The author and publisher would like to acknowledge and credit the many photo contributions of flexible circuit assemblies in this text which were generously provided by Lenthor Engineering of Milpitas, California. www.lenthor.com.
Flexible Circuit Technology

THIRD EDITION

by

Joseph Fjelstad
Flexible Circuit Technology
Third Edition

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# Table of Contents

**ACKNOWLEDGEMENTS** ................................................................. i

**FOREWORD** ........................................................................... v

**CHAPTER 1** Flexible Circuit Technology Overview ................. 1

**CHAPTER 2** Flex Circuit Drivers, Benefits & Applications ........ 9

**CHAPTER 3** Flexible Circuit Materials .................................... 41

**CHAPTER 4** Implementing Flexible Circuit Technology ............. 65

**CHAPTER 5** Practical Design Guidelines for Flex ...................... 75

**CHAPTER 6** Flex Circuit Manufacturing Processes .................. 117

**CHAPTER 7** Flexible Circuit Assembly .................................... 155

**CHAPTER 8** Inspection and Test of Flex Circuits ....................... 163

**CHAPTER 9** Documentation Needs for Flex Circuits ................. 179

**CHAPTER 10** Flex Circuit Specifications ................................. 185

**REFERENCES** ........................................................................... 193

**INDEX** .................................................................................... 198

**SPONSOR ADVERTISEMENTS BEGIN** ..................................... 199

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**FOR THE FIRST TIME, WITH THE GENEROUS SUPPORT OF THE FOLLOWING WORLD CLASS CORPORATE SPONSORS, THIS BOOK IS BEING MADE AVAILABLE FOR FREE TO HELP MORE RAPIDLY SPREAD THE ADOPTION AND IMPLEMENTATION OF THIS VITAL INTERCONNECTION MEDIUM.**

<table>
<thead>
<tr>
<th>SPONSOR</th>
<th>PAGE</th>
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<th>PAGE</th>
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</thead>
<tbody>
<tr>
<td>Rogers</td>
<td>199</td>
<td>Eltek</td>
<td>213</td>
</tr>
<tr>
<td>Lenthor Engineering</td>
<td>201</td>
<td>Mektec</td>
<td>215</td>
</tr>
<tr>
<td>Multek</td>
<td>203</td>
<td>Compass Technology</td>
<td>217</td>
</tr>
<tr>
<td>3M Electronics</td>
<td>205</td>
<td>Flex Interconnect Tech</td>
<td>219</td>
</tr>
<tr>
<td>Altaflex</td>
<td>207</td>
<td>Dyconex AG.</td>
<td>221</td>
</tr>
<tr>
<td>Dupont</td>
<td>209</td>
<td>Silicon Pipe</td>
<td>224</td>
</tr>
<tr>
<td>Tessera</td>
<td>211</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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Following our formal education, we inevitably become teachers and students of each other. Significant numbers of people cross our paths over the course of our careers, whether directly and in person or indirectly through the written word. Many have thus contributed to my education.

While it is not possible to acknowledge here all of the many mentors, coworkers and colleagues who have contributed to my experience and thus to the writing of this book, I will attempt to do so. For those I may fail to note, I ask your indulgence, but please know that you are acknowledged here with intent.
Foreword

This is the Third Edition of Flexible Circuit Technology—an updated and significant expansion over the previous editions. Achieving third-edition status based on demand extends credence that flexible circuits are of continuing value and enduring interest. Recalled here is the opening sentence to the very first edition: “The flexible circuit has been at the head of a quiet revolution in the world of electronic packaging, a revolution that has gone largely unnoticed, lost in the excitement of continued advances in semiconductor technology.” Much has changed in the decade since those words were first written for this book. Flexible circuit technology is now squarely in the sights of circuit designers around the globe and, even with the bursting of the dot com bubble, it has held fast and, in fact, the flex circuit market actually grew while other interconnection-technology markets receded.

Flexible circuits are now a key enabling technology for products ranging from simple consumer goods to spacecraft. They are critical elements in such diverse products as medical equipment, keyboards, hard disk drives, printers and cellular phones. Every day, flexible circuit technology opens doors to new opportunities for engineers and product and system designers to make a complete transition to the third dimension of interconnection. Short of wireless interconnections, flexible circuits also continue to provide the very best and most practical solutions to interconnecting electronic elements that must move relative to each other. These two important features — motion and three-dimensional interconnection — remain at the top of the list of key attributes of flexible circuits; however, there is much more on the horizon and more yet to come in the years beyond, with flexible circuit technology now opening new doors to the realm of high speed in the budding era of higher performance at reduced power.

While there is no universal solution in the world of electronic interconnections, flexible circuits come closer to being such than all others. The diversity of flex circuit applications remains bound more by the limits of the engineer’s imagination than by any other single factor. Flexible circuit technology requires a good foundation of understanding
in order to gain the greatest benefit from its use. Materials and processes must be understood, and design rules followed, if success is to be enjoyed consistently. Thus, the purpose of the authors, in this third edition of this book on flexible circuit technology, remains unchanged from the first edition—that is, to provide the reader with a solid foundation on which the practitioner can build their skills and understanding.

This edition is significantly expanded over earlier editions and takes advantage of advances in technology to provide the user with much more information than before. While more complete than earlier editions, this effort still does not represent itself to be an exhaustive treatise of the subject. Indeed, with a technology that moves as rapidly as flex, the best one can hope to do is to write about the state of the technology up to the moment of publication, after which time the text begins to drift into technology history. Nevertheless, this book is believed to be properly comprehensive and it is hoped that it provides an engaging introduction to the world of flexible circuitry.

As with previous editions, readers are advised to access the various design standards and specifications described and referenced in this text to complete their flex circuit reference library. In addition, many flex circuit suppliers have design guides specific to their processing capabilities that will often prove of value. Such additional materials will serve well to fill whatever gaps readers may experience in this book. If you are new to flexible circuits, you will no doubt find the field a rewarding one. Finally, readers are invited to send comments and suggestions as to how the book might be improved, for the better to serve the needs of future edition readers.

Joseph Fjelstad
September 2006
Flexible Circuit Technology Overview

INTRODUCTION

Flexible circuits are not new to electronics manufacturing. The technology actually has a surprisingly long and rich history. Patents issued at the turn of the 20th century show clear evidence that early researchers were thinking of how flat conductors sandwiched between layers of insulating material could ease the layout of certain, primitive types of electrical circuits in early telephony switching applications. Some very famous turn-of-the-century researchers and scientists apparently turned their thoughts to novel methods for producing electrical interconnections as well. For example, based on notes in one of Thomas Edison’s lab books, it appears that he envisioned the flexible circuit’s precursor. In the notebook, Edison responded to an inquiry from his technical assistant, Frank Sprague, (later founder of Sprague Electric) as to how one might put conductors on insulating materials. One of Edison’s suggestions was to use conductor patterns of graphite powder in cellulose gum applied to linen paper. There is no evidence that it was introduced into practice, but the idea is close in concept to polymer thick film circuits of today, which are common in a wide range of applications.

Significant production and use of flexible circuits in electrical or electronic applications seems to have been delayed until they were pressed into service during World War II, during which period German scientists were using flat conductor wiring harnesses, both in the gun turrets of tanks and in the V2 rocket. One story offered by US flex circuit pioneer Pat Bryan has it that a captured V2 rocket, used by US space-program researchers in the early 1950s, transported at least a portion of flex technology to the United States. Bryan, then working for Lockheed, took a piece of the circuit with him back to California to study and, ultimately, to employ in aerospace products.

Another important point of development was on the East Coast of the United States. Sanders Associates in New Hampshire, through the efforts of Victor Dahlgren and company founder Royden Sanders, made significant
in the same time frame, developing processes for printing and etching flat conductors on flexible base materials to replace wire harnesses. It appears, from advertisements of that time, that Photocircuits in New York was offering at least the idea of metal circuits on flexible base material (see Figure 1-1). Parlex was another early East Coast flex circuit manufacturer that became a leading supplier of flex to the military.

Growth and proliferation of flex circuit technology from that point was slow initially, but it has been accelerating ever since. Today, flexible circuits—which are also known around the world also as flexible printed wiring, flex print and flexi circuits and the acronym FPC—are used in nearly every imaginable type of electrical and electronic product. Much of the credit for the expansive use of flex circuits is due largely to the efforts of Japanese electronics packaging engineers who have found countless new ways to employ flex technology. Over the last several years, flexible circuits have remained one of the fastest growing of all interconnection-product market segments. Given the versatility of the technology, it is easy to forecast that flexible circuits will continue to attract increasing numbers of both users and manufacturers.

Flexible circuits represent a multibillion-dollar global market, with Japan—because of its application leadership—enjoying a significant market share. The USA, once a close second, has fallen behind in share as production continues to shift to China and other places in Asia and South Asia. The USA remains a high-technology leader in areas such as high-frequency applications.
While the growth of the flex circuit industry from its infancy has been impressive, it has not been without problems. Failures have been experienced and recorded by a substantial number of users of flexible circuits throughout the course of their history. Most troubled by failure have been those who have entered into the flex circuit arena not fully prepared. These new industry participants—manufacturers and users alike—often lacked the specific experience and knowledge needed to prevent the types of problems they encountered. The mistakes were, unfortunately, repeated by others until the lessons learned eventually became available to a broader base of participants. That experience has been codified and formalized in the standards, specifications and design guidelines we use today.

