

Material Selection and Evaluation for the Lexmark 7000 Printhead

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Abstract

The materials selected for the printheads used in Lexmark's Color Jetprinter™ series 7000 and 5000 inkjet printers represented radical departures from those practiced in our previous generations of thermal inkjet heads. In order to achieve cost, performance and schedule targets, significant changes were needed in the materials of construction and processes employed to assemble the printheads.

This paper will focus on the evolution of the laser ablated polymer nozzle plate, a key component of the Lexmark 7000 printhead technology that has succeeded in producing print quality rivaling electrophotography. The rationale for selecting the materials set and the impact these choices had on manufacturing processes will be discussed. In addition, the testing methodology for verifying the performance of the printhead materials will be described. Materials compatibility, process capability and printhead performance data will be presented.

Introduction

Meeting the print quality, cost and reliability requirements for an inkjet printing system is a challenging task. In a fast changing technology, short time to market is essential. Innovations, forethought, acceptance of risk, aggressive scheduling and quick decision making are necessary in order to deliver products on time with excellent performance. This was the philosophy that guided the development of the Lexmark 7000 inkjet printhead system. Three years prior to the launch of the Lexmark 7000 printhead a vision was created. The goal was to develop printheads that produced outstanding print quality at 600 dot per inch (DPI) black and color resolution while achieving high speeds. The words of *The Hardcopy Observer* are testimony to the success of this project: **"the Lexmark 7000 Color Jetprinter is the first ink jet printer from any vendor that can truly claim to offer laser-quality text printing"**[1]. Figure 1 shows a comparison between print from a Hewlett-Packard LaserJet® 5L and a Lexmark Color Jetprinter 7000.

The use of a polymer nozzle plate with integrated flow features is perhaps the most important element of the 7000 printhead. The nozzle holes and flow features are formed by ablation using an excimer laser. In the excimer process, a burst of energy is transferred to the polymer film material and the material is vaporized. The sizes of the holes and the patterns of the flow features are determined by a mask that the laser light is projected through on its way to the film surface. Figure 2 shows a micrograph of one flow channel/nozzle hole combination. There are two components of the structure. The first level (in the vertical direction) is visible as the ink flow channel and the square firing chamber that surrounds the heater. The second level is the actual nozzle hole. A key feature of this structure is the near perfect alignment between the firing chamber and the nozzle hole.

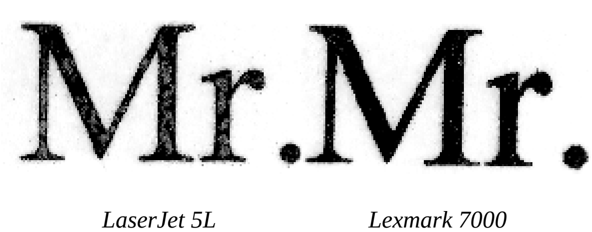

Figure 1. Print Quality comparison with 600 DPI Laser on Hammermill Laserprint Paper

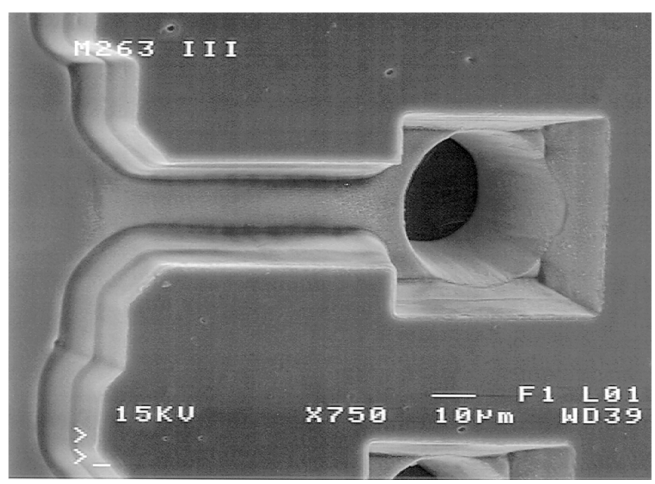

Figure 2. 750x Micrograph of Nozzle and Flow Chamber

Excimer Laser Ablated Nozzle Plate

The factors that drove Lexmark away from the gold coated, electroformed nickel nozzle plates used in earlier products were tolerances, achievable resolution, cost and extensibility to longer print swaths. In particular, variations in the nozzle diameter cause inconsistencies in the mass of the drops of ink ejected by the printhead, which then lead to print quality defects. The nozzle hole diameter tolerance at $\pm 3\sigma$ (3 standard deviations) of the electroforming process is about ±2µm. At 600 DPI, a ±2µm tolerance causes a 15% - 18% variation in nozzle diameter for black and color print-heads. For the polymer nozzle plates, the excimer laser process capability for hole diameters is ±1µm at $\pm 6\sigma$. This significant reduction in nozzle diameter variation is an important factor in achieving consistently good print quality.

