

A Review of Flexible Circuit Technology and its Applications

Flexible circuits are a high-growth technology in the area of electrical interconnectivity and look set to deliver improved performance against the demands of many twenty-first century products.

The compact nature of flexible circuits and the high electrical-connection density that they can achieve offer considerable weight, space and cost savings over the use of traditional rigid printed circuit boards, wire and wire harnesses. The technology offers the potential of reducing the total costs of electrical interconnections by up to 70% and reducing cable and wiring use by up to 75% when married with an appropriate application. It is to be noted that flexible printed circuits have replaced hand-built wire harnesses in many applications.

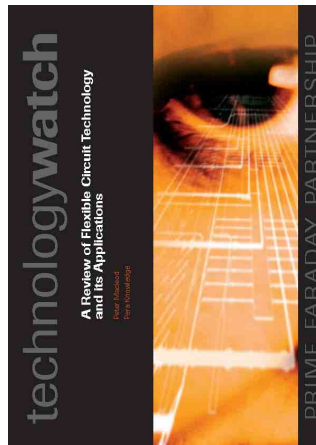
This review will provide a basic assessment of Flexible Printed Circuits (FPC) technology, flex circuit construction and manufacture, flex circuit materials, market developments, technology developments within the FPC field, along with major applications of the technology. It is hoped these applications exemplify how FPC has the potential to offer product developers and designers significantly more design freedom, enabling them to meet the higher circuit-density demands of tomorrow's electronic systems.

Peter Macleod

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1.0 Introduction

Flexible printed circuits are found in everything from automobiles, VCR's, camcorders, portable phones and SLR cameras to sophisticated military and avionics systems. High-profile applications of flexible circuits are many. one example is the application of flexible-circuit technology in a rigid flex wire harness used on Sojourner, the robot that roamed the surface of Mars collecting data during the summer of 1997.

On a somewhat less romantic level, something as common as a notebook computer or flip-lid mobile phone would not be possible without flexible printed circuit technology which allows components to be electronically connected in a dynamic, three-dimensional, way.

Flexible-circuit technology has a well-established history that goes back nearly one hundred years. Early patent activity highlights the fact that concepts for flexible-circuit materials and designs, which have only come into commercial use within the last few decades, were speculated upon by inventors such as Thomas Edison, Frank Sprague and others in the early twentieth century.

The heart and soul of Flexible Printed Circuits (FPCs) are the flexible films and thin layers of conductive circuit traces. These typically constitute the base flexible-circuit laminate, which can be utilised to interconnect electronic devices – such as the LCD screen and keyboard of a laptop – as a reliable wiring replacement, or can have electronic components directly attached to it via soldering or conductive adhesive, to form a finished, pliable circuit board.

Any assessment of the technology of flexible circuits quickly identifies a whole range of benefits that complement and surpass the capabilities of rigid printed circuit boards (PCBs). For many, the technology of flexible circuits and their wide applications may be new, and the view of flexible circuits may be restricted to that of simple point-to-point connections, as a replacement for traditional electrical wire for example. This is currently far from the case and the promise of flexible circuitry is highly significant. With new applications and new materials continually being designed and developed, the technology promises to revolutionise many aspects of electronic circuit design.

This report introduces the subject of flexible circuits and highlights their advantages and applications beyond the currently rigid, planar circuit-board technology. The report also highlights areas of opportunity for the application of flexible circuits, and in doing so conveys the potential for the technology to deliver new product development freedoms and capabilities that may be used to develop both product and competitive advantage.

2.0 Flexible-Circuit Technology

The advance of electronic systems into our everyday lives is evidence of a major digital technology revolution. The success stories of the personal computer and the mobile phone serve to demonstrate that consumer and business demand for innovative products are significant. Increasingly electrical and electronic systems are entering our lives in many unanticipated ways. They can be found in our homes in the form of cordless phones and digital TVs, in our cars in the form of hands-free communications and telematics, and in business in the form of notebook computers and mobile personal data assistants (PDAs).

Importantly, and also covertly, within the above applications flexible printed circuits have also been entering our lives. Traditionally employed in the role of wire replacement, removing the need for complex wire harnesses, and replacing costly and increasingly complicated wired assemblies, flexible circuits offer a much simpler and often significantly more cost-effective interconnection method.

However, alongside increasingly innovative applications flexible-circuit technology is branching out significantly from this initial role and it is poised to be a technology that will provide enormous design freedoms for electronic engineers and product designers over the coming years. As the demands of modern electronic systems call for increasing functionality, greater circuit density, higher connectivity, better environmental performance, and all at lower cost, flexible circuitry is poised to deliver on the promise of twenty-first century electronics.

2.1 A Definition for Flexible Circuits

Confusion still exists regarding what constitutes a flexible circuit. When asked to envisage a flexible circuit, the image in most people's mind will be of a bendy printed circuit, typically consisting of a flexible film with a pattern of copper conductors on it.

Whilst the image is not far from the truth, in order to better understand flexible circuits it is important at the outset to establish a working definition. The IPC (formerly the Institute for Interconnecting and Packaging Electronic Circuits), through its role of setting standards and guidelines for the electronics industry, has established such a definition:

Flexible Printed Circuit

A patterned arrangement of printed circuitry and components that utilizes flexible base material with or without flexible cover lay.¹

¹ IPC (1996) *IPC-T-50: Terms and Definitions for Interconnecting and Packaging Electronic Circuits*, Revision F (June 1996), IPC, Northbrook, IL

The above definition, although strictly accurate, does little justice to the complexity of the technology but does serve to convey some of the potential given the available variations in base materials, conductor materials, and protective finishes.

2.2 Flexible-Circuit Constituents

From the above definition, there are a number of basic material elements that constitute a flexible circuit: a dielectric substrate film (base material), electrical conductors (circuit traces), a protective finish (cover lay or cover coat), and, not least, adhesives to bond the various materials together. Together the above materials form a basic flexible-circuit laminate suitable for use as a simple wiring assembly, or capable after further processing of forming a compliant final circuit assembly.

Within a typical flexible-circuit construction the dielectric film forms the base layer, with adhesives used to bond the conductors to the dielectric and, in multilayer flexible circuits, to bond the individual layers together. Adhesives can also be used in a protective capacity to cover the final circuit to prevent the ingress of moisture and dirt, when they are termed 'cover lays' (also 'cover layers') or 'cover coats'.

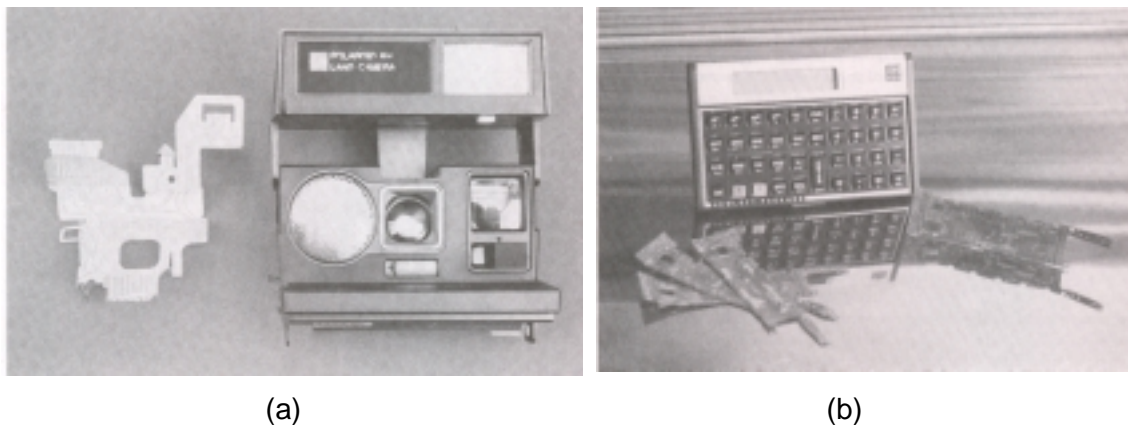
2.3 Materials Diversity Overview

Many individual materials exist that time and extensive prototyping have proven suitable for application in flexible circuits. There are numerous substrate materials (termed dielectrics) available as very thin films of 12–120 microns in thickness that have been prototyped as base materials upon which to build flexible circuits. However, the two most common dielectric substrate materials are polyester and polyimide. Both are widely available from a number of global sources and both have unique advantages that make them suitable as base materials.

At costs of pennies per square metre, polyester materials are used to provide millions of exceptionally low-cost flexible circuits that find their way into calculators, cameras, touch panels, keypads and automotive dashboards. Polyesters are also highly flexible and are the material of choice for dynamic flexing applications. One example is the connection between a notebook PC keyboard and its screen, an application where many thousands of flexing operations are required.

Polyimide is the material of choice for more demanding flexible-circuit applications. Unlike polyesters, polyimides have excellent high-temperature characteristics and low thermal expansion, which has led to their use being effectively standard practice within the demanding aerospace and defence sector, where complex multilayer circuits are required. They can withstand service temperatures approaching 700°C.

Figure 1. Applications of flexible circuits in consumer goods



FPCs provide interconnection solutions for a diverse range of end-user applications, including (a) the flash and control circuit in an instamatic camera and (b) modern calculators, which consist entirely of low-cost flexible circuitry.

In the area of conductors, fine metallic foils are used, with copper being the material of choice. Whilst there are more than a half-dozen variations of copper officially recognised by the flexible-circuit industry, each with its own particular characteristics, there are two main classification for copper conductor material. These are electrodeposited copper and rolled-annealed copper.

There are important distinctions between the two classifications of material. Being easier to deposit onto the base substrate, by spraying or sputtering, electrodeposited (ED) copper foils offer the industry low-cost circuitry, whilst rolled-annealed (RA) copper foils, processed between rollers and bonded onto the base laminate, offer high resistance to continuous flexing required of circuits in dynamic applications. New developments are blurring the lines between the various categories of copper, allowing designers continually increasing freedom.

Aside from copper, just about any conductive metal that can be supplied as a foil, sprayed, sputtered or electrodeposited, such as gold, aluminium, nickel or silver, can be used as a conductor.

Also many adhesive systems exist. Common practice is to utilise an adhesive system that offers maximum compatibility with the chosen base material. Hence, polyimide and polyester adhesives are common, as are 'universal' adhesives such as acrylics, epoxies, and phenolics, which have migrated from the world of rigid circuit boards.

In conjunction with the basic building blocks many other materials find applications in flexible circuits. It is not uncommon that appropriate stiffening materials – aluminium, steel and moulder polymers – are integrated into the circuitry to provide unique solutions to electrical interconnect problems.

Increasingly within areas such as the automotive and aerospace sectors, where thermal performance is highly important, flexible-circuit laminates are populated with surface mounted electronic components, to form a complete circuit assembly, to overcome the thermal expansion mismatch problem that has plagued the use of rigid circuit boards and surface mounted components.

Research and industry knowledge has demonstrated that during exposure to large changes in temperature, the rigid nature of conventional circuit boards, typically made from stiff FR4 composite, tend to expand at a slower rate than the surface mounted electronic components.² Such a mismatch in thermal expansion levels leads to excess stress being generated in the components and their joints, in the worst cases leading to either joint or component cracking, and circuit failure.

On the other hand, a flexible substrate, populated with components, bonded to a rigid base makes for a circuit assembly which though unsuited to use in a dynamic, flexing, capacity exploits the inherently pliable nature of flexible laminates to provide a thermally compliant circuit, with high reliability, at low cost. The area of flexible circuits as compliant, flexible 'packaging' for electronic components and assemblies is currently one of the most intense areas of flexible-circuit research.

As stated, many variations on the basic theme exist. Flexible circuits with or without cover lays, with or without adhesives, with or without substrates, rigidised and stiffened, are possible. The approach, like the technology, is highly flexible.

2.4 Flexible-Circuit Construction

Despite the variability of flexible-circuit materials there is a topology to flexible-circuit construction that follows a number of generic variations. Many of the flexible circuits found in the vast proportion of interconnection and flexible packaging applications follow six basic designs.

2.4.1 Single-Sided Flexible Circuits

Single-sided flexible circuits are the most common types of flexible circuit available. They consist of a single conductor layer on a flexible dielectric film with access to circuit-termination features accessible from one side only. They can be manufactured with or without cover lays and protective coatings, and their relatively simple design makes them highly cost effective. The conductors used can be conventional metal foil, or, for low-cost, polymer thick-film (PTF) ink can be used. This is simply printable

² Kühl, Reiner W. (1999) Mechanical stress and deformation of SMT components during temperature cycling and PCB bending, *Soldering & Surface Mount Technology*, Vol. 11, No. 2, 35–41

conductive ink, loaded with carbon or silver particles, which is directly applied to the flexible substrate in the circuit pattern required by a variety of printing and stencilling techniques.

