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The engineer's guide to multi-layer flexible printed circuits (FPCs): technologies and applications

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The concept of flexible printed circuits (FPCs) originated in the early 20th century and, over the ensuing decades, FPCs have been adopted for use in a wide variety of industrial and consumer electronic products. FPC manufacturing techniques traditionally limited their length to less than one metre, but an innovation in the manufacturing process by Trackwise using their patented Improved Harness Technology (IHT™) has removed these restrictions, enabling many new applications. This paper reviews the definition, construction and benefits of FPCs, before looking at traditional and emerging applications.

Flexible printed circuit definition

The IPC, a global trade association serving the printed board and electronics assembly industries, defines an FPC as follows:

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

This definition can be expanded to describe the main elements or layers from which an FPC is constructed:

- A **dielectric substrate film**, or base material, provides both the base on which the conductive circuits sit and the mechanical properties of the FPC, e.g. flexing strength and durability
- **Electrical conductors** or circuit traces, which provide the electrical connectivity and performance characteristics required by the application
- **Adhesives** used either to bind the metal foil to the base material to create a laminate, or to bind layers of laminate material together in multi-layer FPCs
- **A cover lay or cover coat**, a protective finish applied to the surface of the FPC to protect against moisture, contamination and abrasion, and to reduce conductor stress during bending

[1] IPC-T-50M: Terms and Definitions for Interconnecting and Packaging Electronic Circuits, 26 May 2015.

Figure 1 shows a single-sided FPC, with a single conductor layer bonded by adhesive to a flexible base substrate and with a protective cover layer. In reality, there are several different configurations of FPCs, described in more detail later, including double-sided and multi-layer – but, whatever the configuration, the flexible laminate formed by the above materials serves as a simple wiring assembly or, after further processing, such as soldering components, as a final circuit assembly.

FPCs are further defined by whether they will be used in static or dynamic applications. In a static application, the flexibility is required only at the time of installation, e.g. to fit inside an awkward or confined area. In a dynamic application, the FPC will be required to flex many times during its operational life, such as in a printer cable or a car door hinge.

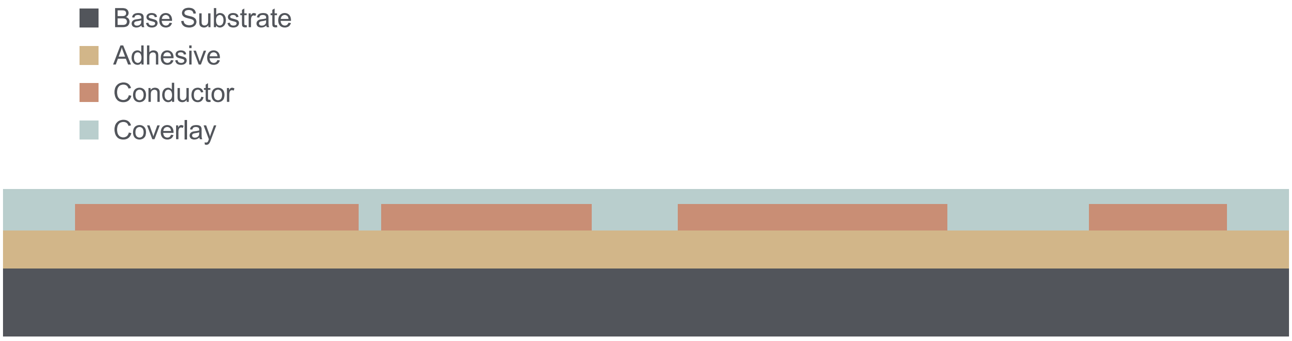

Figure 1: Basic FPC construction

(Source: *PRIME Faraday Partnership: Flexible Circuit Technology*, June 2002, ISBN 1-84402-023-1)

Evolution of FPCs

Today's industrial and consumer electronics products provide increased functionality in ever-shrinking enclosures. In response to the challenges of miniaturisation – demanding light weight, low cost, high reliability and greater product design freedom – designers are increasingly turning to FPC technology, owing to the range of benefits that it offers, as summarised in Table 1. The growth in surface-mount technology (SMT) has also favoured the use of FPCs, since they are better able to counteract the effects of thermal stress than rigid laminates.