Thus, the primary objective of this book is to provide the basic knowledge required to begin designing, manufacturing and using flexible circuits while avoiding many of the potential problems. Further, it is hoped that the text will help to build a simple foundation from which it will be possible to advance the boundaries of opportunity for this highly useful interconnection technology.

The format of this book is designed to be simple. It is structured to take the reader in an ordered fashion through the key aspects of flexible circuit technology. The linear progression from materials to design and to manufacture and assembly is intended to enhance the reader’s understanding of flex circuit technology by building on each preceding layer of information, starting with the straightforward definitions that follow below.

From basic definitions, the book moves to matters that help to determine where and how flex circuits can best be used, and then on to key issues of materials, design practices, manufacture and assembly. It is hoped that this presumably logical progression through the various aspects of the technology will provide the best possible understanding of flex circuits. Hopefully, by the end of reading this text, the reader will understand not only where and when flexible circuits are best used but also how to employ
Flexible circuit technology to the best advantage, as well as many of the “ins and outs” and “ups and downs” of flex circuit design and manufacture.

The building of sound bridges of knowledge and understanding is a major intention of this book; thus, an assumption is necessarily made that a lot of basic information about flexible circuits is missing from the reader’s knowledge. Patience is requested from the more experienced reader as basic details are reviewed for the benefit of the new or prospective user of flexible circuit technology.

DEFINITIONS

While there are many ways of defining a flexible circuit, the most broadly accepted definition is the one that is found in the industry standard IPC-T-50 “Terms and Definitions for Printed Boards.” In that document, flexible circuits are defined as “A patterned arrangement of printed wiring utilizing flexible base material with or without flexible coverlayers.”

This is an adequate but overly simple definition and one that belies the breadth of flex circuit technology. The term actually requires significant amplification to embrace all aspects of the technology. The extra definitional detail brings a broader sense of meaning to the term flexible circuit. As a result, it is necessary to define flexible circuits further—not only according to their type of construction but also as to how they are used in their final application.

To extend understanding, one should know if the circuit will be used only for static application. These are situations where circuit flexibility is required only to install the circuit and fit it properly into its application. This first condition is common to most flex circuit applications. The other obvious condition is one wherein the flexible circuit will be dynamically flexed—a condition common to disk drives, hinges, printer cables & the like.

While dynamic applications come to mind first for most individuals, the number of such applications is much lower compared to static or flex-to-fit applications. Thus, describing the application of the flexible circuit is an important element of accurate flex circuit definition, and it is a vital piece of knowledge when it comes to flexible circuit design and use.

FLEX CIRCUIT TYPES AND CONSTRUCTIONS

There are a few basic constructions of flexible circuits, but there is some significant variation among the types in terms of their construction. Following is a review of the most common types.
**Single-Sided Flex Circuits**

Single-sided flexible circuits are, obviously, flexible circuits consisting of a single conductor layer of either metal or conductive (metal-filled) polymer on a flexible dielectric film. Component termination features are, by definition, accessible only from one side, but holes in the base film to allow component features to pass through are an obvious requirement. Single-sided flex circuits can be fabricated with or without such protective coatings as coverlayers, however, the use of a protective coating over circuits is the most common practice.

**Double-Access or Back-Bared Flex Circuits**

Double-access flex, also known as back-bared flex, are flexible circuits with a single conductor layer, but are processed to allow access to selected features of the conductor pattern from both sides. An example of such a feature would be a lead termination. While this type of circuit has a number of apparent benefits, it is not as commonly manufactured as single-sided flex circuits. This is because of the special processing required to provide access to the features discretely, although laser technology is certainly well applied to the task. Finally, it is important to note that TAB circuits have long taken advantage of the method, but their circuit features are accessed en masse.

**Sculptured Flex Circuits**

The term “sculptured flex circuit” is mentally engaging, and it is an interesting subset of flexible circuit technology. The process involves a special flex circuit construction method that yields a flexible circuit having finished copper conductors, the thickness of which vary at different places along their length. For example, the conductors are thin in flexible areas and thick at interconnection points. This method involves selective etching of thick copper foil to different depths in various areas of the circuit.

The method, patented by Advanced Circuit Technology, has often been used to create bare metal contacts, which protrude from the edge of the circuit to allow plug-in connection. The raised interconnection land also can serve to improve solder joint formation and enhance its strength as compared to normal, single-metal-layer flex circuits.
DOUBLE-SIDED FLEX CIRCUITS

Double-sided flex circuits are flex circuits having two conductor layers. They can be fabricated with or without plated through holes, though the plated through hole variation is much more common. When constructed without plated through holes, and connection features are accessed from one side only, the circuit is defined as a “Type 5” according to military specifications. It is not a common practice, but it is an option.

Because of the plated through hole, terminations for electronic components are provided for on both sides of the circuit, thus allowing components to be placed on either side. Depending on design requirements, double-sided flex circuits can be fabricated with protective coverlayers on one, both or neither side of the completed circuit, although as with all flex circuits, omission of a protective film rarely occurs.

MULTILAYER FLEX CIRCUITS

Flex circuits having three or more layers of conductors are known as multilayer flex circuits. Commonly, the layers are interconnected by means of plated through holes, though this is not a requirement of the definition, for it is possible to provide openings to access lower circuit-level features.

The layers of the multilayer flex circuit may or may not be continuously laminated together throughout the construction, with the obvious exception of the areas occupied by plated through holes. The practice of discontinuous lamination is common in cases where maximum flexibility is required. This is accomplished by leaving unbonded the areas where flexing or bending is to occur. This practice will be discussed in more detail later.
**Rigid Flex Circuits**

Rigid flex circuits are, most fundamentally, a hybrid construction consisting of rigid and flexible substrates that are laminated together into a single structure. They are then electrically interconnected by means of plated through holes. Unlike multilayer flex, use of plated through holes is typically a requirement for rigid flex products.

Over the years, rigid flex circuits have enjoyed tremendous popularity among military product designers. In more recent years, the technology has made inroads into the commercial world as well.

While often considered a specialty product for low-volume applications because of the manufacturing challenges, an impressive effort to use the technology was made by Compaq computer in the production of boards for a laptop computer in the 1990s.

Rigid flex boards are normally multilayer designs, but double-sided constructions having only two metal layers are possible as well. In fact, such two-layer rigid flex constructions have been used in the past in miniature form for medical applications. A wide number of variations is, of course, possible.

When it comes to discussion of rigid flex, a common point of confusion relates to products that are frequently referred to as rigidized flex. Rigidized-flex constructions are simply flex circuits to which a stiffener is attached to support the weight of the electronic components locally.

A rigidized or stiffened flex circuit can have one or more conductor layers. Thus, while the two terms may sound similar, they represent products that are quite different. The subject of stiffeners or rigidizers will be covered in more detail in a later chapter.

**Polymer Thick Film Flex Circuits**

Polymer thick film (PTF) flex circuits are true printed circuits wherein the conductors are printed onto a polymer base film. They are typically single-conductor-layer structures; however, two or more metal layers can be printed sequentially, with insulating layers printed between printed conductor layers. While lower in conductivity, PTF circuits have successfully served in a wide range of low-power applications at slightly higher voltages. Keyboards are a common application, but there is a wide range of potential uses for this cost-effective approach to flex circuit manufacture.
COMMON FLEX CIRCUIT CONSTRUCTION

Figure 1-4 Representative examples of basic and selected flexible circuit construction.

SUMMARY
Flexible circuits have a rich history and are extremely diverse in their nature. This diversity opens them to use in a wide range of applications, with new applications being developed on a regular basis.

It is hard to predict where the technology will go next; however, roll-to-roll processing is likely to play an important part. At the time of this writing, the US government through DARPA is funding a number of projects targeted to deposit transistors directly onto flexible substrates in a web. If successful, this effort will open the doors to a new generation of flexible circuit constructions.
**Flex Circuit Drivers, Benefits & Applications**

**INTRODUCTION**

Diversity is a hallmark of flexible circuits, and they are as diverse in their application as they are in their design. Flexible circuits have, for long into the past and continuing today, served in a wide variety of demanding applications. As an interconnection method, they are unmatched in terms of their versatility. The trend of wide usage is expected to continue as more and more engineers become familiar with flex circuit technology’s many benefits.

As mentioned earlier, the evolutionary path of flex circuit technology has not been challenge-free, and many early users suffered some setbacks. The first users of flexible circuits experienced difficulties and failures due to a combination of factors. For example, early flex materials were not of the same standard as they are today. This factor—combined with a general lack of fundamental understanding of the technology’s capabilities and limitations in terms of the product design and/or the design rules needed to assure success—made the development path rocky for some users. Fortunately for us, flex circuit technology survived its infancy to become the vitally important solution it is today in the arena of electronic packaging technologies.