Single-sided circuits can offer the lowest cost and relative ease of production. Because of their thin and lightweight construction such circuits are best suited to dynamic-flexing or wiring-replacement applications such as computer printers and disk drives. Nearly all of the world's calculators consist of PTF flexible circuits on polyester film, a combination that offers an exceptionally low circuit cost.

2.4.2 Double Access Flexible Circuits

Double access flexible circuits have been developed to meet the demand for low-cost circuitry that can handle an increase in component real-estate demand. Such circuits allow designers to place components on both sides of the flexible dielectric film.

To access both sides of the film requires careful design to allow exposed areas of the conductor to be available for underside component attachment. This often means punching through-holes in the dielectric film prior to its lamination with the conductor. Other methods involve after-lamination machining – laser or chemical milling for example – to provide rear access to the conductive layer. Because of the process steps required to produce double access circuitry it is not widely used.

2.4.3 Double-Sided Flex Circuits

The double-sided flexible circuits are also very popular. With the demand to place more components on a circuit and increasing circuit density and power-handling capabilities comes the need for greater conductor numbers. This can be met by incorporating more than a single conductive layer on the same base film.

Double-sided circuits can be constructed by various means such as separate conductors on both sides of the base film and printed conductors separated by printed insulating cover lays.

With double-sided circuits an issue is ensuring reliable connectivity paths between components mounted on the top and the bottom of the board. Various techniques have been developed to provide connectivity through such multilayered laminates. Early examples include conductive metal staples, pins and rivets. The most popular flexible-circuit through-board interconnectivity technique is the plated through hole (PTH), which is also the most popular approach in the rigid-circuit world, from which it has successfully transferred.

In PTH, holes are drilled or laser cut in or through the conductors and base film laminate. These holes are then primed and plated with conductive materials to produce a reliable interconnect feature.

2.4.4 Sculptured Flex

Sculptured flex is a derivative of flexible-circuit architectures in which a specialised, patented technique is used to yield a conductor layer of varying thickness. The conductive layer is selectively etched back in places to provide thin layers where flexibility is required, and thicker layers for joining and circuit interconnection. It is typical that the thicker layer forms leads that protrude from the circuit, to provide plug in connectors or greater lands for improved solder joint formation. Typically such leads also provide the circuit with improved mechanical strength and rigidity.

2.4.5 Multilayer Flex Circuits

Flexible circuits that have three or more layers of conductors are referred to as multi-layer flex. These circuits are complex to construct and have high costs, but they meet designers', manufacturers' and consumers' demands for even greater circuit density.

A multilayer circuit consists of bonded conductive layers that are interconnected by means of plated through-holes. Unlike their rigid multilayer counterparts, the individual circuit layers in flexible multilayer circuits may or may not be continuously laminated together, depending upon the flexing and dynamic characteristics required.

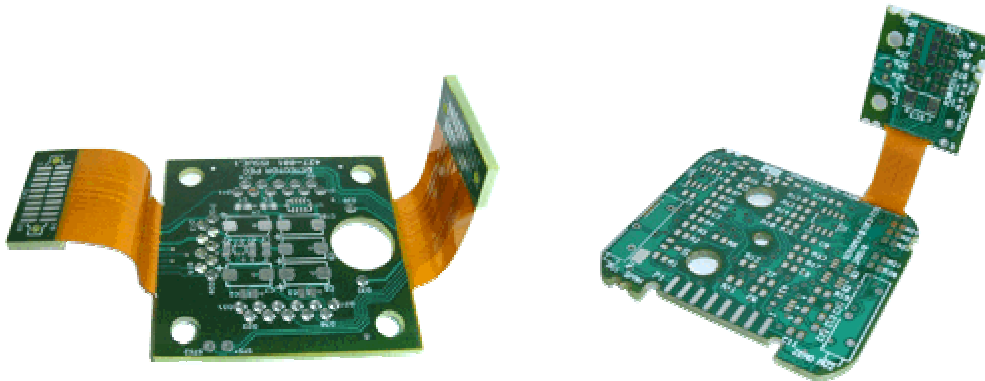
Flexible multilayer circuits are popular within the defence and aerospace sectors where they provide dynamic high-density circuits. Their drawback is that with current substrate and conductor materials they are often restricted to a maximum of twenty-five layers. Even with flexible circuit there is a degree of mismatch between the coefficient of thermal expansion of various materials used in their construction, particularly the adhesives. This means that over multiple layers laminate stress can cause through-hole interconnects to barrel and stretch, restricting their reliability.

2.4.6 Rigid-Flex Circuits

Rigid-flex circuits are hybrid constructions consisting of rigid and flexible substrates laminated together. Predominantly, the rigid circuits are used to house the components, whilst the flexible circuitry provides the necessary interconnects between them.

Like double-sided and multilayer circuits they make use of PTH interconnects where required. These types of boards have found particular favour in the defence sector where the combination of reliability, strength and flexibility has not been lost on equipment designers. They are used in a wide variety of commercial microelectronics applications such as laptop computers and notebooks and extensively in the construction of hearing aids.

Figure 2. Rigid-flex circuitry



Rigid-flex circuits are a combination of rigid circuitry and flexible interconnects. The interface between the flexible and rigid elements requires careful design, particularly if it is to be subjected to repeated flexing. If this is the case, compliant materials are often applied to the join to reduce the direct flexing of the interconnects as they reach the rigid board. (Pictures courtesy of Amphenol)

There are a number of variations of rigid-flex available. Amongst them is 'rigidised' flex which is in effect a flexible circuit which has a stiffening material attached, to support the weight of mounted components and to provide the circuit with some rigidity to aid assembly. Suitable stiffer materials depend upon the application at hand but plastic, composite and metal backing materials are commonly used.

Beyond the generic variations of flexible-circuit constructions there are a number of alternatives. One such major variation is moulded circuits. These are typically three-dimensional moulded plastic components with mechanical capabilities, into which electrical circuitry is incorporated. For some types of moulded circuits the electrical functionality is provided via a flexible circuit that is introduced into the mould at the time of manufacture. Other variations utilise complex moulding and selective plating techniques to form suitable conductor patterns in and on the component. For a more detailed discussion of this evolving technology please refer to the Technology Watch report *Moulded Interconnect Devices*.

3.0 Flexible-Circuit Materials

As discussed initially, flexible circuits typically represent a composite (laminated) of materials, chosen to work together to deliver a desired overall combination of electrical and mechanical performance. However, these criteria are not alone in enabling the determination of an appropriate combination of circuit materials. Other typical factors that play heavily on the selection of suitable materials are:

- Application environment
- Volumes
- Reliability requirements
- Dynamic or static flexing required
- Duration of flexing or dynamic operation (cycles)
- Additional electrical requirements of the circuit – e.g. impedance
- Connections to components and other circuitry
- Method used for component assembly
- Costs

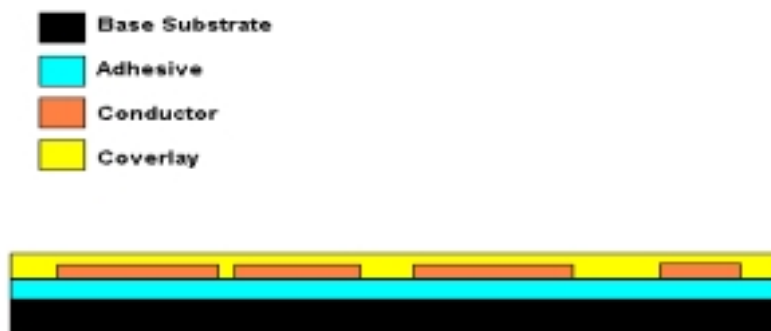
3.1 Material Configuration

Within a typical flexible circuit, four distinct classes of materials are used:

- Base material (dielectric film/flexible substrate)
- Conductors (foil or conductive coating)
- Adhesive (optional)
- Cover lay (film or coating)

Other materials utilised include numerous surface finishes and anti-tarnishing coatings, and integral stiffeners or backing substrates, all designed to give additional properties and performance capabilities to the circuit assembly or enhance the ease of manufacture. A simple typical circuit make-up is detailed in Figure 3 below.

Figure 3. Flexible-circuit make-up



3.2 Base Materials

A suitable base material has to perform a variety of important functions. It must electrically insulate the conductive circuit tracks from one another and it must be compatible with any adhesives used for conductor or cover-layer bonding. Under normal circumstances the base material will also provide the circuit with much of its mechanical characteristics, such as its flexing strength and durability. In the case of adhesiveless laminates, which will be discussed later, the base substrate provides all of the circuit's strength.

Typically, the major criteria and properties required of a suitable substrate are:

- High dimensional stability
- Good thermal resistance
- Tear resistance
- Good electrical properties
- Flexibility
- Low moisture absorption
- Chemical resistance
- Low cost
- Consistency from batch to batch
- Wide availability

A singular benefit of flexible-circuit substrates is that unlike their counterparts within the rigid-circuit world they are not restricted to processing in sheet form. Many manufacturing processes for flexible circuits take advantage of the nature of the materials used in their construction to manufacture circuits in a continuous roll-to-roll fashion. Base materials such as polyester are supplied in roll form and processed as a single web, a metre or so wide. The processed circuits (minus components) can then be rolled up for further processing and component attachment, or die-cut from the web to the final circuit shape in the case of simple wiring interconnects.

Many of the substrate materials used in flexible laminates are themselves cast or produced from web-based processes, making their supply in roll form straightforward and highly economic. A significant proportion of manufacturers have enabled their manufacturing stages – plating, cleaning and rinsing amongst others – to use roll-to-roll techniques.

Roll-to-roll processing poses distinct technical challenges such as ensuring accurate layer registration and correct web tension. However, there is no doubt that compared to the conventional press lamination process, which uses rigid sheets, it offers higher production rates of thousands of circuits per hours, improved reliability and improved material handling.

There are many materials that have been used as substrate materials with varying degrees of success over recent decades. Materials that have been widely used for various FPC applications include:

- Polyimide
- Polyester
- Fluorocarbon films
- Aramid papers
- Composites

These materials present a range of differing properties (see Table 1), which are called upon by circuit designers where their blend of electrical and mechanical performance capabilities and costs best suit the application at hand. As previously discussed, the two materials that receive by far the most attention are polyimide and polyester films.

Table 1. Typical properties of dielectric materials

Property	Polyester	Polyimide	Fluorocarbon	Composite	Aramid
Tensile strength	E	E	F	G	H
Flexibility	E	E	E	G	F/G
Dimensional stability	F/G	G	F	G	E
Dielectric strength	G	G	E	VG	G
Solderability	P	E	F	E	E
Operating temperature	105–185°C	105°C	+220°C	150–180°C	220°C
Coeff. of thermal expansion	L	L	H	M	L
Chemical resistance	G	G	E	VG	F
Moisture absorption	VL	H	VL	VH	L
Cost	L	H	H	M	M

E=Excellent	VG=Very Good	G=Good
F=Fair	M=Moderate	
H=High	L=Low	VL=Very Low

3.2.1 Polyimide

Polyimide films are manufactured from a condensation polymer of an aromatic dianhydride and an aromatic diamine. The film is often cast in various thicknesses of 7.5–125 microns.

Polyimides are non-flammable thermoset polymers and as such do not exhibit a softening or melting point. However, unlike many thermosetting plastics, polyimide films are highly flexible, exhibit good flexing and electrical properties across a wide range of temperatures, have good high temperature resistance, and resist soldering conditions.

Polyimide films are produced in several varieties by companies such as DuPont (USA), Ube Chemical (Japan) and Kaneka (USA) under trade names such as Kapton, Apical and Upilex. The standard use of polyimide substrates is significantly more prevalent in Japan than in other regions of the flexible-circuit manufacturing world.

Polyimide is the flexible-circuit dielectric of choice for about 80–85% of applications, as reflected in the materials relative FPC market volume sales. Whilst they are relatively expensive, up to nine times the cost of polyesters, their tough nature and resistance to thermal or chemical damage make them an obvious choice where circuitry is required with a high degree of reliability and immunity to environmental influences.

A downside to polyimides is the fact that they readily absorb moisture, typically up to 3% by weight. This requires the material to be thoroughly dried prior to processing, and requires monitoring of the material as it passes through various production stages to ensure that the chances of further moisture uptake are minimised. It is also conventionally the case that polyimide flex is produced via a panel process, with the material being bonded to a conductive substrate via a number of methods. This means that polyimide flex is provided in sheet form, negating the processing advantages achievable by roll-to-roll processing. However, developments are underway to develop roll-processable polyimides.