The multiple benefits delivered by FPCs have driven their adoption in a wide spectrum of electronic and electrical products across a number of sectors, including automotive, consumer, medical, entertainment, IT and industrial equipment. In the automotive sector, they can be found in instrument panels as well as engine control systems. Consumer goods such as digital cameras, wearable exercise monitors, electronic games consoles and smartphones rely heavily on FPCs, as do a wide range of medical instruments such as hearing aids, pacemakers and insulin pumps. Perhaps the biggest users of FPCs to date have been the military and aerospace sectors, where they can be found in applications ranging from satellites, through smart weapons to jet engine controls. These are just a few examples which illustrate the widespread adoption of this flexible technology.

Cost reduction	Simplified assembly, elimination of wiring errors, reduced component count, higher levels of automation resulting in greater repeatability/precision and lower installation costs.
Electrical performance	Crosstalk, noise and electromagnetic compatibility (EMC) performance controlled by manufacturing characteristics of FPCs. FPC layer build constructions can provide lower inductance and lower radiated emissions than conventional wiring. Designing for better-controlled impedance is more easily achieved. Flat foil conductors within the FPC can dissipate heat better and carry more current than equivalent round wires.
Space and weight saving	FPCs provide for significantly improved packing density. Very thin dielectric substrates, some down to 25µm or less, coupled with their planarity, also make it possible to bond the circuits to, or within, the structure of a product enabling multi-functional structures. The corresponding reduction in weight is amplified as fewer connectors and fixings are required. Smaller conductors and reduced copper content make an additional contribution.
Versatility and reliability	Versatility: FPCs are custom-designed to fold, bend and fit into virtually any shape of housing. Reliability: Fewer interface connections increase reliability. Physically more resistant than rigid PCBs to vibration and shock. Higher operating temperature: thermal stability is better, particularly with polyimide materials, allowing the circuit to withstand more extremes of heat than rigid PCBs. Thermal mismatch is also reduced.

Table 1: Summary of FPC benefits

FPC construction

As discussed above, FPCs are constructed using different layers of materials laminated together, with the materials chosen to deliver a desired overall combination of electrical and mechanical performance. Six main types of FPC are commonly used (see Figure 2), each with specific characteristics and benefits, depending on the needs of the application.