Provided in Table 2-1 is a small sampling of the many markets and products that have been successfully served by flexible circuits, giving an indication of how pervasively the technology is being used today to solve electronic packaging problems.

**APPLICATION DRIVERS & BENEFITS**

There are a great many reasons for using flex circuits to make the interconnections in an electronic package. In some cases, such as dynamic flexing applications, the choice to use flexible circuits is an obvious one, driven strictly by the lack of any viable alternatives. However, there are many more subtle areas of opportunity to employ flexible circuits, and this has proven to be the real measure of their success.
Examples of Flexible Circuit Applications

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<td>Instrument panels</td>
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<td>ABS systems</td>
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Table 2-1 Flexible circuit applications are found in products of every type and in all of the basic electronic products markets.

Following, in no particular order, are some areas and instances where flex circuits have served to solve a difficult packaging problem:

**Reduction in package size**

Flexible circuits employ the thinnest dielectric substrates available today for making electronic interconnections. In some cases, it is possible to produce flexible circuits having a total thickness less than 50µm (0.002”), including a protective cover layer. As a point of reference, rigid material counterparts might be twice as thick, with, generally, the ruggedness afforded by flexible-base material substrates. While thinness is generally more attractive, it is the formability of flex circuits that enables a package-size reduction, and rigid materials may be a suitable choice if planar thickness is the only point that truly matters.
Reduction in package weight

A side benefit of thinness is light weight. Flex circuit materials can be very lightweight, owing to the fact that they do not employ reinforcements, which are characteristically higher in density than unfilled polymers. The result is that use of flexible circuits can, in some cases, reduce the weight of an electronic package significantly. For example, weight reduction of as much as 75% or more is possible, depending on the exact nature of interconnection technology that is being replaced.

The feature of light weight is one of the main reasons that flex circuits have remained so popular in aerospace applications over the years, but it is also an attractive feature in portable electronics, which now regularly compete on size and weight as well as performance and appearance.

Decrease in assembly time

Flexible circuits are an integrating technology. As such, they have an intrinsic ability to seamlessly integrate form, fit and function of a design into a single circuit. Because of this natural benefit, flexible circuits can offer an excellent means of reducing the time of assembly of a product. This feature is especially evident when point-to-point wiring is a requirement as a part of the final assembly process. While point-to-point wiring is, admittedly, no longer a commonly designed in-process step, engineering change orders are often performed in just such a manner, and flexible circuits can greatly improve the second operation assembly process.

Assembly cost reduction

Continuing the line of thought related to assembly time reduction,
assembly cost reduction is an easily reasoned extended benefit. Thus, it is clear that flexible circuits should have a significant impact towards reducing assembly cost over other methods, depending on the application.

The main reduction benefit is derived both from the ability to reduce the number of assembly operations required and from the user’s ability to construct and test the circuit completely prior to committing the circuit to assembly. This especially applies to wire harness replacement applications.

**Assembly error reduction**

While the design may be in error, a flexible circuit cannot induce errors of a human nature. Human error in hand-assembly is a constant risk. An area especially vulnerable is in the assembly of hand-built wire harnesses. With flexible circuits, all design features are controlled by the design itself. As a result, with the exception of process-induced errors in manufacturing, it is not possible to route circuits to points other than those designated by the circuit design.

**Increased system reliability**

Reliability engineers have always been quick to point out that, when an electronic package of any type fails, it most typically fails at some point of interconnection. Flexible circuits are ideally designed with an eye to reducing the levels of interconnection. As such, when properly designed and applied to an electronic packaging problem, flexible circuits should prove an excellent means of increasing reliability by reducing the number of levels of interconnection required within an electronic package or assembly.

**Point-to-point wire replacement**

A rule of thumb long employed in the flex circuit community suggested that a flex circuit should likely be used when more than 25 point-to-point wires were required. The number was somewhat arbitrary, but the underlying concept is important. It is, however, worth a moment to consider if flexible circuits are a viable alternative regardless of wire count.

As a part of the calculus, one must evaluate the desirability weighed against cost, application, product volume and other factors. Some product designers have found flexible circuits more cost-effective or otherwise desirable with as few as two or three wires. Still other applications are best served by wire harness technology, and force fitting flex into such applications is not advised. Figure 2-2 shows an example where a wire harness is a better choice.
Dynamic flexure of the circuitry

Dynamically flexing a circuit is one of the more commonly pursued applications for flexible circuits. While other interconnection solutions, such as flat-ribbon cable, have served the purpose of dynamic flexing satisfactorily in some applications, flexible circuits have generally proven superior as a standard method of making reliable interconnection between moving parts.

The thinness of base materials, coupled with the ability to use very thin copper foil, make flexible circuits the best candidate for dynamic flexing applications. This important topic will be discussed in more detail later.
CONTROLLED IMPEDANCE SIGNAL TRANSMISSION

Many base materials used in the manufacture of flexible circuits have some exceptional intrinsic electrical and mechanical properties. Key to signal transmission line creation is the materials’ uniformity in both thickness and electrical properties. Because of this, it is relatively simple to produce flexible circuits suitable for high-speed transmission line cable applications.

With such uniform materials, the only requirement for flexible circuit manufacturers is that they accurately etch the copper foil to achieve the desired characteristic impedance.

For the commonly selected value of 50 ohms microstrip structure, flex circuits are quite a good choice. Higher characteristic impedance designs and stripline structures tend to get rather thick in their construction, thus losing some of their flexibility. To overcome this problem, it is necessary to make the signal line widths of the transmission line cable quite small, and this can reduce overall manufacturability due to accuracy limits.

Fortunately for high-speed signaling, conductor loss is a lesser-order concern, and the dielectric properties of the circuit materials are of true benefit, as the signal propagates through the polymer rather than through the conductor—a phenomenon called the skin effect.

IMPROVED HEAT-DISSIPATION CAPABILITY

Flat conductors have a much greater surface-to-volume ratio than round wire. This extra surface area facilitates the dissipation of heat from the circuit. When compared to rigid-board constructions, the thermal path for flex circuit constructions is not only shorter, but also—owing to circuit thinness—heat can be effectively dissipated from both sides of the circuit.

With typical one- or two-layer rigid boards, the dielectric substrate is a thermal insulator inhibiting the flow of heat through it. That fact aside, rigid PCBs with heavy copper inner layers or metal cores can also be highly effective at dissipating heat.

3D INTERCONNECTION AND PACKAGING

Much has been written over the years, extolling the benefits of three dimensional interconnection structures. In recent years, there has been a surge in interesting 3D IC-packaging methods for system-in-package devices and, now, even the stacking of semiconductor wafers.

In earlier times, 3D interconnection was also of interest, and the advantages of injection molded boards to create three-dimensional interconnection structures has been discussed since the late 1970s. With flex circuits, such 3D benefits are an intrinsic quality and natural feature of the substrate. The truth is that some molded-board technologies employ
flex circuits in their process by inserting them into the mold prior to plastic injection.

![Flexible circuit technology](image)

**Figure 2-4** Flexible circuit technology offers the designer the ability to create 3D assemblies from 2D substrates.

**AIRFLOW AND THERMAL MANAGEMENT IMPROVEMENT**

The uniform planar nature of flexible circuits serves to improve the flow of cooling air through an electronic box. The massive bundles of wire that they often replace typically act as barriers to good air circulation inside an electronics assembly container.

**COMP liant SUBSTRATE FOR SURFACE MOUNTING**

Surface mount technology presented many difficulties in its early years. A significant reason was the mismatch between the coefficients of thermal expansion of the board and the component. This mismatch resulted in solder joint stress, which was the cause of many failures in early electronic assemblies.

While material scientists and engineers have since remedied most of the problems through better design practices, one method that worked very well was the use of flexible base materials, which are naturally compliant and thus introduce less stress on solder joints of devices mounted on the circuit surface.

**IMPROVED PRODUCT APPEARANCE**

Although this may be considered a trivial concern by some, the internal appearance of an electronic package can have a subtle influence on the decision-making process of a prospective user of the product. This is especially so if they are already aware of the many advantages of flex. In truth, the “mass of spaghetti” represented by some wire harness construction often looks hopelessly disorganized.

Wire harnesses have a long history in a wide range of large system structures. Mostly, they have been used for electrical power distribution for lighting, ignition and the like. They are also well suited to use in many complex systems such as “fly by wire” aircraft and increasingly complex automobile electronics. However, in smaller product applications, flexible circuits may not only prove more cost-effective, but they will also supply the “engineered” look that may serve as a subtle sales point.
**IMPROVED SIGNAL INTEGRITY**

In tune with the earlier discussion on transmission line construction, there is need to discuss the matter of signal integrity, especially with the general trend towards higher-speed digital signaling in electronic systems. The net impact is that signal integrity has become increasingly important. In this respect, flexible circuits are ideally suited to the task, as was noted. This fact gives rise to a discussion of the versatility of flexible circuits relative to the need.