3.2.2 Polyester

Polyesters, also known as polyethylene terephthalate (PET), are similar in most ways to polyimides but because they have a melting point of 250°C and a glass transition temperature of 80°C, they generally have lower heat resistance that precludes their use in assemblies that require the use of soldering. However, many OEM manufacturers have developed in-house processes that enable them to solder to various grades of polyester with high degrees of success.

Due to their lower raw-material cost and ease of roll-to-roll manufacture, polyesters are found in a high proportion of high-volume, low-cost, environmentally undemanding applications such as calculators and VCRs. In these applications they are often used as simple wire replacements or as rigidised assemblies with surface mounted components. Despite its low temperature resistance many companies have explored techniques for mounting components onto polyester. A commercially proven approach is through the use of conductive adhesives.

Polyester films are the preferred dielectric material for the remaining 20% of the market that polyimide has not captured. Polyester films are generally available in thicknesses of 25–125 microns. They are characterised by their excellent flexibility, good electrical properties, and high chemical and moisture resistance. Given the recent advances in overcoming the poor temperature resistance of polyesters, the material looks set to approach even closer to becoming the ideal flexible-circuit substrate. Developments are well under way with various polyester formulations, such as polyethylene naphthalate (PEN), which offer the increasingly higher service temperatures suitable for soldering. Overall, polyester is easily modified at low cost. It can be readily drilled, punched, embossed, thermally formed, coated and dyed.

3.3 Conductor Materials

Material considerations for FPC conductors are similar to those of rigid circuit boards. The conductor material must survive processing and provide adequate electrical and mechanical performance in the application environment. The list of conductor candidate materials includes elemental metal foils, such as copper and aluminium, and metal mixtures including stainless steel, beryllium-copper, phosphor-bronze, copper-nickel and nickel-chromium resistance alloys. Both silver and carbon polymer thick-film (PTF) inks are also used.

Copper is the material of choice for flexible-circuit conductors. In practice, of the wide variety of possible conductor materials, only a selected few have found use within volume applications.

As well as providing the electrical connectivity and electrical performance features of flexible circuits, conductor properties greatly influence the fatigue life, stability, and mechanical performance of FPC assemblies. In many static applications bending is limited to installation and general servicing. In dynamic applications, the assembly is flexed or folded repeatedly during normal use. As a general rule, for dynamic applications, conductors should be of the minimum acceptable thickness and their material of construction must be carefully chosen, along with their grain orientation and deposition technique, to match the performance levels required.

3.3.1 Copper

The relatively low cost of copper, its high workability, good plating and good electrical characteristics make it an excellent material for flexible-circuit conductors. It is also the case that there are several different kinds of copper available, which can be matched by the circuit designer to specific applications.

Copper foils suitable for use in flex circuits typically fall into two categories – electrodeposited (ED) or wrought (W). The IPC standard IPC-MF-150 ('Metal Foil for Printed Wiring Applications')³ details these categories and defines four types of copper within each, giving flex designers eight types of copper to select from. Table 2 is a guide to the common grades of copper available.

Table 2. Summary of IPC-MF-150 copper foil categorisation

Copper foil category	Number	Designator	Description
Electrodeposited (E) copper foils	1	STD – (E)	Standard electrodeposited
	2	HD – (E)	High ductility electrodeposited
	3	THE – (E)	High-temperature elongation electrodeposited
	4	ANN – (E)	Annealed electrodeposited
Wrought (W) copper foils	5	AR – (W)	As rolled wrought
	6	LCR – (W)	Light cold rolled wrought
	7	ANN – (W)	Annealed wrought
	8	LTA (W)	As rolled wrought low temperature annealable

Source: IPC (1991)⁴

Electrodeposited copper (E) is recommended for use in applications where the need for dynamic flexing is minimal. The grain structure of E copper consists of vertical grain boundaries that extend through the material's deposited thickness. These grain boundaries allow cracks to propagate through the material very quickly, causing E copper's electrical and mechanical performance to fall dramatically.

Wrought (W) copper, sometimes referred to as 'rolled and annealed' or 'RA' copper, is the material of choice for flexing applications. Unlike the vertical grain structure of E copper, W copper is produced by heating and mechanically rolling ingots of pure copper to the desired thickness through rollers. Whilst this places restrictions on the ultimate thickness of the foil that can be economically rolled, typically 18 microns, the process produces a grain structure that resembles overlapping plates. This plate-like structure has a significantly longer crack propagation path and gives W copper a higher tensile strength and a much higher resistance to repeated bending.

Other differences between the two main forms of copper are that typical E coppers have a lower conductivity and more pinholes and inclusions than W coppers. However,

³ IPC (1991) *IPC-MF-150: Metal Foil for Printing Applications*, Revision F (October 1991), IPC, Northbrook, IL

⁴ IPC (1991) *IPC-MF-150: Metal Foil for Printing Applications*, Revision F (October 1991), IPC, Northbrook, IL

E copper foils can be readily heat-treated to form improved grain structures, and they generally have a more uniform response to surface treatments which can significantly improve their adhesion to base laminates.

Whilst the copper options defined in IPC specifications provide scope for the design of a wide variety of copper circuits, a number of alternative copper platings are unaccounted for. These include vapour-deposited, sputtered and electroplated copper, each of which has its own relative merits and pitfalls.

Electroplated copper, using either electroless or electrolytic plating techniques, allows copper to be directly plated onto the base laminate material. It is distinguished from electrodeposited copper by its 'as plated' properties, which are significantly different from the properties of E copper. The plating process allows greater control over the materials grain structure, which, given the addition of suitable additives, can produce a layer of material that has an amorphous or equiaxed grain structure resulting in properties that are superior to W copper.

Sputter copper films are similar to electroplated foils but allow the application of a very thin copper layer (typically less than 1 micron) that can be used as a seed layer for an additive electroplating process. Here copper is added to the laminate in specified areas to give the level of circuit thickness required. The very thin layers produced by sputtering have been proven to be beneficial in the fabrication of very fine-lined circuits, which find applications in specialist areas such as low-temperature (cryogenic) circuits. Very fine-lined circuits are also of benefit in highly dynamic circuit applications such as computer disk heads, where hundreds of thousands of dynamic flexing operations are required.

3.3.2 Other Metal Foils

As stated, where the occasion presents itself, circuit manufacturers have utilised metallic foils other than copper. For example, aluminium foil has found use in circuits where low costs and weight reduction are driving factors, or where electric shielding is required. Unfortunately, aluminium cannot be processed with conventional soldering equipment and so, to keep costs down, is often used in circuits that employ conductive adhesives to form connections.

Metal mixtures, such as phosphor bronze and beryllium copper foils, have been employed where a combination of reasonable conductivity, good mechanical strength and spring-like mechanical properties has been required. Whilst typical beryllium copper offers only a quarter of the conductivity of copper, such material also provides improved corrosion resistance in electrical contacts. Table 3 shows the fundamental properties associated with some of the candidate conductor materials.

Table 3. Conductor material properties

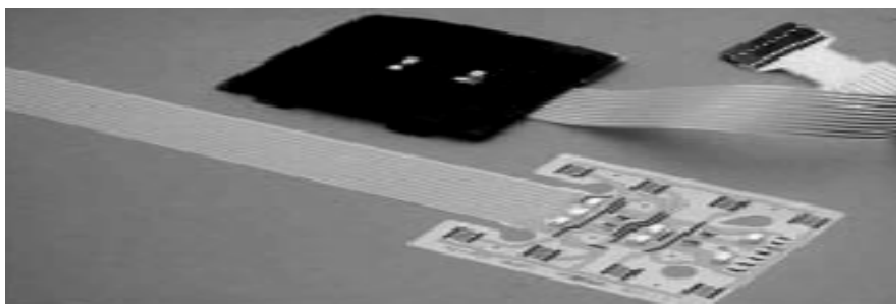
Property	Aluminium	Copper	Gold	Iron	Nickel	Silver
Resistivity ohm-cm x 10 ⁶	2.8	1.7	2.4	10.0	6.8	1.7
Density oz/ft ² @ 1 mil	0.22	0.74	1.6	0.64	0.74	0.87
Harness Brinell	15	42	28	80	110	95
Thermal conductivity Cal/sec/cm ³ /°C	0.48	0.92	0.70	0.16	0.14	0.97
Coeff. of thermal expan. (TCE) ppm/°F x 10 ⁻⁵	1.3	0.93	0.79	0.51	0.76	1.05

Source: Gilleo (1992)⁵

3.3.3 Polymer Thick-Film Processes

A further method for generating conductors on FPC base films is by screen printing or stencilling conductive inks onto polymer films to directly create circuit traces. The method is commonly referred to as the polymer thick-film (PTF) method. PTF has been used for decades as the world's most cost-effective and successful fully additive, waste-free circuitry and assembly technology. Computer keyboards, hand calculators and telephones are key examples of high-volume goods that benefit from this economical method of circuit manufacture.

Figure 4. PTH keyboard



Source: Gilleo *et al.* (1999)⁶

The most common substrate for PTF is thick polyester film of 3–5 microns thickness, but almost any non-conductive flexible film or rigid non-conductor can be used. Films are often heat-stabilised by the film producer or the flexible-circuit manufacturer so that

⁵ Gilleo, K. B. (ed.) (1992) *Handbook of Flexible Circuits*, Van Nostrand Reinhold, New York

⁶ Gilleo, Ken, Bob Boyes, Steve Corbett, Gary Larson and Dave Price (1999) High volume, low cost flip chip assembly on polyester flex, *Circuit World*, 25 February, 11–17

very little shrinkage will occur at ink- and adhesive-processing temperatures of up to 150°C.⁷

PTF inks consist of a mixture of a polymer binder, such as polyester, epoxy or an acrylic, and a finely granulated conductive material such as silver or resistive carbon. Alternatively a blend of both silver and carbon may be used. The ink is applied directly to the base laminate without the use of a resist, often in a single-step operation. This capability makes PTF a very low-cost process and it is considered more environmentally friendly because it negates the need for laminate stripping, cleaning and treatment, as would be required with other ways of applying conductors.

Aside from the environmental benefits, PTF inks have been demonstrated to have a flex life that is similar to that of copper foil of equal thickness. The most commonly used metal for filling PTF inks is silver. Whilst silver metal has one of the highest conductivities of all metals, the conductivity of silver-filled polymer inks is relatively low, six to sixty times more resistive than copper metal (7–50 milliohms per square at 25 microns thickness versus approximately 0.9 milliohms per square for 25 microns copper). PTF inks are also difficult to solder to using conventional means. Connections with PTF circuitry is usually made via pressure contact using a conductive adhesive, as is the case with keyboards and touch pads.

The relatively low-cost and versatility of the PTF approach, combined with an upsurge in the use of conductive adhesives for circuit interconnection, has made PTF a much researched technology.

3.3.4 Emerging Direct Apply Technologies

The benefits of PTF technology has spurred much research in the development of direct conductor application techniques. Emerging technologies that are considered good candidates for commercial applications include a number of printing techniques transferred from other industry sectors.

The company Extended Length Flex Technologies have patented a technique for producing long lengths of flexible circuits through the use of catalytic toners which can be electrostatically deposited onto a substrate material by means of a modified laser printer. The toner pattern produced can then be electroplated over with copper to produce an additive circuit-production method.

Other direct application methods include lithographic printing and using conductive or resistive inks. The process employs standard offset lithographic printing – used to

⁷ Gilleo, Ken, Bob Boyes, Steve Corbett, Gary Larson and Dave Price (1999) High volume, low cost flip chip assembly on polyester flex, *Circuit World*, 25 February, 11-17

produce books and magazines – to deposit electrically conductive traces onto a wide range of flexible media. Lithography ink deposition lends itself to high-volume production; a typical lithographic machine can perform between six thousand and ten thousand impressions per hour, and line thickness can be in the order of 3 microns, which compares favourably with the 50-micron line thicknesses achieved by screen printing of low-cost circuits.⁸

Table 4. Typical Conductor Applications

Conductor	Application	Rationale
Copper	95% of all flex circuits	Best balance of properties
Aluminium	Shielding for membrane switch and some circuits	Low-cost but adequate
Silver	Electrical contacts	High conductivity; oxide is conductive
Nickel	Low heat-resistance circuits or components	Easily welded
Gold	Conductor and contact plating	Maintains very low plating electrical resistance
Stainless steel	Resistance heaters, high-stress applications	High strength; corrosion resistant
Phosphor bronze	Corrosion resistant contacts, integrated springs	High corrosion resistance, good elasticity
Beryllium-copper alloys	Springs	Good electrical, durable spring
Copper-nickel	Corrosion resistant circuits or heaters	High corrosion resistance, lower conductivity
Nickel-chromium	High-resistance circuits	Low conductivity
Polymer Thick Film	Low-cost switches and circuits.	Simplified additive processing
Toner/lithographic Inks	Low-cost switches and circuits; high volumes of circuits	Long lengths of circuits; economical manufacture of single circuits

Source: Gilleo (1992)

3.4 Adhesives

Adhesives play an important role in flexible circuits. They are used to provide a secure join between the substrate and the chosen conductor material, to join circuits together

⁸ Evans P. S. A. (2001) Lithographic film circuits – A review, *Circuit World*, 27 March

where multi-layer or rigid-flex constructions are required, and to provide a protective cover lay over exposed conductors once they are formed.