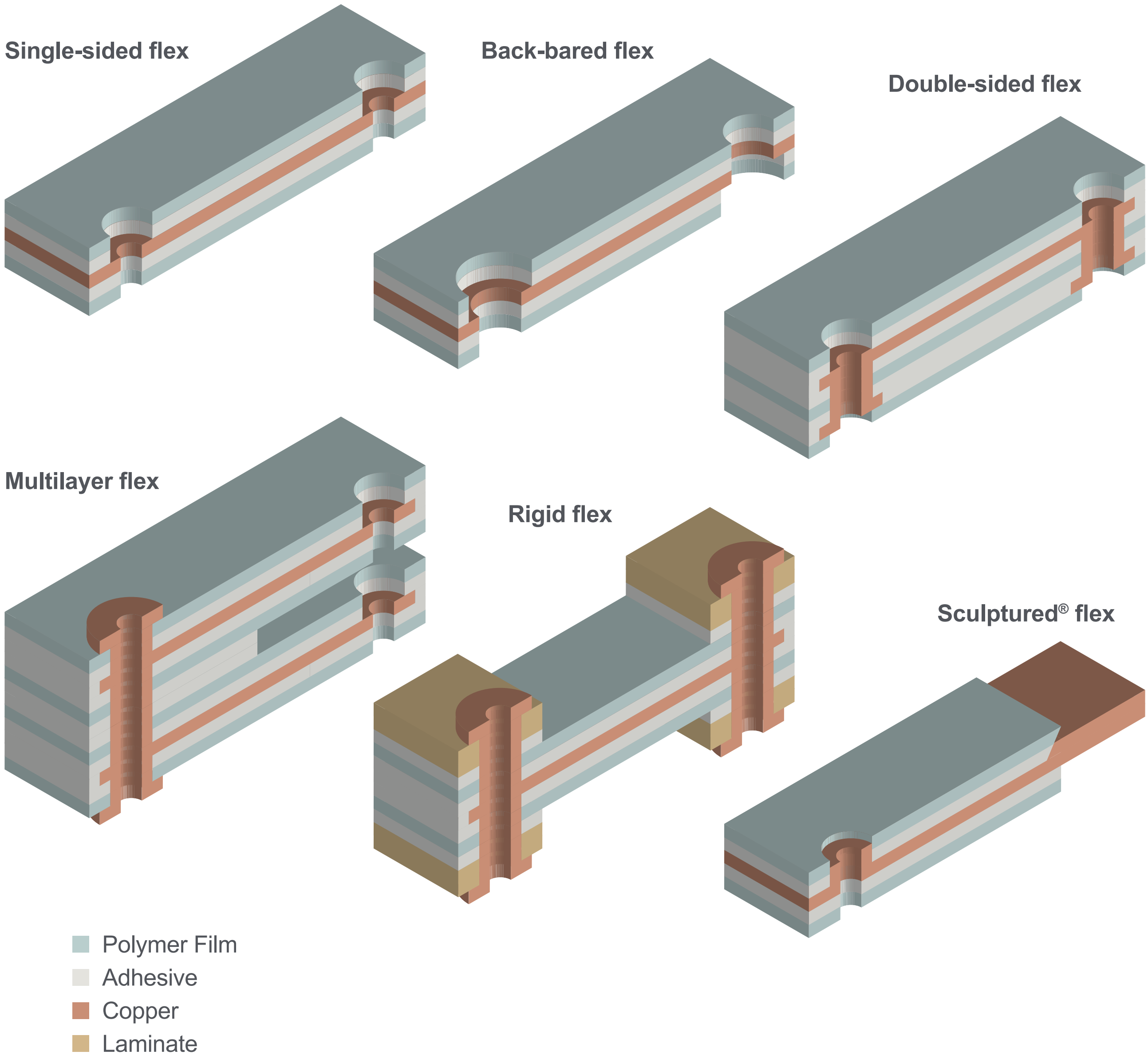

Figure 2: Six types of FPC

(Source: *Flexible Circuit Technology*, Fourth Edition, Joseph Fjelstad)

The six FPC types and their characteristics are summarised in Table 2.

Single-sided	• Among the most common types of flexible circuit available. • Single conductor layer, manufactured with or without cover lays/protective coatings and with circuit-termination features accessible from one side only. • Highly cost-effective due to relatively simple design. • Thin and lightweight construction makes them ideally suited to dynamic-flexing or wiring-replacement applications, e.g. computer printers and disk drives.
Double access	• Developed for applications requiring higher component density. • Enables placement of components on both sides of the flexible dielectric film. • Not widely used due to the relative complexity and number of process steps required in production.
Double-sided	• Very popular due to incorporation of multiple conductors on a single film, catering for applications requiring high circuit density and power-handling capabilities. • Constructed by various means, including conductors on both sides of the base film and printed conductors separated by printed insulating cover lays. • Inter-layer connectivity achieved using plated through-hole (PTH) techniques.
Sculptured flex	• Produced using a patented technique to give a varying-thickness conductor layer, with thin layers where flexibility is required, and thicker layers for joining and circuit interconnection. • Thicker layers typically form leads, protruding from the circuit, providing plug-in connectors or larger pads for improved solder joint formation.
Multi-layer flex	• Popular within the defence and aerospace sectors as they provide dynamic high-density circuits. • Three or more layers of conductors, consisting of bonded conductive layers interconnected by PTH. • Individual circuit layers may or may not be continuously laminated together, depending on required flexing and dynamic characteristics. • High construction costs and complexity offset by greater circuit density opportunities.
Rigid-flex circuits	• Hybrid constructions of rigid and flexible substrates laminated together, with the rigid circuits predominantly housing the components, and flexible circuitry providing interconnects. • PTH interconnects used where required. • Popular in the defence sector due to their combination of reliability, strength and flexibility. • Also used in a wide variety of commercial electronics applications including laptop computers and notebooks and, extensively, hearing aids.

Table 2: Summary of FPC types

A variety of materials are available for each FPC layer, which must be carefully chosen by the circuit designer, based on the electrical and mechanical performance requirements of the application. Typical selection criteria include the application's environment, costs, reliability requirements, whether dynamic or static flexing is required, electrical requirements and mechanical/connection requirements. The remainder of this section examines the options available for each of the layers in a typical FPC.

Base layer material

The base substrate insulates the conductive circuit tracks from one another and provides the mechanical properties of the FPC, such as flexing strength and durability. The base substrate must also be compatible with any adhesives used for conductor or cover-lay bonding to avoid thermal stress-related issues. Key base substrate properties include:

- 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 variety of base substrate materials have been used over the years, including polyimide, polyester, fluorocarbon films, and aramid papers and composites, and the relevant properties of all these materials are summarised in Table 3.