In practice, high speed basically means rapid rise times, and anything that degrades the ideally square wave pulse signal must be managed. In this respect, dielectric constant and loss tangent of materials become of greater concern than the conductor loss. In response, some excellent flexible circuit materials have been developed. These will be discussed in more detail later.

Design approach is also critical because common design features can degrade the signal. Some designers have opted for unusual constructions with respect to signal integrity. An example is a transposed pair construction created using flex circuits to approximate twisted pair constructions. (See Figure 2-5.)

![Figure 2-5 Flexible circuits offer unusual capabilities. The top figure shows a flex circuit in a mock twisted pair configuration. On the bottom is an actual manufactured circuit. (Photo courtesy Minco)](image)

**SMT AND FLEXIBLE CIRCUITS**

Increased electronic circuit density and performance has been achieved by mating flexible circuits with other density improvement techniques, such as SMT (surface mount technology). This has proved an area of great technological synergism. The advantage of density improvement is multiplied by the use of small electronic components to complement and enhance flex technology’s minimalist packaging ability.
An advantage resulting from this technological marriage is improved interconnection reliability. This is made possible by the flexible base material providing the surface mount components a low modulus compliant substrate to help mitigate the effects of mismatched coefficients of thermal expansion between the component and substrate, as has been demonstrated in a number of research studies.

**CHIP ON FLEX (COF) TECHNOLOGIES**

Driven relentlessly by the vision of maximum interconnection in the smallest possible space, circuit designers and packaging engineers have married flex circuit and chip on board (COB) technologies to create chip on flex (COF) technologies. In practice, the bare IC is, in essence, packaged in situ on the flex circuit. There are several approaches to meeting the needs of different applications; each method shares the goal of achieving the ultimate reduction in electronic packaging interconnection size. A number of methods exist for building chip on flex structures, but the three major categories are chip and wire constructions, TAB structures and its variations, and flip chip constructions.

**CHIP AND WIRE FLEX CIRCUIT CONSTRUCTIONS**

Chip and wire construction of chip on board (COB) product on rigid substrates has been in use commercially since at least the late 1970s. A natural extension is chip on flex (COF). In manufacture, bare IC chips are bonded to the flexible substrate using a suitable die-attach material and then interconnected to the flex by means of either gold or aluminum wire bonds. Adhesiveless base flexible substrates are favored by many users for this technology because most adhesives used for flexible circuit applications tend to be relatively soft, and a soft substrate can attenuate the wire bonding energy, leading to insufficient bond strength and lower reliability. In contrast, adhesiveless constructions, especially those based on polyimide films with their higher temperature abilities, tend to be more...
compatible with wire bonding technologies, especially those requiring high-temperature bonding.

**TAB-Type or Flying Lead Flex Circuits**

Another approach to integrating a chip directly into the flex circuit is the use of integral beam leads in the flex circuit. The technique is not widely used, but it has potential application. The technology has been given various monikers, including TAB Featured Flex and TAB FLEX. When researching interconnection history, one finds that one of the first descriptions of such a type of circuit was made in a patent application issued to ITT in the late 1960s. Figure 2-7 shows one of the drawings from the original patent. Due to the technological lag between innovation and implementation, it was not until 1980s that such constructions saw some serious consideration.

This type of construction is designed to accept bare integrated circuit chips for interconnection directly to flex circuit signal traces, which extend into the free space of windows within the circuit. The construction is also called a flying lead construction or a beam lead construction. The term most common to such constructions is TAB (tape automated bonding). TAB is an interconnection technology that is well understood and accepted with leading manufacturers of volume flex circuit production, such as 3M Corp., have developed unique capabilities for producing such products. Fine featured flex of this type should prove of interest to those seeking the higher levels of circuit density and has found use not only in IC packaging but for ink jets and display drivers. One concern is handling circuits with unsupported or flying bonding leads, which can easily be inadvertently bent, resulting in a yield loss of either the tape or assembly. The rework alternative is very expensive.

**Flip Chip on Flex**

The final chip on flex construction option is flip chip on flex. The flip
Flexible Circuit Technology

Chip method of interconnection was first explored by IBM and Bell Labs in the early 1960s. The most famous method is the “Controlled Collapse Chip Connection” or C4 process developed by IBM. It has since spawned a number of interesting approaches to address high density interconnection problems.

Interconnection of the upside down or “flipped” chip is normally made by soldering the chip directly to the interconnection substrate. In this process, the solder-bumped die is mated to a flex circuit with either mating bumps or solder-paste-coated lands and joined together using an appropriate reflow technology.

Today, however, there are some newer approaches to making interconnection. The new methods include the use of conductive polymers and adhesives to achieve interconnection. Because of the short interconnection path to the circuit and the small “footprint,” the flip chip method is capable of providing maximum density with the highest possible performance, with minimal concern for common electrical parasitic effects associated with longer wire leaded devices.

**Chip on Flex Constructions**

Figure 2-8 The use of flex circuits connected directly with the IC is becoming more common. Illustrated above are top and side views of three of the most common methods.

There are some challenges when using flip chip technology for IC interconnection. One is the fact that the flipped chip must be underfilled with an encapsulant to protect the delicate solder joints. Processes are much improved today, but at one time it was a lengthy process, and voids in the underfill could result in hotspots and reduced reliability. One drawback of flip chip constructions is the fact that die shrink will change pad locations from generation to generation and there is no compatibility between die from different suppliers, so a new circuit design may be required for each
new die. A final concern is the fact that the die being used may or may not be good—meaning there is a possibility that the entire assembly will be lost due to a limited ability to rework flip chip assemblies. It is this “known good die” (KGD) concern that has delayed some applications. Even so, flip chip technology is being actively promoted, and the method provides an excellent and easily adapted solution for many applications such as smart cards and in applications with very small die with low I/O counts.

IC Packaging Interposers

With the major chip on flex assembly methods described, it is possible to examine application of flexible circuits as a packaging medium for bare integrated circuits. A novel technology that became quite popular over the last 10 years is one that can, perhaps, best be characterized as a “flex on chip” construction, first developed by chip scale packaging pioneer Tessera, Inc. (San Jose, Calif.). The approach was unusual when it was introduced in that it allowed the chip to be interconnected in TAB like fashion using a specially designed and manufactured flex circuit to create a small grid array of solder balls on the chip itself. (See Figure 2-9.) The novel IC packaging approach allowed chips to be packaged at near chip size, resulting in a more easily tested and burned-in device prior to assembly. This answers what has long been a vital concern in direct chip-attach assemblies.

This packaging format is now widely known as the micro ball grid array (µBGA) chip-scale package (CSP). The µBGA, one of the first chip-scale packages to allow for significant size- and cost-reductions in electronics, now dominates package selection in handheld and portable electronic applications.

Area array interconnection CSPs afford a more generous joining pitch than can be attained using more traditional flip chip approaches, thus facilitating both board manufacture and the assembly process.

A specific advantage of µBGA construction is the
compliance of the flexible circuit in combination with a low modulus encapsulant, both of which make it an attractive chip-packaging solution as no underfill is required. Flexible circuit construction also make possible foldover structures, which allow for IC packages to be stacked one on top of another. This concept is illustrated in Figure 2-10.

**STAIR STEP PACKAGING (SSP) FOR ICs**

Another approach to packaging ICs at high density and with controlled impedance is one predicated on stair step interconnections. A key feature of the new structure is that it is possible to create a multilayer laminated IC package with a complete lack of plated through vias. This new approach is aimed at simplifying electronic design and manufacturing processes, while simultaneously offering the potential for much improved electronic performance. The SSP IC packaging concept builds forward from a concept first employed for improving the density of wire bonded IC packages such as pin grid arrays (PGA) in the mid 1980s, the tiered wire bond pad package structure, which successfully addressed I/O density problems of the time. The SSP takes that concept further by extending it to the I/O terminations on the package surface. Creating a stair stepped or “wedding cake” like structure (see Figure 2-10a).

The advantages of the simplified method are significant in all of the prescribed areas including, cost, performance and reliability. Manufacturing cost is reduced by reducing the number of manufacturing steps, particularly the elimination of plated vias. This should allow for improved manufacturing yields. Electrical testing cost should also be greatly reduced, if not eliminated, because the circuits are only on one side (though a ground layer may be provided on the second side of each layer if desired) and they can thus be easily examined visually for shorts and opens and non uniformities which could affect electrical performance.

Performance is also improved by the elimination of vias. Because of the
directness of the pathways, complex field solver analysis of the critical signals as they pass through the package is not needed. Moreover, differential pairs, common to most of today’s high speed circuit designs, can be designed such that they have virtually zero skew and cross talk can be almost completely eliminated. Also, because of the versatility of the method, substrates of differing material types can be used when and where required so higher cost materials that are often desirable of high speed signals can be used sparingly and mixing of I/O pitch on a package is also possible. While the advantages are compelling, reliability must be still be fully proven and plans for full testing are underway. Fortunately, because of the simplicity of the structure, it is anticipated it will be very good.