There are a number of methods for applying adhesives but generally they are coated onto the dielectric substrate and then laminated to the conductor foil. Depending upon the nature of the base this can be done via a heated press for sheet processed materials such as polyamides, or through heated rollers for roll-to-roll materials such as polyester. Some form of post curing at elevated temperature is usually required after roller lamination due to the relatively short contact time between roller and laminate.

Adhesives must be carefully chosen to offer compatibility with both substrate and conductor materials. They must be able to provide adequate mechanical strength, have good chemical resistance, and be able to withstand the conditions used in FPC manufacture without delamination. Typical adhesives systems used for flexible-circuit manufacture include:

- Polyester
- Polyimide
- Acrylics
- Epoxies
- Fluoropolymers
- Phenolics

It is also important that adhesives act as part of the dielectric packaging of the signal, power, and ground circuit traces. They determine a fundamental part of the circuit's electrical behaviour. Adhesives are typically available in a range of thicknesses from 0.5 mil to 5 mils in 0.1 mil increments.

It is often the case that the chosen dielectric material determines the type of adhesive used. For example, polyester adhesives are typically used with polyester laminates, and new formulations of high-temperature polyimide adhesives are increasingly used for polyimide substrates.

Importantly, developments are ongoing within the industry regarding the commercialisation of adhesiveless laminates, in which the substrate material and conductor layer are intimately joined without adhesives. Such laminates allow for improved environmental performance because it is often the adhesive layer that is the limiting factor in high-temperature applications. Developments in this area will be covered in more detail later in this report.

3.4.1 Polyimide Adhesives

Polyimide adhesives are thermoplastic materials, their high-temperature performance capabilities, withstanding temperatures as high as 500°C, has made their use and

development attractive within the defence, aerospace and satellite sectors. Projects are underway to develop commercial systems at the likes of NASA, Rogers Corporation (USA), NEC (Japan) and others. Aside from providing matched performance with polyimide substrates used for demanding flex-circuit applications, the adhesive also has a very low coefficient of thermal expansion, which makes it a good choice for use in demanding multilayer circuits.

The downside to the material is its high cost and the limited sources of supply. Proven processing experience with high commercial-scale volumes of flexible circuits using polyimide adhesives is currently limited.

3.4.2 Polyester Adhesive

Polyester adhesives are low-temperature thermoplastics. They are relatively low-cost materials and can be processed using low temperatures. Their drawback is that they exhibit poor high-temperature performance and have relatively low bond strength. However, modified polyester adhesives are available that have better high-temperature properties and high flexibility and can withstand many soldering operations.

Polyester adhesives are widely used in applications where polyester is the dielectric substrate material, and where the application itself does not present extremes of temperature or forces that will significantly stress the circuit. **Error! Reference source not found.** enumerates the four main types of adhesives used in flexible-circuit construction. These will be reviewed in brief.

3.4.3 Acrylic Adhesive

Acrylic adhesives are thermosetting materials and have a higher resistance to soldering conditions than polyesters and modified epoxies. The materials are relatively low cost and their ease of processing and low flow characteristics during coating have made them a popular choice for flexible-circuit manufacture.

On the downside, the material does have a higher coefficient of thermal expansion and higher moisture absorption than polyesters and epoxies, which means that it can swell during processing. Flexible laminates with acrylics are generally available in sheet form, which can significantly increase the cost of FPCs made with acrylics. However, acrylic resin systems are being developed and marketed that offer better performance for roll-to-roll processing.

3.4.4 Epoxies and Modified Epoxies

Epoxies and modified epoxies are the most widely used adhesives for rigid circuit boards. They possess excellent resistance to high temperatures and modified grades offer excellent bond strength and material compatibility.

They are generally less flexible than other adhesive systems but they can be modified by the addition of other polymers, like polyesters, to increase their flexibility.

3.4.5 Other Adhesives

In developing flexible circuits to meet their applications, designers have used many varieties of adhesive materials. A number of these adhesive systems have enjoyed commercial success in other areas of electronics production and have been transferred over to flex by designers familiar with their capabilities and performance.

Examples of other adhesives include phenolics, which have been used in TAB (tape automated bonding). The material also demonstrates very low flow characteristics which reduces the risk of the material migrating to cover neighbouring connection lands and circuit pads. They are thermosetting materials and have physical properties similar to epoxies. Fluoropolymer-based adhesives are also used and offer a good range of electrical and mechanical capabilities over diverse environmental conditions. Their main drawback is their relatively high cost.

Table 5. Properties of flexible-circuit adhesives

PROPERTY	Polyimide	Polyester	Acrylic	Mod.-epoxy
Peel strength lb/in:	2.0–5.5	3–5	8–12	5–7
After soldering:	no change	?	1–1.5 x higher	variable
Low-temp. flex	All pass IPC-650 2– 8. 18 @ 5+			
Adhesive flow	< 1 mil	10 mils	5 mils	5 mils
Temp. coeff. of expan.	<50 ppm	100–200	350–450	100–200
Moisture absorption:	1–2.5%	1–2%	4–6%	4–5%
Chemical resistance:	good	fair	good	Fair
Dielectric constant @ 100 kHz:	3.5–4.5	4.0–4.6	3.0–4.0	4.0
Dielectric strength: kV/mil:	2–3	1–1.5	1–3.2	0.5–1.0

Source: Gilleo (1992)

3.5 Adhesiveless Laminates

As discussed previously, adhesiveless laminates represent a new emerging class of base material for flexible circuits. Today many flexible circuits consist of a base film and

foil bonded together with an adhesive. Industry experience, research and product histories have shown that it is often the adhesive used in flexible circuits that is the principal limiting factor in many of the circuit's capabilities. The performance of the adhesive chosen hinders high-temperature performance in particular but also chemical resistance and multilayer build capability. For example, the relatively poor thermal expansion characteristics of adhesives causes excessive expansion problems in multilayer circuits, which causes stress in conductors and delamination of fine circuit features if unchecked. Adhesiveless materials avoid all of these pitfalls by doing away with the adhesive layer.

Adhesiveless laminates are manufactured in a number of different ways. A thin coating of seed conductor material, typically copper of less than 1 micron, may be placed directly onto the base laminate via techniques such as sputtering and electroless plating. These thin surface layers can then be selectively electrodeposited up to the required circuit thickness, and finally the whole circuit is given a flash etch back to remove the web of copper connecting the circuit traces to produce the final circuit. This manufacturing process is termed semi-additive and it will be discussed further in Section 5. Overall, additive circuit manufacturing processes produce less waste and can generate extremely thin circuit tracks suitable for high-density circuits.

Alternatively, the base laminate material, such as polyamide, may be cast in resin form onto a carrier foil, such as copper, and when processed through heated rollers and allowed to cure, forming a continuous adhesiveless laminate suitable for further processing.

Driving the market uptake of adhesiveless laminates is demand for complex high-speed circuits that are capable of operating at higher temperatures and frequencies. These must make use of multilayer construction techniques. In this regard an adhesiveless copper-polyimide, for example, will be more suited to the application, and has the added advantage of being thinner.

Traditional foils adhesively bonded to base films are proving too thick for high-density circuitry. Also the extra copper thickness associated with adhesively bonded laminates requires extra processing time to etch back and is less environmentally friendly. Adhesiveless copper-polyamide laminates are now offered with thicknesses ranging from 0.3 microns to about 35 microns, with the thinner material proving much more suitable for fine line circuitry.

Since coming onto the scene in the mid 1980's, adhesiveless manufacturing techniques have improved, as has appreciation of their worth. They have now captured a significant proportion, some 10%, of the flexible-circuit market and research into their development and future potential is ongoing.

3.6 Protective Coatings

Protective films or coatings may be selectively applied to the surface of FPC to protect it from moisture, contamination and abrasion, and to reduce conductor stress during bending. The protective layer is placed over the circuit once the conductor pattern has been established.

3.6.1 Cover Lays (Cover layers)

A cover lay (also known as a 'cover layer') is usually a combination of a flexible film and a suitable pressure-sensitive or thermosetting adhesive. The most commonly used materials are polyester film coated with polyester adhesive, polyimide film with acrylic adhesive, and polyimide film with epoxy adhesive. As stated, in circuit design the usual practice is to match the cover-lay film to the material of the base substrate.

The purpose of a cover lay is threefold: to provide circuit and conductor protection; to allow access to circuit pad and contact areas for further processing such as soldering and conductive adhesive bonding of components; and to enhance circuit flexibility and reliability.

To enable access to required conductor features beneath the cover lay, such as pads and contact points, registration holes are drilled, punched, or laser machined into the film. The cover lay is then registered over the conductor pattern and laminated using heat and/or pressure according to the adhesive's requirements.

To reduce conductor damage from frequent bending, the thickness of the cover lay should be the same as the thickness of the dielectric layer. This arrangement places the conductor traces near the neutral axis of the finished circuit assembly, in effect in the centre of the layered construct, which significantly reduces conductor stress during flexing.

An increasingly popular alternative to pre-punched and drilled adhesive films is the photoimageable cover lay. A layer of light-sensitive material, either in film or liquid form, is placed over the top surface of the conductor trace layer. The layer is exposed to light through a photographic negative that acts as a mask, selectively exposing areas of the film to the light. The light-sensitive coating cures in the exposed areas and subsequent processing strips uncured material to leave a patterned covering which provides access to contact pads and soldering lands.

3.6.2 Cover Coatings (Cover Coats)

'Cover coating' is a broad term denoting a growing range of thin coatings applied to flexible circuits instead of cover lays. Such coatings are usually applied in liquid form via techniques such as screen printing. This allows access features to be generated at

the stage when the coating is applied. The coatings are then rapidly cured thermally or by exposure to UV radiation.

Cover coats are best suited to applications where no or minimal flexing is required as, unlike thicker cover lays, they do not protect the conductor layer to the same degree for flexing-induced forces. Typical cover-coat materials are acrylated epoxy and acrylated polyurethane, both of which are applied as liquid polymers, are solvent free, and are rapidly cured by exposure to UV.

4.0 Flex circuit Market and Applications

The diversity of flexible-circuit design is indicative of the numerous applications to which the technology has been applied. It is clear that flexible-circuit technology is suited to a wide range of circuit applications where rigid board technology is currently used. As circuit designers and engineers become more familiar with the capabilities of FPCs it is anticipated that the technology will begin to make serious headway in the heartland of rigid-circuit applications.

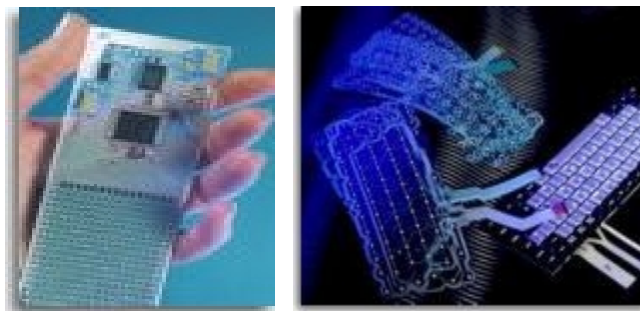
4.1 Market

According to the report *"World Market for Printed Wiring Boards and Substrate Materials,"* by the IPC Technology Market Research Council (TMRC), world production of printed wiring boards (PWB) and flexible circuits reached a record high of US\$42.7 billion in 2000. Japan ranked number one in 2000, producing the most rigid PWBs in the global market with 27%, followed by the United States, 25%, Taiwan, 11%, China/Hong Kong, 9%, and South Korea, 5%.