Cost improvements over metal nozzle plates are realized through both material savings and yield improvements. It is fairly obvious that the cost of a polymer film will be less than the cost of electroformed nickle. The better yield of the laser ablation process compared to electroforming provides another cost advantage for the polymer nozzle plate. As the number of orifices on a metal nozzle plate increases to accommodate wider swath widths and improved print resolution, producing a defect-free part becomes more difficult. This is due to the random nature of defects on the nozzle plate. Because precise optics and a high resolution mask define the holes and features formed in the excimer process, yield is not sensitive to nozzle plate length or the number of orifices. Therefore, the polymer nozzle plate technology provides a path toward achieving wider print swaths and faster printers by increasing the nozzle plate length while providing cost savings of ~80% and yield improvements of ~20%.

The choice of a polymer nozzle plate over electro-formed nozzle plate technology is not in itself revolu-tionary. Hewlett-Packard and Canon have both practiced this technology since the early 1990’s. The unique aspect of Lexmark's nozzle plate is the incorporation of ink flow features into the nozzle plate structure. In previous generations of products, a ~30µm acrylate thick film photoresist was laminated onto the heater chip and patterned to form the flow channels. This technology was not capable of meeting the demands of 600 DPI printing. The reasons for this were: 1) Poor resolution of the acrylate thick film photoresist when imaged at the dimensions needed for 600 DPI, 2) The lack of a commercially available photoresist with the desired thickness of ~20µm, 3) The difficulty of achieving precise alignment of nozzles to firing chambers. The alignment that the integrated structure provides had been found to be critical for producing satellite free print. The decision to form both nozzle holes and flow features in the polymer film complicated both the development and manufacturing processes. Its payback is seen in the outstanding print quality produced by the system.

Figure 3 is a representation of the cross section of the nozzle plate. The material stack consists of a 50µm thick polyimide base film, a 12.5µm thick phenolic adhesive layer, and a thin (<5µm) sacrificial layer[2]. A 2.5µm layer of a proprietary photoresist called Lexfilm is applied to the heater chip before the nozzle plate is bonded. As will be described later, Lexfilm acts as a planarizing and passivating layer.

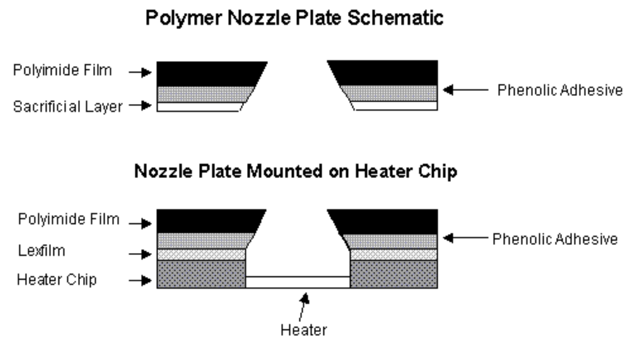

Figure 3. Nozzle Plate Cross Section

Nozzle Plate Materials Selection

The general requirement of any adhesive or plastic used in a printhead is that it must withstand contact with ink for the 2-year life of the device without degradation. The selection of the nozzle plate material combined both practicality and engineering. Polyimide was a logical starting point. Kapton® H polyimide from DuPont has long been used as a TAB interconnect circuit material in inkjet printheads. Its has reasonable compatibility with ink. Kapton however had been observed to degrade when exposed to high pH inks. To provide maximum flexibility in ink formulation, Upilex® S polyimide from Ube Industries was also evaluated as a polymer film. Figure 4 shows the structures of the two materials[3]. Soaking of samples of both polyimides in inks at 60°C for 2 weeks demonstrated that Upilex provides better resistance against higher pH inks. The Kapton gained weight and curled, while the Upilex was essentially unchanged. The reason for Upilex’s better ink resistance is not well understood.

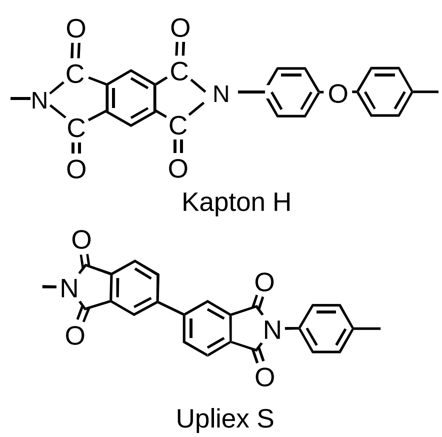

Figure 4. Structures of Kapton H and Upilex S

A second advantage of Upilex over Kapton is its greater stiffness. Based on the tensile moduli data provided by their manufacturers, Upilex is about a factor of 3 times stiffer than Kapton. The difference is due to the ether linkage in Kapton's structure.