**ALTERNATIVE MULTILAYER FLEX STRUCTURES**

Flexible circuits have been studied to create unusual multilayer structures by a number of manufacturers over the years in order to produce high performance interconnection structures. In some such cases, it is not the flexibility of the circuit that is sought but the amenability to certain types of processing and immunity to certain potential defects—such as conductive anodic filament (CAF) shorting between closely-spaced plated through holes—that make it an attractive choice. Following are a few examples of alternative multilayer flex structures.

**PRE-DRILLED STANDARD GRID SUBSTRATES**

One scheme for producing high density multilayer structures that has been examined by a number of companies around the world was based on the use of a standard grid pre-drilled substrate, spurred on by the advent of area array packaging. This gave rise to the notion that a standard grid could be used to facilitate construction of fundamental base grid materials.

Flex circuit pioneer Sheldahl (now Multek) of Northfield, Minn. tried to offer such high density substrates based on their (then) advanced
microvia technology. They developed a flexible-base material product that was pre-perforated with tens of thousands of holes (up to 400 holes per square centimeter or 2500 holes per square inch), all positioned on a selected grid, which it was hoped could be standardized.

The intention was to deliver to the circuit manufacturer a flex material with the through holes already plated and the panels pre-coated with photoimageable resist, based on an inexpensive hole formation technology with all holes produced on a common grid. The product was designed for, and intended to address, some of the major issues in the pursuit of higher-density interconnection structures, one being the provision of small holes that improve wire-routing capability on substrates. Unfortunately, the method did not take hold for a number of logistical and business reasons. Even so, the idea is still of interest and could be of some future value.

**Z-axis Interconnection Technologies**

Another area of investigation relative to high density flex circuit interconnection investigation was Z-axis interconnections for construction of multilayer circuits. The Z-axis interconnection technology contrasts markedly with sequential buildup technologies used in rigid multilayer board manufacture. The intent of such structures was to lower the cost of high density multilayers by making simple, high-yielding single- or double-sided substrates and then joining and interconnecting them in a high-yielding lamination process. Several companies have worked on developing such methods. The general idea seems to be well-suited to flexible circuit interconnection, and rigid-board constructions using the same basic concepts have been demonstrated in Japan. The technology is divided into two general classes: anisotropic and isotropic.

**Anisotropic Interconnection**

Anisotropic adhesives have been in use for a number of years; however, it has only been in the last several years that they have gained widespread attention. Generally, the technology—which is, invariably, a combination of an adhesive with a dispersion of conductive particles—allows for the creation of interconnections in the “Z” or vertical direction only while maintaining lateral circuit isolation.

As a result, any point of intersection between two mating circuit halves will be electrically connected. This is particularly well-suited in concept for interconnecting flex, as the use of coverlayer will protect the circuits from shorting in areas other than those open to shorting by design. This concept is illustrated in Figure 2-11.

The technique is also useful for lapped interconnection between a flex circuit and a rigid circuit and is increasingly used for such purposes.
Display driver circuits for use with liquid crystal displays (LCD) and light-emitting diode (LED) displays are prime examples.

![Image of circuits aligned for lamination with Z-axis bonding film](image1)

**Circuits aligned for lamination with Z-axis bonding film**

![Image of circuits joined and interconnected by Z-axis adhesive](image2)

**Circuits joined and interconnected by Z-axis adhesive**

Figure 2-11 Anisotropic conductive films can be used to join and interconnect layers of flexible circuits. A coverlayer may be required on one side to prevent unwanted connections from being formed.

**Programmable Interconnections**

Alternatives to anisotropic interconnection are members of the family of programmable interconnection structures wherein the interconnection points of the laminate structure are predesigned and prepared. One such version was developed at Tessera (San Jose, Calif.). As illustrated in Figure 2-12, the technology allows for the formation of interconnections at the same time as the multilayer structure is being formed.

Other methods of this general group include the Buried Bump Interconnection Technology, also know as B2IT, which was developed by Toshiba and has been applied to flexible circuit technology by Yamaichi Electronics of Japan. See Figure 2-13. There is also the Any Layer Interstitial Via (ALIV) process developed by Matsushita.
Flexible Circuit Technology

Figure 2-12. Illustrated above is multilayer structure construction for a multilayer circuit based on the co-lamination of pretested inner layers and a "programmable" joining and interconnecting film.

The most pronounced advantage that such approaches to interconnection have in common is their ability to produce extremely short interconnection paths between components. This short-path grid-

Figure 2-13. Buried Bump Interconnection Technology (B²IT) processing avoids drilling and plating processes. Illustrated above is the process for a two-layer circuit. For a multilayer circuit, the process steps are repeated.
Flexible Circuit Technology

based routing is frequently referred to as “Manhattan routing,” owing to its conceptual similarity to the combined grid-like structure of New York City’s streets and office buildings. The use of standard grid materials and interconnection approaches such as those described may well be commonplace in future electronic packaging.

SELECTED FLEX CIRCUIT APPLICATIONS

While the historical role of flex circuits was most often as a wire harness replacement, the technology has gown well beyond such mundane applications. Today, flexible circuits are continuing to increase the breadth of their application. Electronic packaging engineers around the world are devising newer ways of using flex circuits and are expanding on the basic promise of the technology by developing ever more fanciful, yet practical, electronic interconnection structures.

It is worth exploring briefly some of flexible circuit technology’s unique abilities to increase electronic circuit packaging density and performance in terms of some of the many novel applications that are either in use or in development. Some of the new applications and approaches to the use of flexible circuit technology have further demonstrated the ability of the technology to increase circuit density in unusual ways, such as in IC packaging where the new package structures typically occupy a small fraction of the volume of more conventional design approaches.

HIGH SPEED CABLE STRUCTURES

High-speed flex circuit assemblies have proven a viable alternative for high-speed applications for board-to-board distances up to 75mm (30 inches) at data rates up to 10Gbps with the flex circuit integrated directly into connectors. An example is shown in Figure 2-14.

Commonly available high-speed flex circuit products are available in pitches down to 0.5mm (0.020”) and less for both differential pair and single-ended configurations. With the move to ever-higher data transmission speeds, these types of flexible circuit applications will become increasingly important. High-speed structures made possible by high-speed cables will be discussed in more detail later.
Hearing aids

Lightweight, behind the ear, hearing aids were among the first electronic products developed after the invention of the transistor. Up until then, hearing instruments were worn on the body. They were heavy, and expensive to use due to high battery consumption. However, with the invention of the transistor, hearing instruments were much changed. They were small, cheap and effective and very low in battery consumption compared to the vacuum-tube instruments they replaced.

Manufacturers introduced their first transistorized behind-the-ear instruments in the early 1950s. These were, of course, extremely large by today’s standards and battery life was not very long. In contrast, hearing aids of today fit nearly invisibly into the user’s ear. In a great many cases, hearing-aid technology miniaturization has been aided by the use of flexible circuits, which allow the circuit to be folded compactly after assembly.
MICRO COILS

Micro coils are most commonly used for sensing applications. Figure 2-16 shows a scanning electron micrograph of a coil on a flex substrate, produced by Metrigraphics using their proprietary fabrication processes.

The width of the conductors is 10 microns (0.0004”), and their height is 25 microns (0.001”). The spaces between the conductors are also 10 microns. Dimensional tolerance is less than a micron. The resulting coil has sharp, vertical walls and flat top surfaces.

ELECTRONICS IN CATHETERS

Medical electronics are a true modern marvel, and often flexible circuits are an enabling element in such products. Flexible circuits have proven themselves valuable in a variety of catheter-based medical diagnostic and therapy applications, such as in electrophysiology studies for mapping the nerves of the heart and radio ablation of arrhythmia causing nerve defects. Figure 2-20 shows an example of a multiprobe catheter disposed and ballooned within a model of a heart.

CELL PHONES

Cell phones are a major beneficiary of flexible circuit technology. Most cell phones employ flex circuits in some manner, but most especially those cell phones that are foldable.

In the early 2000s, some innovative developers at Dieceland Technologies fronted a concept of a foldable phone that was designed to be “disposable.” The idea was to create a very-low-cost phone that could be used for a predefined period and then recharged—something akin to the disposable camera. Figure 2–21 is a photo of the structure.
Flexible Circuit Technology

ULTRASONIC TRANSDUCERS

Medical diagnostic equipment frequently uses flexible circuit technology to achieve desired results. Perhaps one of the more successful applications has been in the interconnection of ultrasonic transducer heads for ultrasound imaging, wherein the flex circuit is used both to send and receive electric signals to and from a piezo ceramic to create an electronic image based on reflected sound. While medical applications are most familiar, ultrasonic imaging technology has proven a useful tool in screening electronic manufacturing processes as well, due to its ability to detect voids in encapsulants.

A variety of configurations has been developed over the years to achieve extraordinary image clarity. An example of one such flex circuit is shown in Figure 2-22.