The same report also comments that global flexible-circuit production has grown significantly, reaching \$3.9 billion in 2000. The IPC states that the figures were generated by input from industry experts, manufacturers and organisations around the world. Accordingly, the flex-circuit world market in 2000 was also led by Japan, accounting for 36% of production, followed by the US producing 28%, Taiwan, 7%, Thailand, 6%, and Germany, 4%.

In general terms the largest single usage of FPCs, more than a third of all sales volume, is in computers, a category which includes peripheral equipment, such as printers and scanners. There is also a large consumption of FPCs in ink-jet cartridges and similar consumables.

Figure 5. Calculator touch pad and keyboard



Source: Polyflex Circuits Inc.

The second biggest application sector is the automotive, where FPCs can be found in many locations from the relative calm of the dashboard to the more demanding under-bonnet, where engine management and control and ABS control systems are to be found. Automotive applications account for a fifth of the market.

Telecommunications, including mobile phones, pagers and all manner of communications infrastructure equipment, accounts for a further fifth of the market. The remaining areas of the market are typically low-volume applications for defence or aerospace, principally high-tech, in the form of very expensive but indispensable flexible and hybrid circuitry.

4.2 The Benefits Of Flex

By far the biggest drivers for flexible-circuit technology are the range of benefits and capabilities that the technology offers. Some of the advantages of flexible printed circuits are highlighted in Table 6.

In the face of increasing industry challenges and consumer demands such as miniaturisation, lightweight products, lower cost, greater product design freedom, high reliability and more environmentally extreme applications, flexible circuits are proving their worth.

There are many advantages to using FPCs. They utilise the thinnest dielectric substrates available for electronic interconnection, down to 0.002", and are known for their ability to reduce package size as well as package weight. FPCs can reduce the weight of an electronic package significantly – by up to 75%. This weight reduction makes flexible circuits extremely popular in the aerospace industry. Another advantage of FPCs is assembly costs. Reduction of assembly costs is achieved by reducing the number of

assembly operations and having the capability to test the circuit prior to committing it to assembly. A properly designed flexible circuit is an excellent means of reducing the number of levels of interconnection required in an electronic package. Flexible printed circuits can eliminate wiring errors associated with hand-built wire harnesses, since it is

Table 6. The benefits of FPCs

Cost Reduction
Elimination of wiring errors associated with manual wiring harnesses
Simplified assembly
Reduction in component numbers
Reduced assembly effort and time
Increased reliability
Performance
Dynamic flexing
3D packaging
Excellent control over transmission impedance
Lower inductance than conventional wiring
Improved heat dissipation
Improved airflow capabilities
Compliant substrate for minimising thermal mismatch
Others
Reduced weight
Reduced assembly size
Convenience of roll-to-roll processing
Increased package density
Improved product appearance/aesthetics
More integrated design
Source: PERA

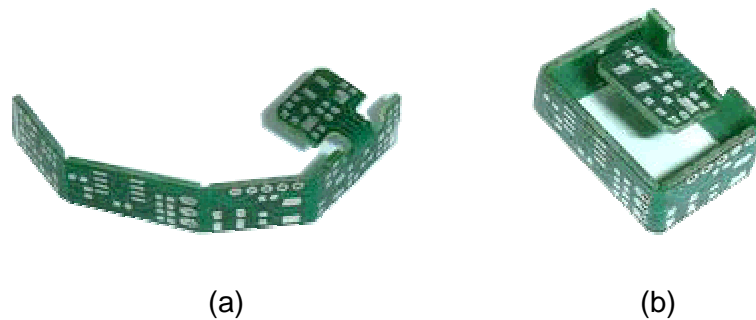
not possible to route flexible printed circuits to points other than those designated in the artwork.

Developments within the field of electronic components are also positive developments for flexible circuits. The growth in surface mount technology (SMT) and the development of conductive adhesives, used to attach such components to circuit boards at relatively low temperatures, has favoured the use of flexible substrates. Such components are highly sensitive to thermal mismatch between substrate, mounting and component materials. It is recognised that flexible circuits offer a highly compliant material that is able to counteract the effects of thermal stress with more success than rigid laminates, making their use in environmentally taxing conditions highly appealing.

4.3 Applications

There are currently two basic use categories of flexible-circuit applications, flex-to-install and dynamic operation. As the names imply, flex-to-install applications, which represent the majority of use, are those that require the circuit to be formable at the time of assembly, to fit into a product with maximum ease.

Figure 6. Assembly of flexible circuit



A single-sided flexible circuit for generating a 3D interconnection to minimise space requirements (a) as produced and (b) after assembly (Courtesy of Lyncolec Ltd)

Dynamic applications are those that make full use of the circuit's dynamic capabilities, often resulting in applications that require many thousands of flexing operations throughout the circuit's lifetime. Examples of such applications include typewriters and printers, where the requirement is for a connection between a moving element and its control system.

Within the consumer arena, the major application currently demanding the greatest dynamic flexing applications is in the area of computer disk drives, where the read-write head tracks along the surface of the hard disk. This highly demanding application requires billions of flexing operations of the products life and so requires a highly reliable interconnect between the head and its control module.

Figure 7. Printer flexible circuits



The major application within computer printers – the interconnect between the printing head and its control system
(Source: Polyflex Circuits)

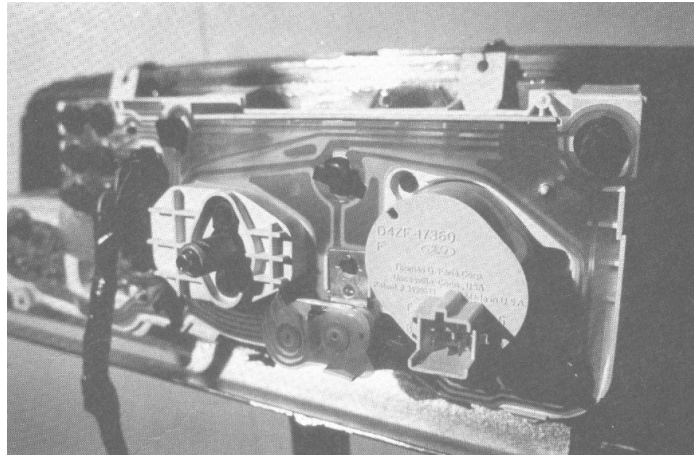
4.3.1 Automotive

Polyester substrate and copper-conductor-based flexible-circuit constructions have been utilised for high-volume instrument-cluster wiring and interconnections for over twenty-five years. Indeed, the automotive instrument-cluster market was one of the original, flex-to-install, volume drivers for the flexible-circuit market. Such circuits are used to deliver both power and connectivity to instruments mounted on vehicle dashboards, including lighting, power, sensor connection and touch buttons.

In the early years automotive cluster circuits were single-sided and of low complexity. They could be accurately formed by die stamping. However, the modern trend within vehicles of incorporating an increasing array of sophisticated sensors and the general proliferation of automotive electronics has turned dashboards into electronic nerve centres. Current designs of dashboard-based instrument-cluster flexible circuits can typically consist of a number of interconnected layers, with greater circuit area to handle increased power requirements.

The major growth in in-vehicle electronics is a significant area of opportunity for FPC technology. It is anticipated that in 2002, 30% of a car's price will be accounted for by its electronic equipment, notably antilock brakes, air bags, electric windows and power steering. The growth in driver safety and maintenance features such as ABS and engine management and control requires the application of flexible interconnects and circuitry in increasingly new and more demanding environments. Under-bonnet applications are on the increase, where circuits are exposed to temperature extremes, chemical contaminants and dirt and an environment sensitive to, and generating a lot of, electrical interference.

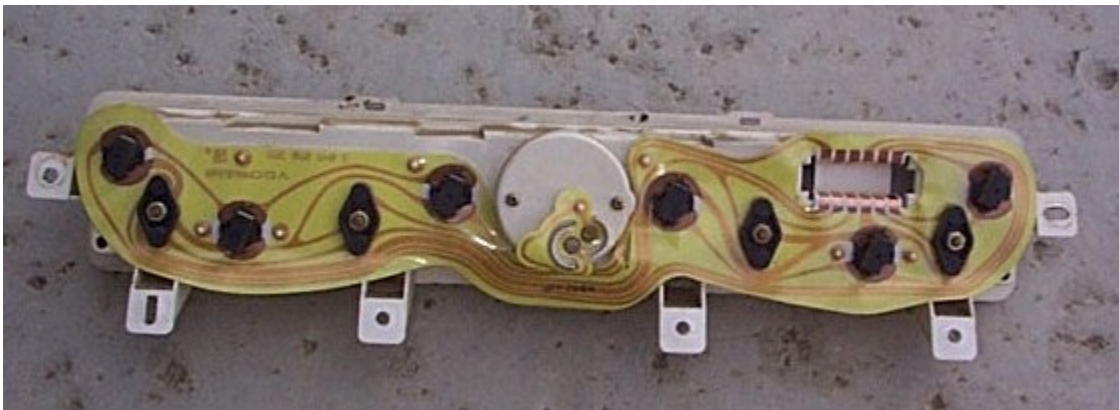
Figure 8. Instrument cluster



Source: Gilleo (1992)

The original volume growth of automotive circuits was met by low-cost polyester circuits of relatively low technology. An increasing call for circuits that are required to form more safety-critical functions in an environment where they are exposed to extremes of temperature, aggressive chemicals and high levels of dirt has led to the adoption of more robust circuit constructions and base materials.

Figure 9. Automotive dash flexible circuit



<http://www.lyncolec.co.uk/case-studies/hybrid.htm>

Source: Polyflex Circuits Inc.

The scope of the potential for flexible circuits within the automotive arena can not be underplayed, and the technology is seen as key to reducing the complexity of modern vehicle assembly, reducing assembly errors and meeting increasing demands for low weight, low cost and reliable connectivity. These demands are set to escalate as the vehicles are forecast to contain an increasing array of electronic automotive systems.

A report on the North American Printed Circuit (Single, Double Sided Flexible PC Market, Multilayer Flexible PCB) market published by Frost & Sullivan in February 2001

predicts that the US automotive market for flexible circuits has grown at a compound rate of over 13% over recent years. This trend is forecast to continue until 2006. More detail is contained within Table 7.

Table 7. Flexible-circuit market for the US automotive industry

Total Single/Double-Sided Flexible-circuit Market For The Automotive Industry: Revenue Forecasts (US) 1996–2006		
Year	Revenues (\$ Million)	Growth Rate (%)
1996	83.0	–
1997	97.4	17.4
1998	114.4	17.5
1999	135.2	18.2
2000	151.9	12.3
2001	170.9	12.5
2002	190.3	11.3
2003	219.1	15.1
2004	251.3	14.7
2005	287.7	14.5
2006	331.5	15.2

*Compound Annual Growth Rate (2000–2006) 13.7%

Source: Frost & Sullivan

The automotive sector makes extensive use of wiring in harness for a variety of on-vehicle control applications. The length of cable used varies significantly from motor vehicle model to model, with 500 metres in the Fiat Punto, typically some 1,600 metres in an S-Class Mercedes and up to 2 or 3 kilometres in a larger BMW. For some vehicles the figure for copper-cored cable is increased to five kilometres by multiplying the length of multi-core cable by the number of cores enclosed within a wiring sheath.⁹ Typical automotive applications of wire and cable are shown in Table 8.

Current wiring-harness technology is finding itself increasingly strained as it struggles to cope with the increase in on-board electronics. Even the task of routing numerous wires around a modern vehicle is becoming a challenge. Also, as vehicle manufacturers find themselves increasingly driven by regulation and legislation regarding recycling vehicles and better vehicle fuel economy, greater attention will turn to FPCs, which use less raw material, are easier to recycle, reduce weight and offer a reliable low-cost interconnection method.

⁹ Cousins, Keith (2000) *Polymers for Wire and Cable*, RAPRA

Table 8. Automotive applications of wire and cable

Engine	
Special cables	ABS
Winding wires	Starter/alternator
Coils and transformers	Starter/alternator harness
Optical bus	Fibre-optic control
Power source	Electric vehicles
Microsystem	Injection
Interior / Exterior	
Special cables and sensors	Air bags
Winding wires	Electric windows, seats
Printed circuits	Dashboards
Harnesses	Air conditioning, lighting
Antenna	Radio/mobile phone
Lighting fixtures	

Source: Cousins (2000).

4.3.2 Telecommunications

Telephone handsets have utilised flex-to-install FPC technology for many years, the principal advantage being that FPCs are well suited to the cured design of handsets and offer a low-cost, reliable circuit technology.

Flexible circuits can be found in a whole range of telecommunications equipment from low-cost fax machines, where they deliver low-cost interconnectivity, to automated switchboards, where they afford significant space saving and, through the use of multilayered circuits, a high degree of connectivity.

