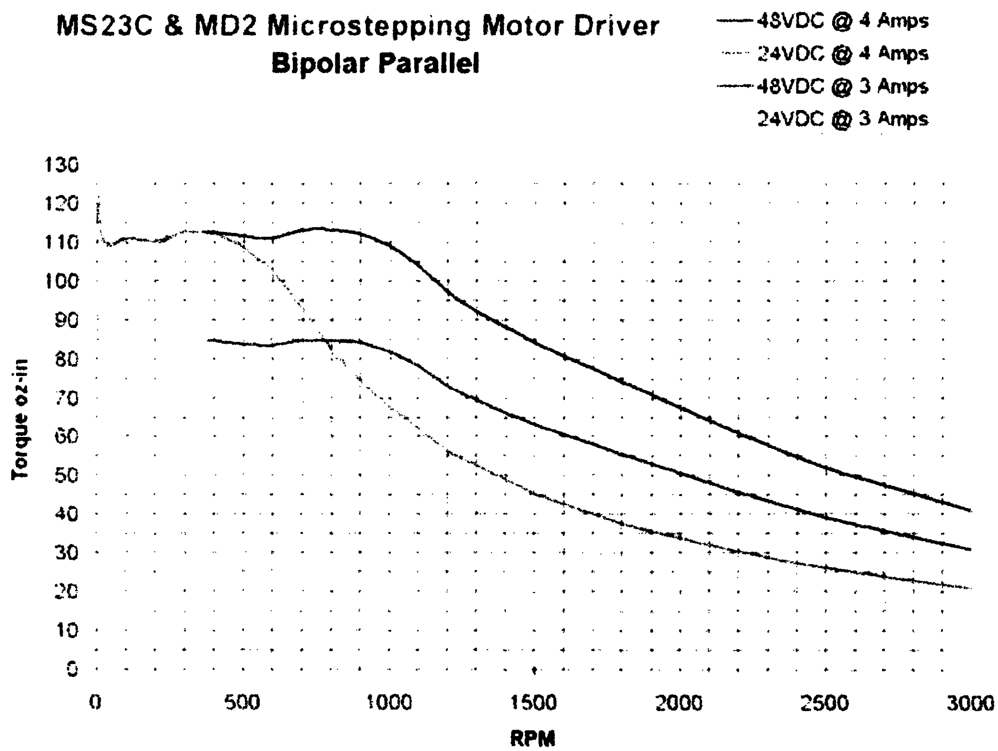



**Figure 5.14** Speed-torque characteristics for the Motor [40]

## 5.3.2 Alternative design: Servo-motor design

As an alternative to an open-loop system using stepper motors, a closed-loop servo system for a take-up reel during peeling off step can offer higher tension accuracy. Since the winding speed for collecting printed substrates has nonlinear characteristics, it is difficult to get a constant tension during peeling off step by controlling stepper motor speed in an open-loop system. However, the servo control system can yield a great improvement in regulating web tension by sending feedback tension signal to control the speed of take-up motor.