INSTRUMENT CLUSTER CIRCUITS

Flexible circuits have maintained a long relationship with the automotive industry. One long-standing application has been interconnecting electrical and electronic elements of automobile instrument clusters. This was one of the earliest volume applications for flex circuits and saved countless hours of tedious hand-assembly. While originally used primarily for panel lighting circuits, as the electronic content of automobiles has increased, the importance of flexible circuit interconnections has also grown.
Flexible circuits offer some highly unique advantages as a test contact technology. Several approaches have been explored by connector and socket developers over the years. An example of a test contact structure developed by Xandex (Petaluma, Calif.) for contacting and testing area array packages such as BGAs is shown in Figure 2-24.

**High Density Connectors**

High density flex circuit-based zero insertion force (ZIF) connector technology, predicated on the use of shape memory alloys to open the connector, was pioneered by Beta Phase (Menlo Park, Calif.) from the mid-1980s through the early 1990s. One of the products they worked on was a high density controlled impedance connector for super-computer company Cray. The device shown in Figure 2–25 provided 500 connections per linear inch.
HIGH-SPEED CHIP TO CHIP INTERCONNECTION

High-speed chip to chip interconnection is a fairly new application for flexible circuits that has been brought about by a convergence of conditions. For example, it has been noted with increasing frequency by electronic industry experts that electrical and electronics interconnections are presently the primary limiters of electronic performance. The electronics industry has not been blind to this fact, but it has been slow to react in a cooperative and coherent manner. This lag is also a product of the simple fact that the electronic industry is no longer the monolithic industry it once was. Electronic design and manufacturing are disciplines that have drawn further apart since the process of eliminating vertically integrated electronics OEM manufacturers began in the late 1980s. In earlier times, the designer was very commonly the manufacturer as well: These were the vertically integrated OEMs. However, with corporate outsourcing of almost everything but marketing and corporate governance, the OEMs of today are much more hollow entities and, as a result, are often much less attentive to the consequences of the diffusion of design and manufacturing processes. An offshoot of that situation is that there is little opportunity to learn and grow cooperatively to meet evolving challenges.

While there has been much discussion about bridging the waters between the island of design and the various islands of manufacturing interconnection structures, it is proving a daunting task. As it presently stands, each element of the electronic interconnection hierarchy is conceived and developed with little anticipation as to the impact of the decisions on what is to come next. It has been pretty much a case of, “I have solved my problem. It’s your problem now.”

For example, the semiconductor is designed with little concern for the package, and the package is designed with little concern for the PCB, etc. An arguably better approach is to implement concurrent design and engineering. To illustrate how a semiconductor chip and package might be better integrated in terms of design and manufacture, it is necessary to dig a bit deeper into the matter.

Semiconductors’ design of today is a far cry from former times. In earlier years, an individual designer or design team would set about the task of designing the chip completely. This included all the gates required to meet the product need. Over time, the process has been simplified. Presently, IP blocks of transistors having different functions are designed by completely different teams. These are collected and integrated together into a chip design, with interconnection and I/O assignment the basic tasks.

As the industry moves inevitably to ever-higher speeds due largely
to chip-feature-size reduction, there will be need for greater cooperation between silicon design and package design. In fact, the package can actually help to improve silicon efficiency greatly if the two are co-designed. The solution resides in the data channel.

When the data or signal channel is very clean and free from electrical/electronic disruptions, it is possible for the signal to propagate at very high rates. This is because signal rise time and edge are not degraded by the materials commonly used that put a drag on the signal due to their high dielectric constant and/or high loss tangent. Moreover, a well designed and clean channel should not be subject to normal circuit route twists and turns, noise, crosstalk and the crowded transmission environment of a standard PCB.

One way to do this is to separate the high-speed signals and treat them as having special needs. In doing so, the high-speed signals can be lifted up and out of the congested onboard signal traffic and rapidly shuttled to their destinations. It is, by way of analogy, basically the application of civil-engineering practices to electronic engineering challenges, with flexible circuits playing a pivotal role.

Figure 2-26 Simple flex circuit constructions can provide significant improvement in circuit design time, performance and yield. Eye diagrams beneath each circuit are modeled for 25Gbps data rate over a distance of 75mm (~3 inches). (Source: SiliconPipe)
Flexible Circuit Technology

An example of what such a “civil engineering” solution might look like in an application, in comparison with standard design approaches, can be seen in Figure 2-26. It is intuitively evident that this elevated-superhighway approach to signal routing has some unique advantages, and the performance benefit has been proven in actual tests. The structure and results can be seen in Figure 2-27.

Figure 2-27 Test setup for demonstrating a 10Gbps backplane solution over a 75cm (~30 inches) channel through two connectors and a backplane. The demonstration unit transmitted the signal nearly 3x the anticipated distance at less than 2% of the anticipated power to drive the signal. (Source: SiliconPipe)

Solar Cell Arrays

Solar-cell technology has made significant advances over the years. There are indications that solar cell efficiency may reach levels of nearly 50%, these are values that were only dreamed of in earlier times. Creating compact, high density energy generating solutions using solar cells is a task that is well-suited to flexible circuit technology.

The military has looked at rollup solar cell arrays as a lightweight solution for field deployable energy generation, and they are a potential candidate for commercial use in the future as the world looks for ways of cutting dependence on fossil fuels. NASA is the world’s greatest proponent and uses the technology to supply energy to the International Space Station. The solar arrays in the deployed configuration,

Figure 2-28 An extreme application of flexible-circuit technology can be found in the International Space Station (ISS) Solar Arrays built by Boeing under contract to NASA JSC. These are the largest solar arrays ever deployed in space, with 16,400 cells/blanket and 262,400 cells total. (Source: NASA)
Flexible Circuit Technology

nearly the size of a football field, are capable of generating tens of thousands of watts at voltages up to 160. An image of the array can be seen in Figure 2-28.

**STILL AND VIDEO CAMERAS**

Product development engineers in Japan were quick to recognize the capabilities of flexible circuit technology for a wide range of products. One of the early beneficiaries was the camera industry. As more automated functions were integrated into film-based cameras, flexible circuits were employed to provide power for motors, light meters and range finders.

![Flexible circuits are used extensively in camera applications, as can be seen above. (Source: Fuji)](image)

With the emergence of digital imaging in the early 1990s and handheld video cameras shortly thereafter, the interconnection role of flex circuits was expanded in the technology, increasing both the number of features and the quality and performance of the products. Examples of flex circuits in a camera application can be seen in Figure 2-29.

**RFID AND SMART CARD CIRCUITS**

Another couple of areas of application and significant growth for flexible circuits are in RFID (radio frequency identification) technology and smart card technology, which are being employed increasingly for inventory control and security access. Flexible circuits are ideal candidates due to their thinness and amenability to mass production at low cost. The circuits themselves are, typically, rather simple.

![Flexible circuits are expected to see significant growth in RFID applications for inventory control. (Source: Technical University Berlin)](image)
often not much more than a coil with interconnected chip. Coil circuits can serve both to power up the device inductively for inquiry and/or to receive and transmit data. Figure 2-30 shows an example of an RFID circuit.

**Volumetric System Miniaturization & Interconnection**

A final topic of discussion in this review of flexible circuit applications is a new one that is actually part of the continuing evolution of both electronics and flexible circuit technology. As the electronics industry moves to ever-higher data rates for digital electronics, electronic interconnection technologies such as flexible circuits are staged to take an ever more prominent role. Some of this was discussed earlier in this chapter.

While semiconductors will, no doubt, continue their every 18 to 24 month transistor doubling march to the tune of Moore’s Law for at least a few years longer, the performance benefit will likely continue to be bottled up until and unless there are suitable interconnection structures to help performance break loose.

Even without the doubling of the transistor effect, there has already been a significant number of interconnection solutions developed over the last few years to improve the density of semiconductors in ways that border on legerdemain. There are many examples of such “magic” being performed by the IC packaging community. Most of these relate to methods of stacking chips in packages, packages on packages, packages in packages, and even wafers on wafers. This is not new: Since the advent of the transistor, electronic product developers have been driven to increase density of semiconductors and make their products ever smaller while offering ever-greater levels of performance at lower cost. And, as fundamental building blocks of electronics, IC packaging technologies have long spearheaded this ongoing effort.

As discussed earlier in this chapter, in recent years IC packages have been reduced to the size of the chip with the generation of chip-scale, chip-size and wafer-level packages. These densification technologies have served to advance the long-held industry objectives of smaller, faster and cheaper. However, the reduction in IC packaging to chip-scale and stacked-package solutions has shifted responsibility to the substrates needed to provide interconnection pathways between these miniature devices. The result has been that interconnection substrates have become increasingly complex and more costly as manufacturers continue to try and apply old solutions to the challenges presented by this technological evolutionary shift.

To adequately address the demands of future systems, next-generation product developers must design and manufacture their systems based on a new paradigm—specifically, a paradigm that considers electronic
Flexible Circuit Technology

interconnection much more holistically. This is especially true as current-generation electronic packaging and interconnection technologies move into the third dimension with these new and various stacked-chip packaging and stacked-package solutions. The transition to the third dimension marks a significant departure from the old ways and the long-held views of electronic interconnections. This is where flexible circuit technology will shine. A new term has been coined to describe this transition accurately. The descriptive term presently being floated in the industry for consideration is “Volumetric System Miniaturization and Interconnection Technology” or VSMI, for short. The concept will help product developers provide a broader view of electronic interconnection technologies as they evolve to address complex volumetric interconnection challenges both now and in the future. VSMI technology speaks openly and directly to the activities that must be addressed to meet the interconnection needs of future electronic systems, wherein matters of component assembly, device integration, interconnection and thermal management transition to a higher level, both in complexity and importance—more so than older terms used to describe electronic interconnection technologies, providing a visual image of the challenge faced by today’s electronic interconnection and packaging technologist.