Significantly, Flexible boards and laminates have greatly benefited from the explosion in cellular technology. Sales of polyester and polyimide flex circuitry in the telecommunications sector amounted to \$56 million and \$471 million, respectively, in 1998.

Within mobile phones, flexible circuits have been employed to solve many of the technical problems that have enabled the technology to keep pace with changing customer and designer demands. Initial applications of flexible circuits in mobile phones were in touch-pad type applications. At the time, button keypads were being replaced with backlit pliable dome buttons, and polyester flex circuits combining the

attractions of low cost and transparent substrate were employed to provide electrical connectivity.

Flexible circuitry can be found in the rechargeable battery packs that power many phones, where it proved an effective way to regulate discharge in nickel metal hydride and lithium ion batteries. In this regard, not only did flex circuits simplify battery-pack assembly, but they also reduced cost and gave designers an easy way to locate fuses, typically on the flex circuitry itself.

As mobile phone screens and LCDs have become more complex, showing an ever greater amount of information, the increasing demands for more inputs and outputs has led to the application of flex circuits to link screens to their driver chips and power supply. Again, designers have saved space, improved reliability and lowered assembly complexity by locating components directly onto the flex substrate. Materials of choice revolve around polyimide due to its strength and ability to accept soldered components.

A further widespread use of flex circuits is for internal and external antennas for handsets. Low-cost polyester flex has been found to be an innovative technology for their production in the face of the tough challenge of improving transmission range while reducing exposure of the user to stray radiation.

Various grades of low-cost polyester laminates are used for antenna construction, and their flexible and lightweight construction make them ideal for flex-to-fit placement within the phone housing. Flexible-circuit tracks and circuit traces have the ability to effectively channel radiation patterns. They can maximise signal effectiveness while keeping radiation away from the user. In external applications the circuits are often coated with a protective rubber or plastic material, to produce a desired antenna shape.

Overall, flexible circuits have evolved to meet many of the major challenges faced by the functionality and miniaturisation requirements experienced by the mobile phone industry. Whilst the use of flex has become advantageous for some aspects of phone design, it is considered essential in delivering the functionality and durability required of both phone, PDA and laptop designs that incorporate hinged flip lids. Previously, only RA copper circuits were considered capable of meeting the demands for many thousands of flexing operations over the lifetimes of such products. However, the developments in adhesiveless laminates with the same level of flexing and durability have been eroding RAs stronghold in the market.

4.3.3 Aviation

Large quantities of cables are used in aircraft. Typically Airbus models have 70–100 kilometres of cable while helicopters require over 12 kilometres of cable.¹⁰ The

¹⁰ Cousins, Keith (2000) *Polymers for Wire and Cable*, RAPRA

importance of the sector, in wiring terms, is underlined by the recent moves of automotive harness manufacturers into this lucrative market.

The FPC applications within the aviation sector are almost exclusively based on polyimide film with copper conductors. The aviation sector and in particular the defence sector were pioneers in the development of flex-rigid boards, which offer the advantages of both rigid and flexible circuits.

Within the aerospace sector flexible-circuit technology has come into its own, driven by the aerospace market's stringent requirements for both reliability and extreme environmental performance.

However, given the Asian financial crisis and the events of September 11th there has been a significant downturn in the sector, which is experiencing restructuring on a global scale. The market is not expected to recover the levels it reached prior to September 11th for some significant time.

5.0 Manufacturing and Design of Flexible Circuits

The design and manufacture of flexible circuits demands production techniques and a design approach that are significantly different from those used for their rigid cousins. The development of a successful flexible circuit requires an approach that combines mechanical and electrical disciplines to produce the end product. It is this combination of disciplines that more often than not leads to ambiguity in the circuit's design, which in turn comes back to haunt developers as expensive manufacturing problems later on in the production cycle.

In this regard it is essential to take the best path and consider all of the relevant options during circuit design to avoid future problems. As with any design and development approach, consideration of manufacturing requirements will be critical if tolerances are to be held, standard materials and processes used, and costs kept low.

5.1 Manufacturing Flexible Circuits

The manufacture of flexible circuits is a highly variable process, with the inherent design flexibility offered by FPCs resulting in many combinations of manufacturing stages for the basic types of circuit constructions.

Some of the keys processing steps for flexible circuits have a high degree of similarity with the manufacture of their rigid counterparts. One of the most significant differences between the two is the amenability of flexible circuits to roll-to-roll processing. As discussed, this approach bestows a significant number of processing advantages on flexible circuits in terms of their high-volume manufacture and low circuit cost. However, as discussed roll-to-roll circuit manufacturing raises distinct production problems, specifically the required accuracy of image registration and difficulties with holding circuit tolerances given the material's ability to expand during processing and its susceptibility to changes in web tension.

Given the number of basic flexible-circuit constructions it would be impractical to discuss all of the various forms of manufacture. For more detailed discussion of these requirements a number of excellent publications exist.^{11,12,13}

The discussion here has been restricted to the major processes associated with flexible-circuitry manufacture and seeks to highlight some of the essential differences between the production of rigid and flexible circuits. It is anticipated that significant

¹¹ Fjelstad, Joseph (1997) *Engineer's Guide to Flexible Circuit Technology*, State Mutual Book & Periodical Service Limited, NY (ISBN: 0901150347)

¹² Gilileo, Ken (1992) *Handbook of Flexible Circuits*, Chapman & Hall, London (ISBN 0-442-00168-1)

¹³ Fjelstad, J. (1998) *Flexible Circuit Technology*, Silicon Valley Publishers Group, Sunnyvale, CA (ISBN 0-9667075-0-8)

opportunities are evident in the area of flexible-circuit manufacture and design that may stand to generate significant business opportunities if identified and exploited.

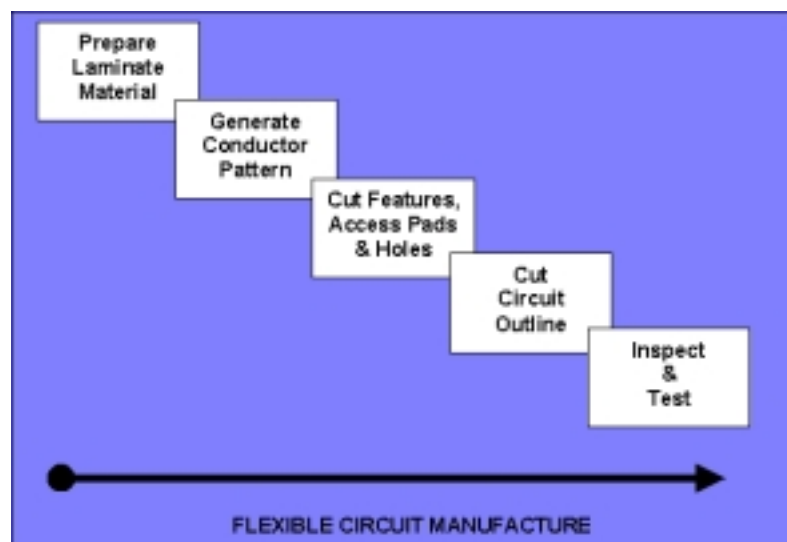
5.2 The Manufacturing Route

It is not surprising to realise that some of the most widely used manufacturing processes in flexible-circuit production have been imported and adapted from the most popular techniques used to manufacture rigid boards. Circuit designers, familiar with the constraints and advantages of rigid-board manufacture, have adapted techniques to the needs of flexible circuits. This factor, along with the widespread use of copper as the conductor material of choice, has meant that established techniques such as electroplating and PTH have successfully migrated to the flexible world.

In considering the process stages for flexible-circuit manufacturing the requirements of a single-sided circuit will be exemplified. The production of double-access and multilayer circuits requires the use of increasingly sophisticated manufacturing techniques and involves additional process stages. Where these involve technologies or process steps that are well established and considered of interest, they will be touched upon in the following discussion.

The broad process stages of single-sided circuit manufacture are shown in Figure 10:

Figure 10. Basic manufacturing stages



Source: Pera

5.2.1 Clean the Laminate

The typical starting point for circuit manufacture is a copper-clad laminate. This may consist of a base material with an adhesive-bonded copper layer or it may be an adhesiveless laminate as previously outlined. There are a variety of reasons for

cleaning the laminate prior to processing. Copper- and foil-clad laminates will most likely be provided with an anti-tarnish treatment on their surface, placed there by the laminate or foil supplier to prevent oxidation and tarnishing. This coating is detrimental to further processing and so is removed by dipping in an acid bath or using an acid etching spray. The exposed foil can then be micro-etched, typically with a treatment of sodium persulphate, to promote resist adhesion. Finally, after a suitable rinse, the board is usually coated with an in-process oxidation agent to prevent tarnishing during further operations.

5.2.2 Image Resist

A pattern is generated to reflect required circuit traces. The two most widely used techniques are screen printing and photoimaging.

Screen printing is an established technique that can deliver deposits on the laminate surface of 4–50 microns in thickness. Control of the screen printing process can be an art form as there are many variables such as deposit (liquid resist) consistency, screen tension, application squeegee profile and screen geometry. In screen printing the desired resist pattern is printed directly onto the laminate.

Photoimaging is typically undertaken using a dry photoresist film that is applied to the entire laminate surface. A photomask, consisting of artwork depicting the desired circuit traces, is placed in close contact with the film resist. The assembly is exposed to UV light which hardens the resist where it is unprotected by the mask. The uncured resist is then chemically removed to reveal a patterned laminate.

5.2.3 Etch the Exposed Conductor

This stage aims to remove the unprotected conductor material to leave a selective conductor pattern on the laminate surface. The resist previously applied is impervious to a selected etchant. This etchant removes the copper in a controlled process, as in the initial cleaning stage. The laminate may be exposed to the etchant by dipping, in an etch bath or by being sprayed with the etchant solution. It is accepted that a spray etchant process allows for the generation of finer line tolerances with straighter edges on circuit traces; dip etching undercuts the circuit traces.

5.2.4 Resist Removal

The resist, having performed its function in protecting the required circuit traces is now removed via a separate chemical or mechanical processing stage.

5.2.5 Cover-Lay or Cover-Coat Placement

It is undesirable to have a circuit where the conductor pattern is vulnerable to scratching and electrical shorting via accidental contact with the conductor layer. In this regard a protective dielectric film or coating is placed on top of the exposed conductive tracks to prevent this, stopping environmental ingress and maintaining electrical integrity.

5.2.6 Produce Holes and Outline

One of the penultimate manufacturing stages is to produce the required circuit outline and any through-laminate holes. A number of manufacturing techniques can be employed at this stage. One of the most popular is die cutting, which consist of a male and female set of tools in a punch press. Modern die cutting machinery offers highly accurate outlining of both circuit outlines and holes, and various tooling arrangements can be developed to deliver precise cutting for both sheet and web-fed materials.

A less costly alternative is the use of a steel rule die, which use a series of punches and blades held in a low-cost wooden or plastic base. This technique offers less accuracy than die cutting and significantly lower tool life. However, it does offer a rapid tooling approach for lower-volume production and a relatively low cost. The cost of steel rule dies is typically between one-tenth and one-third that of die cutting tools.

5.2.7 Test and Verification

The final stage in successful flexible-circuit manufacture is test and verification of circuit performance and quality against the set specification.

Table 9 outlines the key process stages for the three main manufacturing routes. Two generic process routes exist for generating an accurately patterned circuit on a suitable laminate material – additive and subtractive. Subtractive processes, as outlined in the manufacturing stages above, are the most popular route, growing from their use within the rigid-board electronics industry.

Table 9. Flexible-circuit manufacture

Additive Printing Processing	Subtractive Etching Processing	Additive Plating Processing
Clean the laminate	Clean the laminate	Clean the laminate
Print circuit pattern	Apply the image resist	Apply the image resist
Cure	Etch conductors	Plate the conductors

Additive Printing Processing	Subtractive Etching Processing	Additive Plating Processing
Cover coat/cover lay	Strip resist	Strip resist
Cut holes	Cover coat/cover lay	Etchback/flash etch
Die-cut outline	Cut holes	Cover coat/cover lay
Inspection and test	Die-cut outline	Cut holes
	Inspection and test	Die-cut outline
		Inspection and test

Additive processes are under development and are used by a number of manufacturers. In additive plating, the starting material is typically an adhesiveless laminate possessing a very thin layer of exposed conductor material over its entire surface. A negative resist image is applied to the laminate, one that leaves the desired conductor paths exposed. This exposed area is then subjected to an additional plating operation that builds up conductive material in the unprotected areas. The resist is removed and the assembly is given a final flash etch to remove the original thin conductor layer, thus electrically isolating the built-up conductive tracks.