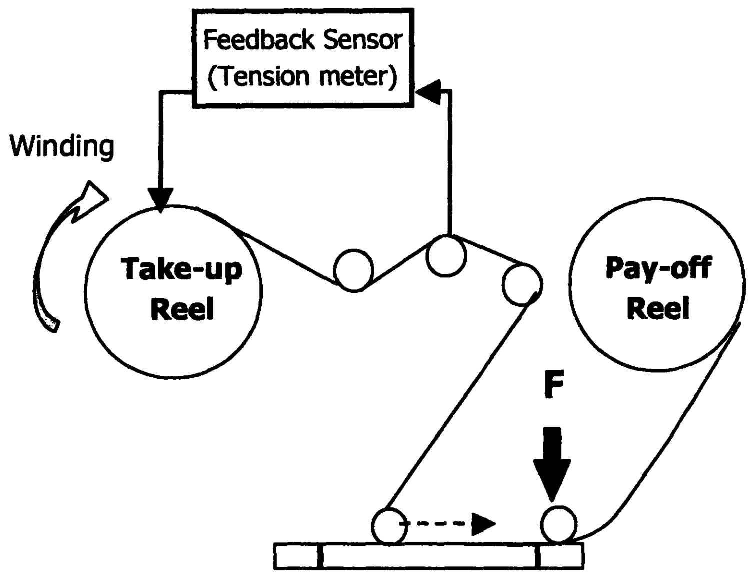
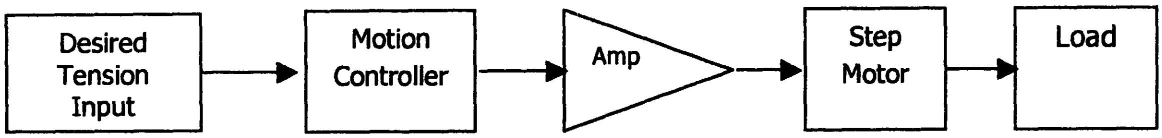
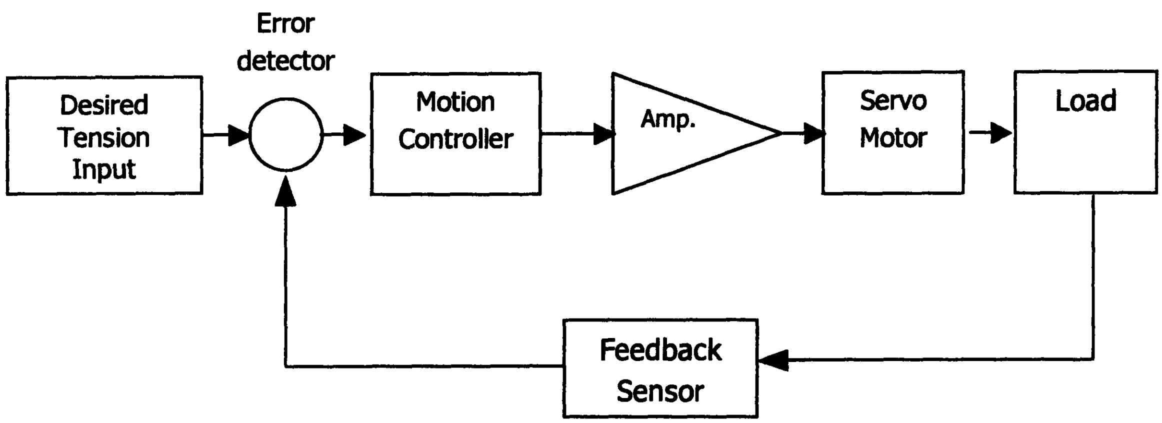



**Figure 5.15** Illustration of tension feedback for controlling take-up motor speed

Figure 5.16 indicates two block diagrams of a position control system (open-loop) and a tension control (closed-loop) servo system which is suggested as an alternative. The open loop position control system (Figure 5.14(a))does not need feedback sensors because position is controlled by the predetermined number and direction of input digital pulses sent to the motor driver from the controller. However, the closed-loop control system (Figure 5.14(b)) has one or more feedback loops that continuously compare the system's response with input commands or settings to correct errors in motor speed.




(a) Open-loop control block diagram




(b) Closed-loop control block diagram

**Figure 5.16** Comparison of two block diagrams

Specifically, desired tension reference input is sent to the motion controller, which transforms tension reference into speed reference for the servo motor, and an amplifier yields speed current for rotating the servomotor. While the servomotor is rotating, tension (feedback) is then sent to the error detector, which compares the actual tension with that of the desired tension. If there is an error, that error is fed directly to the amplifier, which makes the necessary corrections by controlling motor speed. Web tension control systems are commercially available as one package, including motor, controller, tension sensor, and brake, etc.

# 5.4. Design of printing stage

## 5.4.1 Design of guide pins

The key factor in designing printing stage is the alignment with stamp retainer, lifted up from one end of the rotary table to printing stage. The top plate of stamp retainer is design to be fit into the square hole in the middle of printing plate. 4 pin holes are attached to the bottom of top printing plate so that they can guide the stamp retainer during lifting step. The radius of guide pins is 0.22" so that it can compensate 0.22" misalignment. Once four guide pins go through the holes, chamfer of the top retainer plate will enable the retainer to fit into the square hole.