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 P=Poor VH=Very High H=High L=Low VL=Very Low

*Requires a special process

Table 3: Summary of FPC base substrate materials

(Source: *PRIME Faraday Partnership: Flexible Circuit Technology*, June 2002, ISBN 1-84402-023 -1)

In practice, polyimide and polyester are by far the most commonly used materials, with polyimides being chosen for 80–85% of applications, and polyesters making up most of the rest. Polyimides are resistant to the high temperatures generated by soldering, are highly flexible and retain their flexing and electrical properties across a wide temperature range. Polyesters are similar to polyimides in most ways, and can be easily drilled, punched, embossed, thermally formed, coated, dyed and otherwise modified at low cost, but have lower heat resistance than polyimides. Polyesters are common in high-volume, low-cost applications with less-demanding environmental requirements, such as smartphones and consumer goods.

Conductors

The properties of the conductor layer provide the application's electrical connectivity and performance characteristics and also determine the fatigue life, stability and mechanical performance of the FPC assembly. The choice of conductor 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. Polymer thick-film (PTF) ink-based additive processes are also used, as well as a number of printing techniques transferred from other industry sectors, such as lithography ink deposition. Table 4 provides a comparison of the various choices of conductor material.

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 sled	Resistance healers, high-stress applications	High strength, corrosion resistant
Phosphor bronze	Corrosion resistant contacts, intergrated springs	High corrosion resistance, good elesticity
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

Table 4: Conductor materials

(Source: *PRIME Faraday Partnership: Flexible Circuit Technology*, June 2002, ISBN 1-84402-023 -1)

Although there are a number of options for conductor materials, in practice copper is the most popular, with its relatively low cost, high workability, and good plating and electrical characteristics making it an excellent material for FPC conductors. IPC standard IPC-MF-150 ('Metal Foil for Printed Wiring Applications') details two main categories of copper – electrodeposited (ED) or wrought (W) – with four types of copper within each category. Broadly speaking, ED copper is most suited to static applications, whereas W copper has a much higher resistance to repeated bending and is therefore the material of choice for dynamic applications.

Adhesives

Adhesives in FPCs perform a number of important functions, including:

- joining the substrate and the conductor material
- joining circuits together in multi-layer constructions
- providing protective cover lays over exposed conductors
- contributing to the dielectric packaging of the signal, power and ground circuit traces.

Adhesives are chosen for their compatibility with both the substrate and conductor layers, as well as their ability to provide adequate mechanical strength and good chemical resistance. The choice is also based on the FPC manufacturing process, as the adhesive must be able to withstand processing without delamination. With sheet-processed materials such as polyimides, for example, the adhesive is generally coated on to the substrate and then laminated to the conductor foil by a heated press. With roll-to-roll materials, such as polyesters, the lamination is done using heated rollers.

The most common adhesives used in FPC manufacture include polyesters, polyimides, acrylics and modified epoxies, with each having their advantages and disadvantages, again depending on the application – see Table 5. Polyester adhesives are cheap but perform poorly at high temperatures and have relatively low bond strength. They are widely used where the substrate material is polyester, and in applications where there are no extremes of temperature, or forces that will significantly stress the circuit. Although more expensive, polyimide adhesives perform exceptionally well at high temperatures and are popular within the defence, aerospace and satellite sectors, particularly for demanding multi-layer circuit applications.

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	5mils	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	4-4.6	3-4	4
Dielectric strength kV/mil:	2-3	1-1.5	1-3.2	0.5-1

Table 5: FPC adhesive properties

(Source: *PRIME Faraday Partnership: Flexible Circuit Technology*, June 2002, ISBN 1-84402-023 -1)

Protective coatings

Protective films or coatings are applied to the surface of an FPC, once the conductor pattern has been established, to protect it from moisture, contamination and abrasion, and to reduce conductor stress during bending. Protective coatings may be in the form of cover lays or cover coatings.

Cover lays protect the conductor layer, allow access to circuit pad and contact areas for further processing (e.g. soldering), and enhance FPC flexibility. The most common cover lay materials are polyester film coated with polyester adhesive, polyimide film with acrylic adhesive, and polyimide film with epoxy adhesive, with the usual practice being to match the cover-lay film to the material of the base substrate. Conductor damage from frequent bending is reduced by making the thickness of the cover lay the same as the thickness of the dielectric layer, placing the conductor traces near the neutral axis of the finished circuit assembly.

Cover coatings cover a broad range of thin FPC coatings, usually applied in liquid form and rapidly cured thermally or by UV radiation. Cover coatings do not protect the conductor layer against flexing as well as cover lays, and are best suited to applications where no or minimal flexing is required. 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.