The main advantage of the additive process is the general agreement that it results in circuits that have improved performance over subtractive circuit manufacturing. This performance differential is due mainly to the advantage that additive plating removes the need for an adhesive layer between the conductor and the substrate, which typically limits performance at higher temperatures. Additive plating also allows the reproduction of finer circuit tracks because of the way the track are formed.

Whilst a number of manufacturers are unfamiliar with the additive plating process it is anticipated that the popularity of the technique will grow alongside the demand for greater circuit density and the use of adhesiveless laminates.

6.0 Flexible-Circuit Design

With their higher line density, improved impedance control, lighter weight and greater reliability, flexible circuits can be designed for a range of applications beyond the scope of traditional cabling and connectors. Often, flex circuitry is the only design option available that can provide a required combination of interconnect density, and electrical, mechanical and environment performance.

The discussion below lays out some of the basic rules for beginning the process of specifying flexible circuits. It is by no means a definitive guide and further detailed guidance is widely available from sources highlighted in Section 8. Further advice can also be obtained by communication with a chosen flexible-circuit manufacturer.

6.1 Basic Design Rules

Many years of heartache, woes and lost profits have served to harden the flexible-circuit industry to the invariable teething problems that accompany the introduction of new technologies. Basic rules of thumb have evolved that help to minimise design costs and improve manufacture.

- Avoid using non-standard base dielectric material thickness and adhesiveless laminate, both of which would entail special orders. Dielectric material and adhesiveless laminate come in standard sizes. Consult the chosen FPC vendor at the earliest stage of the design process and take the time to study the design guides that major flexible-circuit manufactures have compiled to showcase their products against their competitors'.
- Careful consideration should be given to manufacturing tolerances. It is expensive to request levels that approach the limits of the tooling used and it will potentially result in a significant number of rejects. For example, steel rule dies, used to produce circuit outlines and trim laminates, can hold 0.010" but specified allowances should be 0.015". Go tight on tolerances only where it is absolutely necessary to the functioning of the final circuit.
- Leave sufficient clearance between the edge circuit trace and the circuit outline. This error has been responsible for many circuit failures, not leaving enough clearance in the case of circuits for dynamic application circuit may prevent adequate cover-lay adhesion and promote delamination of the circuit material at the outline. Minimum distance should be in the region of 0.010". Similarly, the edge of any stiffener materials should be pulled back from the final circuit outline. It is advantageous to select a stiffening material that is easily punched. Moulded stiffeners are expensive to fabricate but are commonly found in computer hard disk drives. Tooling holes should be placed within the area to ensure easy registration of the stiffener to the circuit.

6.2 Implementation Recommendations

There are few general implementation recommendations that can be of great assistance to those seeking to implement flexible circuits for the first time. For newcomers to the technology the first major step is the realisation that flexible circuits can help.

Information is usually the second step, seeking a source of flexible-circuit knowledge that can verify any initial finding and help advance the process from potential use to design reality. There is no doubt that among the best sources of such knowledge are flexible-circuit manufacturers themselves.

There are very few generic rules when it comes to flexible-circuit design, which is understandable given the variety of the material, process and assembly options available. There are good-practice guidelines that will help ensure that the design process starts off on the best possible footing.

Awareness of Standards

The list of standards that relate to flexible-circuit design, manufacture and testing is growing all the time thanks to the efforts of organisations such as the IPC. It is recommended that guidance be sought from these publications, which represent an invaluable source of information on all aspects of circuit design and manufacture. Some standards of interest are listed below. It should be noted that these are continually updated and checking for current versions is recommended.

- IPC-FC-231 Flexible Bare Dielectrics for Use in Flexible Printed Wiring
- IPC-FC-232 Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Wiring and Flexible Bonding Film
- IPC-FC-241 Flexible Metal-Clad Dielectrics for Use in Fabrication of Flexible Printed Wiring
- MIL-STD-2118 Design Guide for Flexible and Rigid-Flex-Rigid Wiring
- MIL-P-50884 Flexible Printed Wiring Assemblies

Information on standards may be sought from the organisations identified in Section 8.0

Manufacturer Consultation

Identifying, contacting and involving a flexible-circuit manufacturer at the earliest stage possible can add value to the design process. At the least, the manufacturer will be an excellent source of data on the latest laminate and adhesive options available. With material advances within the industry continually advancing it is important that

advantage be taken of any new developments. Design effectiveness is highly dependent upon a good knowledge of material capabilities and properties, as well as price.

During the important design process the circuit should be assessed for manufacture. As highlighted, initial items to note are edge distances from trace to the edge of the circuit, air gaps, pad encapsulation, connector line quality, circuit construction, stiffeners and materials.

Encompassing Development Team

The development of flexible circuits entails both mechanical and electrical expertise, which may be beyond the skills of a traditional rigid-circuit designer. Examples of circuit success stories have shown that a team approach produces the best result, such teams incorporating a wider scope of design expertise, including elements of production.

Reduce Conductor Stresses

It has been proven that a laminate that incorporates the conductor layer at its centre neutral axis offers improved life and flexing performance over 'unbalanced' circuit constructions. Placing the conductor layer at the centre minimises the dynamic stress it experiences during flexing and can improve time to failure by a factor of ten.

Reducing bend stress is critical to circuit flexing performance. As a rule of thumb, designers should use ten times the thickness of the finished board as the bend radius. Designers have developed various techniques for thinning boards including staggering circuit traces, i.e. not overlapping copper layers, thinning cover lays, and thinning and flattening conductor traces to provide extra flexing potential (see Figure 11).

Specifying the grain direction of the conductor foil is also an issue. Bend lines and direction should be indicated on drawings, and a note should be added on the most applicable foil orientation to give the required grain direction.

Document and Drawings

It is important that the fullest clarity is used in conveying the design to the vendor and for design and manufacture evaluations. The method of describing a flexible circuit or a rigid-flex-rigid circuit on a fabrication drawing should be similar to the conventional method of documenting a rigid PCB. All dimensioned outlines should be drawn in the 'unflexed' view. There are exceptions and where drawings must detail a circuit that will be folded during assembly it is appropriate to provide a view of the circuit *in situ* to

help convey to the vendor the areas that must be compensated to achieve an unstressed circuit.

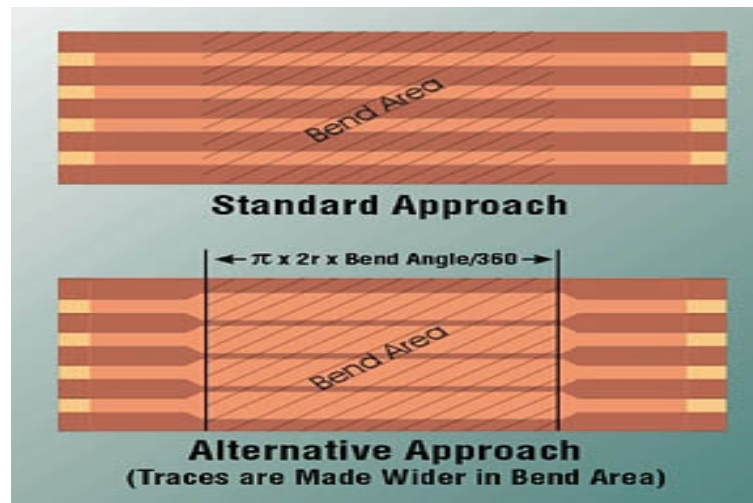


Figure 11. Bend stress reduction

Source: Fjelstad (1999)¹⁴

6.3 Costing Flexible Circuits

It is difficult for any justification of a switch to a new technology, such as flexible circuits, not to consider principally the cost implications and assess the potential savings that may result from change. From an initial perspective flexible circuits offer cost-saving opportunities over traditional rigid circuit board assemblies and can typically reduce costs by 20% to 70% through the elimination of wiring errors, meeting space restrictions, reducing inspections and simplifying assembly.

A point to be borne in mind is that many of the inherent advantages of flexible circuits, such as simplified assembly and reduced errors, are system-level advantages. Therefore it is important to note that often, for a given application, the cost of a single flexible circuit will be more expensive than a rigid counterpart. However, the system-level benefit of moving to flexible circuits in terms of design freedom, flexibility, dynamic performance, reliability and reduced errors, represent the real opportunity to derive value and generate savings.

Simple break-even calculations can be applied to gauge the relative advantage of moving to flexible-circuit technology. To complete such calculations requires an assessment of the recurring and non-recurring costs associated with an application – no simple feat. By way of example, consider a typical scenario in which a wiring

¹⁴ Flexible Circuitry – technology background and important fundamental issues. Joseph Fjelstad. (1999). Circuit World. 25 February, 6-10. ISSN 0305-6120.

harness is replaced by a flexible-circuit alternative. For such a situation the factors for consideration in determining cost are as laid out in Table 10.

Table 10. Costing flexible-circuit applications

Break Even Costing Of Flexible Circuits	
Flex Circuit NRE	Wire Harness NRE
Circuits layout Artwork Documentation Mock-ups Hard & soft tooling	Wiring diagrams Assembly drawings Harness assembly boards Potting moulds
Flex Circuit RC	Wire Harness RC
Unit price Inspect and test circuits Assemble and / or install Inventory	Wire inventory Cut, strip and mark wires Lay out wires on boards Solder wires to connector Test and rework errors Pot wires into connector

Source: (After Sheppler *et al.*)¹⁵

The required formula is:

<p>Break-Even Point Equals</p> <p><u>NRE (Flex) – NRE (alternative)</u> RC (alternative) – RC (flex)</p>

Key: NRE = non-recurring engineering costs
RC = recurring costs

¹⁵ Flexible Circuit Technology. (1998). J Fjelstad. Silicon Valley Publishers Group, Sunnyvale, CA 94087. ISBN: 0-9667075-0-8

7.0 Flexible-Circuit Technology and Process Trends

The flexible-circuit industry is highly dynamic in terms of new applications. There is a certain degree of maturity in some of the processes and materials that are currently the mainstay of the market. Many emerging applications are pushing existing materials and processes to their limits – sophisticated electronic assemblies, optoelectronic modules, liquid crystal displays, microelectromechanical systems (MEMS), disk drives and high-frequency circuits amongst others.

Those within the flexible-circuit sector have responded to market demands by developing new interconnection methods and fostering the development of new materials and new processes designed to meet the challenges ahead.

Currently there is much activity within the flexible-circuit arena that holds promise for improved flexible circuitry for new applications. Whilst developments are numerous, it is clear that certain developments will play a significant role in meeting market demands in the short to medium term by realizing new materials and new processes.

Major developments worth noting relate to new substrate materials, new cover coats, the development of micro-via technology and new manufacturing techniques. What is clear is that with each development, flexible circuits will continue to encroach upon the application areas currently the reserve of their rigid counterparts and that the traditional barrier that has divided rigid and flexible applications will crumble.

Comment is offered below on some of the most promising developments within the flexible-circuit sector, key areas of development identified are:

- Adhesiveless laminates
- Direct circuit application methods
- Cover lays
- Conductive plastics
- Chip-scale packaging opportunities

7.1 Adhesiveless Laminates

One of the most significant developments within the flexible-circuit market over the past ten years has been the growth and advance of adhesiveless laminates. These materials are an example of synergy between advances in new materials and new processes that have delivered functionality above and beyond initial expectations.

With the demand for greater interconnect density, the market penetration and development of adhesiveless laminates that offer higher levels of interconnectivity through finer conductor lines look set to continue apace. Currently the number of

adhesiveless laminate suppliers is small but growing. The challenge ahead for flexible-circuit manufacturers is to make the switch to the technology.

Such a move holds many industry challenges, not least to the expertise of designers in becoming more familiar with the materials, but also in production processes. These represent a radical departure for many production facilities which are biased towards sheet processes while the current mainstays of adhesiveless materials – polyesters and polyimides – are best manufactured by roll-to-roll processing.

It is predicted by some that the unavoidable advantages of adhesiveless material technology will undoubtedly lead to its use in both PWB and FPW constructions and an elimination of the distinction between these two industries. It is anticipated when this change occurs that there will be an order-of-magnitude increase in the utilisation of flexible circuits because of the enormously large and well established PCB market. Market analysts have concluded that equipment for producing adhesiveless laminates in roll-to-roll format is of such efficiency that there is enough existing capacity to service any increased market demand for the first few years of high growth.