Even before the decision was made to include polymer nozzle plate technology in Lexmark's next generation printhead, the development team was forming the conceptual design of the production laser tool. Reel to reel processing on 35mm sprocketed film was planned. In order to reduce the risk of film handling problems, the stiffer Upilex film was preferred. Therefore, because of its greater stiffness, its better ink resistance and its similar cost compared to Kapton, Upilex was the better choice for this application.

In addition to forming the flow features, another function of the thick film photoresist in conventional printheads is to bond the nozzle plate to the heater chip. The film acts as a thermoplastic adhesive. When the thick film was eliminated from the printhead design, there was a need for an adhesive for this purpose. If the adhesive was incorporated into the polyimide film structure, then it could be applied as part of a low cost web coating operation rather than having to apply it to the heater chip or nozzle plate later during the printhead assembly process.

A series of tests were performed on several candidate adhesives. To reduce engineering effort and shorten development time, the adhesive candidates were limited to materials that were already available as coated films from the polyimide supplier. Three B-staged materials, an acrylate, an epoxy and a phenolic/butyral were selected for testing. These were already known to absorb at the 248nm wavelength of the laser. Samples were prepared and then soaked in inks for 28 days at 60°C. After soaking, 180° peel strength was measured. Many of the samples in the initial testing experienced a significant loss of adhesion between the chip and the nozzle plate. The test was repeated with the addition of a silane adhesion promoter spun onto the surface of the wafer before the nozzle plate bonding operation. Table 1 shows that with a silane adhesion promoter, the epoxy and the phenolic/butyral had better adhesion to the chip than the acrylic. The epoxy coating however was noticeably rough and did not ablate as well as the phenolic/butyral coating. Rather than study and solve this problem, the phenolic was simply chosen as the adhesive coating.

The use of the silane adhesion promoter was unattractive because the presence of coating was hard to detect. Lexmark's manufacturing team was concerned that the lack of a technique for measuring the coating made controlling the process troublesome. Since advantages of the integrated structure had already been demonstrated, the development team began researching methods for determining if an adequate silane coating was present on the wafer.

A second complication of incorporating adhesive in the polymer nozzle plate structure is that it needs to be protected from debris generated during the ablation process. Though most of the material ablated by the excimer laser is vaporized, some falls back onto the film as a hot, carbonaceous slag that melts into the adhesive layer. The slag deposit interferes with the bonding of the nozzle plate to the heater chip. To solve this problem, a "sacrificial" layer is applied to the adhesive side of the nozzle plate film before it is ablated. During ablation the debris lands on the sacrificial layer. The sacrificial layer and the debris are removed after ablation by washing the film in a custom tool. For safety and environmental reasons, poly vinyl alcohol (PVA), a water-soluble polymer, was chosen for the sacrificial layer. In the washing tool, jets of 60°C water spray the film and remove the PVA and slag. Although several other water-soluble polymers were evaluated, PVA was selected because its good performance, its safety and its ease of handling.

Table 1. 180° Peel test results in lbs. of nozzle plates bonded to chips soaked and in ink at 60°C

Adhesive Peel Test Results

	Weeks Exposed to Ink at 60°C		
Adhesive	**0**	**2**	**4**
Phenolic	23.0	3.0	0.9
Phenolic + Silane	32.5	46.5	43.4
Epoxy	25.1	6.6	3.6
Epoxy + Silane	45.0	35.0	35.7
Acrylic	28.1	3.1	0.9
Acrylic + Silane	27.3	26.0	22.7

Numerous problems were encountered during development of the washing process. Though washing with organic solvents and surfactants made the film easier to clean, they increased the risks of attack of the adhesive. Also, the lead time for a washing tool designed to meet the safety requirements for handling explosive organic solvents was considerably longer than if it only used water to clean the film. Eventually, optimizing both the adhesion of the PVA coating and washing process conditions solved the problem of incomplete cleaning of the polymer film.

Nozzle Plate Bonding

As discussed earlier, silane was needed to promote adhesion between the nozzle plate and the heater chip. Another nozzle plate adhesion problem arose late in the product development process. A critical yet frequently overlooked step in the launching of a product is scale-up from building prototypes one at a time in a lab to performing high volume manufacturing. Though two processes may be the same, going from individual chip processing to wafer scale assembly always poses new challenges. The most significant problem encountered during scale-up of the 7000 printhead involved the thermal compression bonding (TCB) process.