Included under the umbrella of VSMI technology are all of the many stacked-chip packages, stacked packaged chips, stacked wafers and multichip modules and packages that are moving rapidly into volume production. Also included are the novel flexible-interconnection concepts of folded and multisurface package connections that are beginning to populate the electronic interconnection horizon. By holding to a term that accurately describes the technological focus and direction, product designers can more easily come to visualize their challenge and consider potential alternative solutions. The name also gives rise to the up front consideration of what were often considered ancillary challenges. For example, of particular importance in the transition to VSMI technology is the need to consider the thermal impact of increases in electronic component density. While the potential cost and performance boosts to be gained by employing VSMI—especially those involving flexible circuits—are highly alluring, the increase in energy density of such miniaturized systems cannot be ignored. Thus, the VSMI technology concept openly embraces the integration of thermal solutions and actively includes them in the overall concept.

Another key element of VSMI technologies is that they consider electrical test early on. With the increased density, testing has the potential to be either greatly simplified or exceedingly complicated, depending on
Flexible Circuit Technology

how the system designer approaches the challenge. Testing and burn-in of stacked, flexible, folded and multichip modules and multichip packages have already created a host of unusual challenges for product developers. The risk of having one chip among many fail and rendering the multichip device useless continues to cause a measure of consternation among both product developers and users. It is a statistical risk that must be carefully considered before one sets about taking on such approaches. Current experience is giving courage to developers that these approaches will deliver the desired yields with careful consideration of the semiconductor technology employed and wafer yield history, but it has yet to provide a green light for all die. Thus, again, the VSMI technologist is tasked with making sure that these important considerations are fully vetted before being implemented.

In short, the electronics industry is entering a new age wherein the task of electronic packaging and interconnection will be elevated to a level of importance beyond that which it holds today—one more consistent with
both the challenges that it faces and the myriad of benefits it will ultimately provide. Flexible circuits will be playing a vital role.

**FLEX CIRCUIT INNOVATION TRENDS**

A cursory review of US patents issued over the last 10 years indicates that flexible circuit innovation is alive and well. Moreover, it appears that the technology is proving an exceptional enabler of (or platform for) electronic innovations, as is no doubt already clear.

Flexible circuit technology is full of food for interconnection thoughts and technology dreams. The third dimension it effortlessly offers to the aware circuit or product designer makes possible an endless array of interconnection possibilities and products of every size, shape and application imaginable.

The online database of issued US patents (www.uspto.gov) provides the user the ability to browse the myriad of flex circuit-based or -enabled innovations and can also provide opportunity to see where flexible circuit technology might be headed.

To determine what the rate of innovation has been over the last 10 years, the USPTO search tool, which allows users to look for innovations in a number of different ways, was employed. While one can search in the usual fashion (by keywords), filtering elements allow users to increase the granularity of their search. The search employed in gathering information for this book was relatively coarse: The only limiter was that either of the terms “flexible circuit” or “flex circuit” be included somewhere in the body of the text of the patent. This criterion was deemed adequate for a quick overview. The search was repeated for each of the last 10 years (1996-2005). The results, included in Table 2-2, indicate that the pace of innovation quickened rapidly in the late 1990s and has now stabilized at a high level. For example, the number of issued patents in 2004 is nearly triple the number issued in 1996. The last few years hint that a plateau has been reached, but that is likely owing to factors other than the versatility of flex technology.

To get a sense of the diversity of applications and what areas of application are most represented, the patents issued in 2005 were reviewed as a separate group and by examining their titles, which briefly describe the innovation. The results of this effort were revealing, if not surprising. By way of example, the dominant area of flex circuit-based patents was for disc drive applications such as head assembly suspensions. Medical and dental applications including various probes and sensors were not far behind. These were followed by roughly equal numbers of IC package/electronic module and connector applications. Optoelectronics, which had some overlap with packages, was next. There were a few surprises, antenna
Flexible circuit technology applications being one of them. A number of patents related to antenna design, and there were also a few RFID innovations, but fewer than might have been expected. Printers and print heads, especially inkjet printers, were still being advanced by innovation, as were keyboards. One area of innovation that was also well represented was flex as an enabler for LED technology. This marriage of the two technologies seems like a great one, and it will be interesting to see where it goes.

**United States Patents Issued Over Time for Innovations Using or Related to Flexible Circuits**

<table>
<thead>
<tr>
<th>Year</th>
<th>Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>261</td>
</tr>
<tr>
<td>1997</td>
<td>305</td>
</tr>
<tr>
<td>1998</td>
<td>468</td>
</tr>
<tr>
<td>1999</td>
<td>497</td>
</tr>
<tr>
<td>2000</td>
<td>586</td>
</tr>
<tr>
<td>2001</td>
<td>686</td>
</tr>
<tr>
<td>2002</td>
<td>678</td>
</tr>
<tr>
<td>2003</td>
<td>681</td>
</tr>
<tr>
<td>2004</td>
<td>745</td>
</tr>
<tr>
<td>2005</td>
<td>646</td>
</tr>
</tbody>
</table>

Table 2-2 The table above is a compilation of issued patents over the last decade having either the term “flex circuit” or “flexible circuit” somewhere in the body of the text. Although not exhaustive or all-inclusive, the method is deemed a reasonable measure of the pervasiveness of flex circuit technology in new inventions.

In summary, flexible circuit innovation is alive and well. One should not be overly concerned with the reduction in innovation reflected by the roughly 13% drop in patents from 2004 to 2005. It takes more than one data point to establish a trend. One can assume that there is still much innovation left in the venerable flex circuit. The question is: Where will it apply itself next?

**SUMMARY**

Clearly, flexible circuit technology offers many viable solutions for those challenged with packaging electronic products. The list of flex circuit application drivers will undoubtedly grow in the coming years as the technology finds its way into more and newer product applications. Moreover, as has been shown, the technology is branching out to enhance the ability of electronics packagers to make interconnections at every level, from the IC chip to the wall socket. The limiting factor to finding further application is in the imagination of those assigned the task of packaging the next generation of electronic systems. Hopefully, the examples shown in this book will spark new ideas in the minds of its readers, helping them see a clearer path to the solution of a problem or, perhaps better yet, helping to prevent one.
Flexible Circuit Technology

Flexible Circuit Materials

INTRODUCTION

A wide variety of dielectric and conductive materials has been employed in the fabrication of flexible circuits since their invention. One of the earliest descriptions of what could be called a flex circuit can be found in a patent that referred to a construction consisting of flat metal conductors on paraffin-coated paper. Another conceptual substrate was the linen-paper construction with patterned circuits of graphite-loaded gum adhesive that Edison described to his then assistant Frank Sprague (later of Sprague Electric fame).

It was one of many prescient moments for Edison, for it turns out that he was not far from future marks in his thinking. Decades later, one of the types of substrates used for flex circuits was actually based on a paper made from high-temperature aramid fibers, and polymer thick film inks used in PTF flex circuits and membrane switches are substantially the same as what Edison described early in the last century.

While many different materials have been tried and used over time, only a few are in broad use today. This chapter will examine those materials, along with some new choices to help guide the reader to the proper choice for his or her application. First, however, it is worth reviewing what is, in general, desirable from a flexible circuit base material.

DESIRABLE CHARACTERISTICS FOR FLEXIBLE CIRCUIT LAMINATES

While there is no ideal flexible circuit laminate available today, a number of criteria can be used to define the desirable properties of such a laminate. Those properties encompass a broad spectrum of needs that would enable the material to meet all of the demands that might be placed on a finished flexible circuit. Although no known material can meet all of the often conflicting requirements that the manufacturer and user might have, it is, nevertheless, of some value to have a mental picture of an ideal product as a means of keeping in mind what trade-offs one may be required to make when selecting an appropriate substrate for a product or application.
Flexible Circuit Technology

**Dimensional Stability**

The ideal flexible laminate should be extremely stable dimensionally. Shrinkage or expansion of a flex circuit base material during processing is a concern for both manufacturer and user as it can affect both the fabrication of the circuit and its assembly. It is especially frustrating when dimensional change is not predictable.

A number of steps can be taken to combat the effects of dimensionally non-stable materials (discussed in the chapters on design and manufacturing), but not having to resort to such practices is a definite advantage.

**Thermal Resistance**

Because most electronic assemblers use elevated temperature processes such as reflow soldering for component assembly, it is highly desirable that the flex circuit material chosen for use in manufacture should be able to withstand normal assembly process temperatures reliably without distortion. With the well-meaning but scientifically ill-advised and unwarranted move to lead-free soldering in Europe mandated by legislation, there will be added pressure relative to thermal resistance performance.