7.2 Direct Apply Technologies

New techniques for circuit manufacture are continually evolving. Among the more promising production routes are the direct printing of conductor patterns. The hunt is on for processes that marry the distinct advantages of technologies such as PTF with high-density interconnection capability. Direct PTF-type production of conductors offers cost advantages over the expensive plating and etching processes widely utilised today.

An intermediate direct-print technology of promise is an adapted laser printing technique, which directly deposits material onto the film substrate in the pattern required. The deposited material can then be plated over to deliver a final circuit.

There are a number of companies currently experimenting with techniques that enable flexible circuits to be made without the use of conductive or resistive metal foils through the use of inherently conductive plastics (ICPs).¹⁶

Examples of conductive plastics tailored to deliver specific conductivity are anticipated to revolutionise areas like display technology. It is not unexpected that such technology will find applications in the production of all-plastic flexible circuits that may offer advantageous performance characteristics, most likely by precisely matching material characteristics of conductor and substrate.

¹⁶ Strohmeier, Robert (2000) Flexible circuits - Roll out the next generation of hardware, *Smart Business for the New Economy*, 1 July

The concept of ICP is not new. PTF uses polymers that mimic the conductivity of metals (particularly copper and steel) by compounding into the resin conductive metal particles or resistive carbon powder. Whilst this achieves a measure of conductivity, there are always compromises in terms of manufacture, performance or total part economics.

Research into conductive plastics and polymers is longstanding. In the mid-1970s, the first polymer capable of conducting electricity, polyacetylene, was discovered. By the mid-1980s, the number of patents issued in the field of electrically conductive polymers increased significantly, and the first application, the polymer electrode, was registered.

By the mid-1990s, commercialisation of ICP was still in its infancy and production of these sometimes exotic materials has only been scaled up from grams to pounds. Whilst overall global production and consumption totals are still negligible hundreds of papers and many patents on inherently conductive polymers are published each year. There are a great many scientists and corporations who are optimistic about ICP's commercial potential.

7.3 New Substrate Materials

It is hard to believe that the current commercial dominance of polyimide and polyester materials could be radically altered by new material developments in the foreseeable future as it is very hard for any new material to penetrate the market significantly in the short to medium terms.

However, there are always new materials being offered to circuit manufacturers that offer incremental improvements in performance over existing material. Examples of polymers that have shown major improvements in dielectric or physical properties include Avatrel (BFGoodrich); PBO and PIBO (Dow), and liquid crystal polymers (LCPs) such as Vectra and Superex.

An area of intense research is that of LCP for flexible-circuit applications. In December 2001, 3M introduced their LCP dielectric film for flexible circuits that provides several enhanced properties required for demanding flex circuit applications. Principally cited were lower moisture absorption, 0.1% versus polyimide's 1–3%; an optimised dielectric constant; and higher tensile strength and tensile modulus.

7.4 Cover Coats: The Non-Cover-Lay Process

As discussed, cover coats are thin protective films that can be applied to circuits in preference to more sturdy cover lays. Their principal advantage is that their methods of application eliminate the need for some of the hole cutting and film/circuit alignment required with conventional cover-lay materials.

Cover lays, whilst proven for a wide variety of applications, generate dimensional uncertainties, which test their application with increasingly finer circuitry and high-density interconnect component assemblies. The cover coating is evolving and is set to take over wherever finely detailed and accurately registered openings are needed.

Photoimaging technology, which is also used to define the circuit traces accurately, offers higher levels of placement accuracy. Screen printing technology can also be used to deposit cover coatings with high accuracy. Overall cost is reduced because the materials are applied only where needed, the labour and material consumption involved in press lamination is eliminated, and the inherent cost of the coatings is less than the cost of a dielectric film with adhesive coating.

Like adhesiveless laminates, cover coatings remove the need for the adhesive used to bond protective cover lays. So, like adhesiveless laminates, they offer the potential for improved thermal performance and greater dimensional stability – circuit parameters that are hindered by the presence of an adhesive. With the uptake of adhesives laminates and their penetration into the mainstream flexible-circuit market, cover coat technology looks set to follow.

7.5 The Next Generation of Applications – Chip Scale Packaging

An expanding area for flexible-circuit technology is that of chip-scale packaging. A number of new circuit constructions are emerging that further demonstrate the ability of flexible technology to increase circuit density in unusual ways.¹⁷

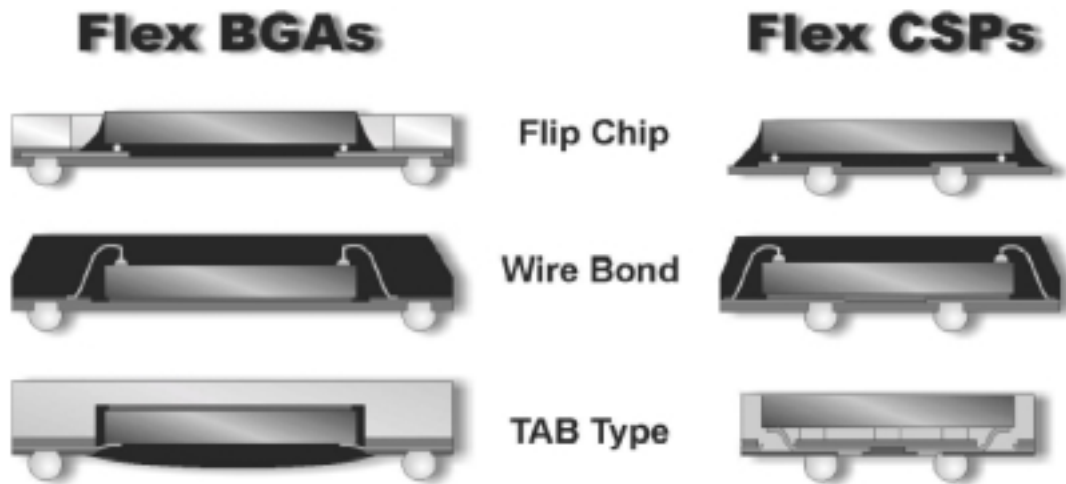
The most compelling application for flexible circuits may well be as an IC packaging medium, termed chip-scale packaging. Flexible substrates have clearly demonstrated that when married with SMT component technology they provide assemblies that can survive many more thermal cycles before failure than assemblies using rigid boards.

There are three primary ways of employing flex circuits to package integrated circuits in an area array format (see Figure 12):

- Attaching the semiconductor IC face-up on a flex circuit and wire bonding the leads to the leads on the flex circuit;
- Flipping the chips onto the flex substrate and joining them with solder followed by an underfill to protect the solder joints or by use of a conductive adhesive;
- Applying a flex circuit or flex film to the surface of the semiconductor IC face-down and interconnecting it to the die using an appropriate joining technique such as wire bonding or ribbon-lead connection.

¹⁷ Fjelstad, Joseph (1999) Flexible circuitry - technology background and important fundamental issues [online], Tessera, Inc., August 1999 [cited 9 May 2002], <http://www.tessera.com/pdf/Overview_Circuit_World.pdf>

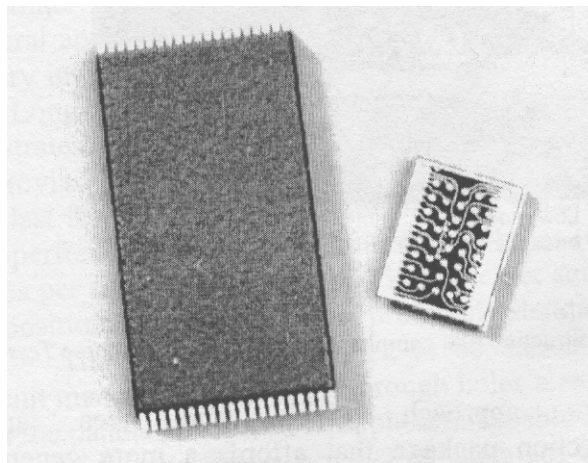
Figure 12. Flex in IC packaging



A popular substrate choice among package IC designers, flex circuits are being used in BGAs and CSPs assembled by three common technologies: flip chip, wire bond and TAB (or TAB-like in the case of the μ BGA[®] CSP at lower right).

The idea of utilising flexible laminates as a compliant interface for semiconductor packaging is not new. They were originally in use in the 1960s and 1970s. Developments in component technology in the interim, specifically SMT, have revived interest. Flexible circuits as semiconductor packaging are currently among the most active research areas of flexible-circuit application.

Figure 13. Packaging size reduction



Micro BGA chip-scale package (on the right) uses a miniature flexible circuit for direct interconnection to the silicon chip. It is shown next to the TSOP package it replaced.¹⁸

¹⁸ Fjelstad, J. (1998) *Flexible Circuit Technology*, Silicon Valley Publishers Group, Sunnyvale

8.0 Sources of Assistance

There are a number of associations and centres of research that specialise in the area of flexible circuits. A number of these organisations are particularly active in the commercialisation of FPCs through the provision of guidelines and standards relating to FPC quality and manufacturing requirements.

A number of organisations are detailed below which are in a position to provide further information on the subject of FPCs.

8.1 IPC - Association Connecting Electronics Industries

IPC - Association Connecting Electronics Industries
2215 Sanders Road
Northbrook, IL 60062-6135

Tel: 001 847-509-9700
Fax: 001 847-509-9798

Email: answers@ipc.org
Website: www.ipc.org

The IPC is a US-based trade association dedicated to serving the benefits of its members within the electrical interconnect industry. It is active globally in the development of standards and quality guidelines for the electronics interconnect sector, and represents the industry at a government and legislative level.

One of the most widely utilised IPC documents that relates to flexible circuit is available, free of charge, via their website:

IPC-6013 Qualification and Performance Specification for Flexible Printed Boards:
Amendment 1
<http://www.ipc.org/html/IPC-6013Amendment1Published4-00.pdf>

8.2 PCIF

PCIF c/o FEI
Russell Square House
10-12 Russell Square
London
WC1B 5EE

Tel: 020 7331 2035
Fax: 020 7331 2040

Email: cyarrow@fei.org.uk
Website: www.pcif.org.uk

The PCIF is a trade federation representing the UK PCB industry, an umbrella organisation representing the electronics interconnection industries in the global marketplace. It was formed in 1988 by the ICT and PCA as a means of representing more fully PCB fabricators, their suppliers and individuals within the industry. The PCIF is now an integrated part of the Federation of Electronic Industries (FEI).

8.3 European Institute of Printed Circuits (EIPC)

European Institute of Printed Circuits (EIPC)
PO Box 2060
6201 CD Maastricht
The Netherlands

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The European Institute of Printed Circuits (EIPC), based in the Netherlands, is an international service provider to the European interconnection and packaging industry. Since 1968, the EIPC has been servicing almost two hundred member companies, including suppliers of machinery and materials to the PCB industry, PCB manufacturers, contract electronics manufacturers and OEMs.

8.4 Molded Interconnect Device Association

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Website: www.midia.org/midialnt.htm

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9.0 Conclusions

Flexible circuits represent a strongly growing sector of the electrical interconnectivity market. Thanks to the high level of demand for electronic products and the increasing penetration of electronic and electrical systems in the home, car and work environment, the need for interconnect and circuitry solutions that can meet a variety of demanding requirements will begin to favour flexible circuitry.

Flexible circuits offer a number of clear system-level benefits over rigid board technology. Factors such as weight reduction, mechanical performance and thermal compliance are becoming ever more important as electronic systems find themselves performing in ever more diverse applications and environments. Particularly key is the forecast growth in mobile electronics such as phones, PDAs, notebooks and portable DVD, which are pushing rigid circuitry beyond its current limits.

There is a clear shift away from the traditional wire-harness replacement of the past to more robust applications of the technology. This is being accompanied by a steady shift to high-quality commercial products and away from government/military production.

Materials of construction continue to be primarily polyimide with adhesively bonded rolled copper foil, but the application of adhesiveless systems is on the increase. With improved production of adhesiveless laminates and their availability from a wider range of vendors should come a greater penetration of their use in the flexible-circuit market. As discussed, adhesiveless systems offer a number of clear performance benefits over adhesively bonded laminates, which make them better suited to a range of demanding applications.

New materials and new processes promise to make flexible circuits an exciting area of future promise for those seeking innovative solutions to a wide range of interconnection problems. Whilst polyimide and polyester material will continue to dominate as the base substrates of choice, new material developments are underway that, as they evolve to greater commercialisation, look set to provide significantly more circuitry options. Specifically developments with LCPs and PEN look set to challenge conventional material wisdom. The growth of direct apply technologies such as toner printing and lithographic circuits also look set to offer improved manufacturing processes which may in turn open up new markets for this exciting technology.

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