The TCB process uses a combination of temperature and pressure to bond nozzle plates to the heater chip wafer. Prior to TCB, individual nozzle plates are aligned and tacked to the wafer before it is diced into separate heater chips. In prototype assembly, this process was done on individual heater chips rather than on entire wafers. It is easier to control of the temperature and pressure during TCB of a single chip than it is on an entire wafer of over 100 chips. The slight temperature and pressure variations across the wafer surface on the manufacturing TCB tool prevented the adhesive from conforming to the heater chip surface. The various layers that form active devices in the thin film structure cause the surface of the heater chip to have a topography in which the differences in the vertical height between the high points and low points range from about 1.5µm to 2µm.

Changing the temperature and pressure of the TCB process did not solve the problem of the adhesive conforming to the chip surface. None of the process changes investigated produced acceptable bond uniformity across the wafer without causing adhesive to creep into the ink flow channels. The process simply was not sufficiently robust to be used in manufacturing. Voids and bubbles formed when there was not good uniformity of the nozzle plate to chip bond. This condition allowed ink to seep between the nozzle plate and chip. Jetting efficiency and therefore drop velocity was decreased because some of the energy imparted to the ink during each heater firing was lost as ink was pushed under the nozzle plate. During shelf life testing at 60°C, the ink under the nozzle plate caused failures of its bond with the chip as well as corrosion of exposed aluminum on the chip surface.

Lexfilm

During work on the 7000 printhead, a separate project to develop a spin-on photoresist was in progress. This material, called Lexfilm, was intended to replace the dry film photoresist that had been used to form the flow features in Lexmark's previous generations of products. The objective of the project was to create a photoresist formulation that provided superior imaging, ink compatibility and thickness control compared to commercially available products. Due to the small amounts of photoresist used in inkjet printheads, photoresist suppliers were reluctant to develop unique materials for Lexmark. Developing our own photoresist was intended to solve this problem.

When the TCB problems on the 7000 printhead became apparent, the application of a 2.5µm layer of Lexfilm to the surface of the wafer was quickly introduced into the production process (see Figure 3). The Lexfilm protected the chip from ink intrusion and it formed a planarizing layer that allowed the adhesive to better conform to the surface of the chip. This prevented bubbles and voids from forming between the nozzle plate and the chip. Figure 5 shows the adhesion of nozzle plates to heater chips when a 2.5µm layer of Lexfilm was spun onto the wafer. In the test a probe pushed on the underside of the nozzle plate through the ink slot in the center of the chip. To accelerate the test, the chips were soaked in ink at 60°C and 75°C for extended periods of time. The force needed to cause the nozzle plate to separate from the chip was measured. In some cases the chip broke or the probe punctured the nozzle plate before the nozzle plate separated. A push-off force greater than 1 lb. is required in order to pass this test. As shown in Figure 5, Lexfilm's adhesion to the chip and the nozzle plate was very good. Subsequent Arrhenius testing has found that the acceleration for aging at 75°C is about 11.5. Therefore, the data shown in Figure 5 represent about 1 year of aging at ambient conditions. Another benefit of using Lexfilm was that silane adhesion promoter could be eliminated

The Lexfilm project almost overnight went from being a research/technology effort to being a component critical to the success for the 7000 printhead. The development team responded rapidly to the challenge, conducting scale-up trials, aging studies, vendor searches and qualifications, manufacturing tool modifications and operator training in order to implement Lexfilm in time for start of production.

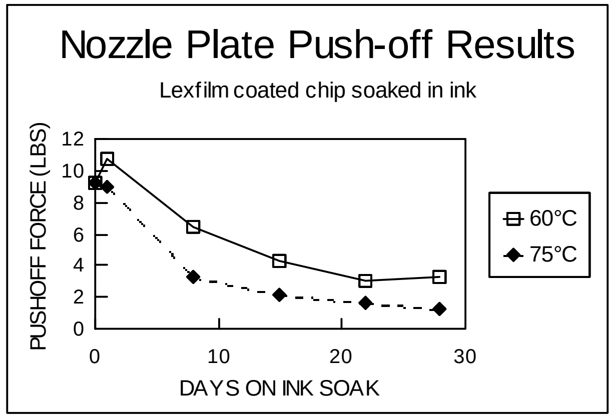

Figure 5. Push-off force for chips coated with Lexfilm

Summary

The new material system for the 7000 printhead has enabled Lexmark to make significant improvements in inkjet print quality. In the future, this technology will continue to be extended to wider swath widths, greater speeds and smaller drop sizes.

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Biography

Jim Mrvos received a BS in chemical engineering from Carnegie Mellon University in 1981 and an MS in chemical engineering from the University of Kentucky in 1992. He has seventeen years of experience with Lexmark International and IBM in the manufacture and development of imaging supplies. Since 1990, he has worked on inkjet ink and printhead development. He is currently manager of inkjet process and materials development for Lexmark. Mr. Mrvos is the co-author of eight patents and is a registered professional engineer.

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