Emerging applications

Limitations in the size of FPC production equipment traditionally meant that very few companies were able to produce FPCs in lengths of more than two or three metres. Recent innovations in manufacturing techniques, however, such as Trackwise's patented Improved Harness Technology™ (IHT), are overcoming these restrictions, paving the way for a wide range of new applications.

Unlike conventional FPC manufacturing techniques, based on static process steps, IHT uses dynamic processes, based on roll-to-roll techniques, to enable the cost-effective production of FPCs of any length. Initial sectors benefiting from these new production techniques include the automotive, aerospace and telecommunications industries, where applications which previously required heavy and bulky wire harnesses can be transformed by FPCs.

Autonomous vehicle technology, for example, is beginning to 'trickle down' into modern cars, with features such as adaptive cruise control and navigation, and collision detection systems. In today's luxury car models this technology can require wire harnesses over a mile in length and containing up to 1,500 copper wires. The growing number of electric vehicles on the roads is also creating opportunities for FPCs produced using IHT, where high- and low-voltage harnesses for electric vehicle battery packs may be replaced by FPCs combining power, control and monitoring circuits. Similar opportunities exist in the aerospace industry, where flight-control and onboard systems are continuously developing, and more and more sensors are being added to modern aircraft.

These are all examples of applications where FPCs can bring significant space- and weight-saving opportunities. The IHT process can create FPC structures that are long enough to span aircraft wings and can be folded into the most inaccessible space within a modern automobile. IHT also enables electronic functionality, such as sensing and signal conditioning, to be integrated, effectively making the FPC a subsystem, with associated system-level benefits. FPCs have been shown to reduce weight by up to 75% over traditional wire harnesses; a key benefit in aerospace applications where weight is directly associated with operating costs and emissions.

Since the implementation of the IHT process, Trackwise has worked with a number of aerospace customers, shipping FPCs of varying lengths for applications, including a 26-metre-long multi-layer circuit for the distribution of power and control signals across the wings of a solar-powered, unmanned aerial vehicle (UAV). Based on a polyimide substrate, this FPC's planar structure dissipates heat better than conventional wiring, enabling higher current-carrying capacity for a given weight of copper conductor.

By using FPCs for the entirety of its interconnect system, the vehicle manufacturer has achieved an estimated 60% systems weight saving compared to a traditional wire harness, resulting in a higher payload and/or improved speed and range for the vehicle. The vehicle's assembly time and cost were also reduced as a result of the characteristics of FPC manufacturing, including circuit consistency and fewer connection points, leading to higher reliability and easier installation.

Figure 3: A 26m-long, multi-layer flexible printed circuit for a UAV

Key steps in FPC specification

From the discussion so far, it is clear that careful analysis and planning is required before embarking on any FPC implementation project. FPCs undoubtedly offer many unique capabilities, opportunities and benefits but, before proceeding, the designer should be sure that an FPC is actually suitable for the application. This can usually be determined through careful consultation with the manufacturer. Also, in order to ensure that the end product performs as intended, a particular design process should be followed, as detailed in Table 6, below. The output from this process will provide the specification required by the FPC manufacturer in order to validate the design and provide relevant quotations.

Design stage	Considerations
End product requirements	• Application details • Reliability and performance expectations • Cost targets • Product life expectancy • Size
Operating environment	• Temperature, pressure, vibration, abrasion, chemical exposure • Thermal cycles • Humidity
Package configuration	• Physical size and shape constraints • Connection methods – PTH, surface mount, flex-to-wire transitions • FPC dimensions: width, length, insulation and conductor thickness
Mechanical characteristics	• Flex requirement: flex to fit (remains static after installation), dynamic flex (required to flex in operation)
Electrical characteristics	• Data and/or power (low and high voltage), shielding • EMC performance, impedance control, arc compliance
Assembly method	• Brackets, soldering, welding, bonding, embedding into structure • Manufacturing limitations: minimum track size and spacing, minimum/maximum hole sizes, plated copper thickness tolerance, number of layers

Table 6: Example FPC design process

Further reading

IPC: The global trade association serving the printed board and electronics assembly industries, their customers and suppliers: **www.ipc.org**

PRIME Faraday Partnership: Flexible Circuit Technology, June 2002, ISBN 1-84402-023-1

*Flexible Circuit Technolog*y, Fourth Edition, Joseph Fjelstad, BR Publishing, Inc.

The First 105 Years of Flexible Circuitry, Ken Gilleo, PhD, ET-Trends LLC

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Trackwise manufactures specialist products using printed circuit technology. With a wide range of potential applications including telecommunications, aviation, automotive and defence, our products are exported around the world, including the USA, Australia, Europe and Asia.

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