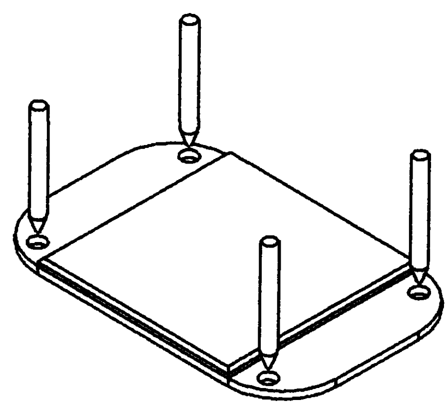


**Figure 5.17** CAD view of guide pins and stamp retainer

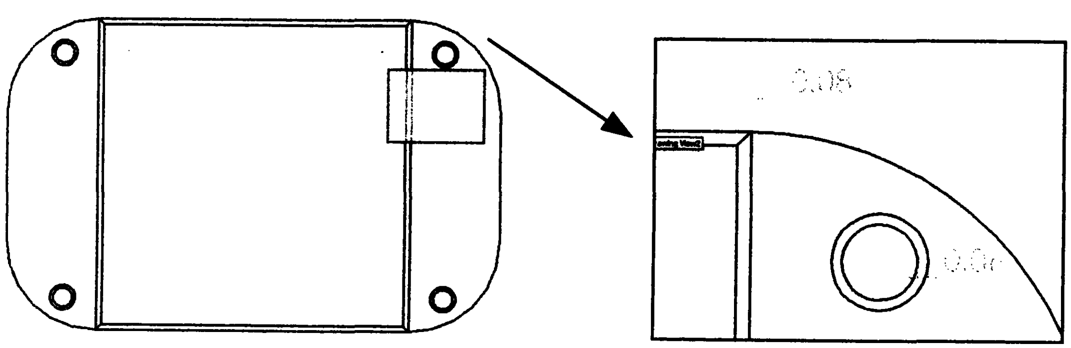


**Figure 5.18** Detailed view of chamfer and hole clearance ( top view )

The chamfer size was determined by the difference between radius of guide pin(0.22") and that of hole(0.28") such that retainer can automatically fit into the top printing plate by chamfer.

## 5.4.2. Alternative Design

In case that higher registration accuracy and repeatability are required, kinematic couplings[38] are recommended instead of four guide pin design. This kinematic coupling mechanism is simple and has been widely used for precision machine that requires frequent connection and disconnection.

A traditional kinematic coupling consists of three "sphere" shaped members mounted to one component and three corresponding "v-blocks" attached to, or machined into the other component [38], Sub-micron repeatability can be achievable by constraining six local contact areas. (One v-block creates two contact areas)

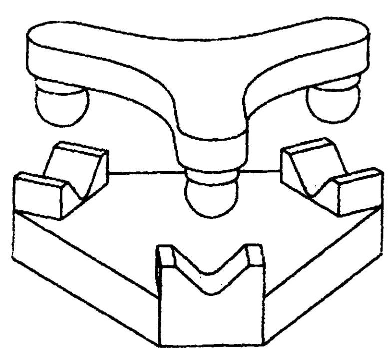


**Figure 5.19** Schematic of kinematic coupling [38].

# 6. Conclusion & Future work

## 6.1 Conclusion

We tested the machine for μCP using paper and an inked PDMS stamp (7" X 7") and the two wiper mechanism showed satisfactory printed results. Linear propagation was successfully achieved by the two-wiper mechanism and no air bubbles were detected during printing. Peeling off and indexing processes that require appropriate substrate tension to collect printed substrate were well executed without tension feedback control. Therefore, we are confident that our project goal, to prove the manufacturability of μCP process, has been accomplished.

Among four main factors – rate, quality, cost, and flexibility – for evaluating a manufacturing process, our design has good potential for high production rate and high quality by applying reel to reel process and printing-side-up design. In addition, one more distinguished feature of this μCP machine is its high scalability to mass production by increasing the length and maximum travel length of wiper. In the case of increasing wiper width, bending of the wiper shaft should be carefully considered or the wipers should be fixed at both ends to generate uniform force distribution.

## 6.2 Future Work

In order to maximize the machine performance, design of experiments (DOE) still remains to be conducted. Propagation speed, contact time, peeling off speed, and normal pressure during propagation can be mechanical factors for DOE and optimal performance can be achieved by tuning these parameters.

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