**Tear Resistance**

As many flex circuit constructions are thin and unreinforced, they are vulnerable to tearing. Thus, a base material for use in flex circuit manufacture should be highly resistant to any tearing.

**Electrical Properties**

The importance of electrical properties of materials has risen and will continue to rise with the increase in signal speed. Preferred materials for flexible circuit applications should have electrical properties tailored to the needs of the design. With high-data singling speeds (greater than 100 MHz) now becoming more and more common, the material's dielectric constant and loss tangent will, ideally, be low. In addition, high insulation resistance is a desirable property for various high-voltage applications. An ideal material would be an electrical chameleon, meeting whatever electrical requirements were present—but that is a dream and not a likely prospect for the future from any known source.

**Flexibility**

An obvious property requirement, flexibility is often a critical matter. Depending on application, flexible circuits can be exposed to extremes of temperature, from cookstove hot to cryogenic cold. Thus, flexibility over a wide range of temperatures is essential. Of particular importance is flexibility at low temperatures, where most materials tend to become brittle.
**Low Moisture Absorption**

Moisture absorption is definitely not desirable for any flexible substrate. Moisture can negatively impact both the manufacturing process (by causing delamination, in process or in assembly) and the performance of the finished product (by altering the material’s dielectric constant and increasing signal loss).

**Chemical Resistance**

Depending on the application, a flex circuit material’s ability to resist a range of chemicals is important to both the manufacturer and the end user. The many different corrosive chemistries used in flex circuit fabrication cause the manufacturer to be concerned as to how well the material will stand up to processing. The material must be compatible with a wide range of process chemistries and common solvents used in assembly and cleaning processes.

**Lot to Lot Consistency**

Variation is the bane of manufacturing, so product consistency is vital to good process control. While the demands of Six-Sigma quality targets may never be truly obtained in manufacture, extreme consistency of all material properties—including physical, mechanical and electrical—is key. Consistency will provide assurance that the product will perform well both in manufacturing and in the field.

**Multiple Sources**

A great concern of any manufacturer is a situation in which only a single source is available for a product. The vulnerability of both the manufacturer and the customer can, unfortunately, preempt the use of a single-source material, which may otherwise have excellent properties. In most cases, existence of a second source capable of producing an equivalent product is a prerequisite in making a material choice.

**Low Cost**

The pursuit of low-cost solutions is a universal activity in electronics. It is inevitable that there will be a never-ending push to seek lower prices for the material so that both manufacturer and user might enjoy slightly better profit margins. It is, however, important to bear in mind that the real value of a product is best measured in terms of how it impacts total cost of manufacture and the finished product, not in terms of how much it costs to get the material in the door.

With these desirable material attributes fresh in mind, it is possible to review the basic elements of flex circuit materials and some of the typical substructures of flex circuit construction and to understand where the limitations lie, relative to meeting the full complement of objectives.
BASIC CONSTRUCTION ELEMENTS FOR THE
MANUFACTURE OF FLEXIBLE CIRCUITS

Being few in number, none of the basic elements of construction of a
substrate for flexible circuits is lacking in importance. Each element must
be able to meet the demands placed upon it consistently for the life of the
product. In addition, the material must play reliably in concert with the
other material elements of the flexible circuit construction to assure ease
of manufacture and reliability. Following are brief descriptions of the basic
elements of flex circuit construction and their functions.

BASE MATERIAL

The base material is the flexible polymer film that provides the
foundation for the laminate. Under normal circumstances, the flex circuit
base material provides most primary physical and electrical properties of
the flexible circuit. In the case of adhesiveless circuit constructions, the
base material provides all of the characteristic properties.

Although a wide range of thickness is possible, most flexible films are
provided in a narrow range of relatively thin dimension, from 12 µm to
125µm (1/2 mil to 5 mils). While it is recognizable from experience that
thinner materials are more flexible, it is worth remembering the engineering
principle that with most materials, stiffness is proportional to the cube of
thickness. This means that if the thickness is doubled, the material becomes
eight times stiffer and will only deflect one-eighth as much under the same
load.

BONDING ADHESIVE

Adhesives are used as the bonding medium for creating a laminate.
When it comes to temperature resistance, the adhesive is also typically the
performance-limiting element of a laminate—especially when polyimide
is the base material. Because of the earlier difficulties associated with
polyimide adhesives, many polyimide flex circuits presently employ
adhesive systems of different polymer families. However, some newer
thermoplastic polyimide adhesives are making important inroads.

As with base films, adhesives come in different thicknesses. Thickness
selection is typically a function of the application. For example, different
adhesive thicknesses are commonly used in the creation of coverlayers in
order to meet the fill demands of different copper-foil thicknesses that may
be encountered.

METAL FOIL

A metal foil is most commonly used as the conductive element of a
flexible laminate. The metal foil is the material from which the circuit paths
normally are etched. Although typical flexible circuit laminates are created using rolled and annealed copper, a wide variety of metal foils of many different thicknesses is available from which to choose and create a flex circuit.

In certain nonstandard cases, the circuit manufacturer may be called upon to create a specialty laminate by using a specified alternative metal foil, such as a special copper alloy or other metal foil in the construction. This is accomplished by laminating the foil to a base film with or without an adhesive, depending on the nature and properties of the base film.

**Flexible Circuit Material Formats**

Having reviewed the basic constructional elements of a flex circuit, it is now possible to discuss mixing and matching these elements to create the different materials that can be required in the manufacture a flexible circuit.

Following are descriptions of the basic material forms used in flex circuit manufacture:

**Laminates**

Metal foil clad laminates are the basic form of material used for most flexible circuit constructions. While copper foil dominates applications, other foils can be used.

Typically, a laminate is created by bonding together a sandwich comprised of a base material, an adhesive and a metal foil. The stack is then subjected to sufficient heat and pressure in a laminating press to create a permanently bonded metal polymer laminate.

In the case of adhesiveless laminate substrates, the adhesive is absent from the construction. Some “adhesiveless” laminates use a thin layer of very-high-temperature adhesive to create a laminate structure that is fundamentally the same as an adhesiveless construction. There are also ways to create adhesiveless laminates without a lamination process. This will be discussed in more detail later.

**Laminated Coverlayers**

Normally, a coverlayer is a two-layer material comprised of a base material and a suitable thermosetting adhesive; however, suitable homogenous thermoplastic films may also be used as coverlayers. The coverlayer serves to protect the conductors of the finished flex circuit and help enhance flexibility, a topic that will be discussed in greater detail later.

Coverlayer materials are commonly used to create flexible laminates by bonding them to metal foil. This is the typical case when a flex circuit maker manufactures his own material.
PHOTOIMAGEABLE COVERLAYERS

Another type of coverlayer for use in flex manufacture is a photoimageable coverlay. This product, which was not mentioned in the discussion of basic material building blocks, is akin to dry film solder mask. Like solder mask, it requires vacuum lamination to assure a good seal around the circuit traces. Then, just like a photoimageable solder mask, the material is exposed and developed to provide access to circuit component attachment features.

COVERCOATS

Again, though not part of the earlier discussion of flex building blocks, covercoats are nevertheless very important construction elements for certain types of flex circuits.

The term covercoat is used to describe a range of thin coatings applied to the surface of conductors in lieu of a coverlayer. Although some suppliers of covercoat material have some impressive flex cycling data, covercoats are normally reserved for applications where no (or minimal) dynamic flexure is required.

In manufacturing, covercoats normally are applied as a liquid by screen-printing and then either cured by heat or by exposure to UV radiation.

Some covercoat technologies now allow the circuit component attachment features to be accessed by photolithographic techniques like those just described to improve feature resolution.

Continued advances in this area appear destined to make covercoats an attractive alternative, especially as they approach performance levels formerly available only from coverlayer materials.

BONDPLIES

Bondplies are flex circuit construction elements comprised of a base film with an adhesive film cast on both sides. The adhesive element of the construction is typically a thermosetting material.

While bondplies can be used for creating two-metal layer laminates,
bondplies most typically are used as building blocks in the manufacture of some more complex flex structures such as multilayer flex and rigid flex circuits.

**CAST ADHESIVE FILMS**

Cast adhesive films are freestanding adhesive materials. The films are most typically thermosetting adhesive films, which are cast onto a disposable carrier or release film.

Cast adhesive films are also often used to bond rigid stiffening materials to a flex circuit. They have also been used as replacement for bondplies in certain applications.

**PRESSURE-SENSITIVE ADHESIVES**

Pressure-sensitive adhesives (PSAs) are a family of semipermanent to permanent adhesive films on peelable carriers, which can be transferred directly to the surface of the flex circuit or other material for later attachment to another surface. Once the PSA is applied to the circuit, it can be bonded later to nearly any surface; however, most typically, pressure-sensitive adhesives, when used in flex circuit manufacture, are employed to attach stiffeners to flexible circuits.

There is also a special subset of the pressure-sensitive adhesive family that can be screen-printed directly onto the back surface of the flex circuit and then cured to provide the necessary tacky finish by exposure to ultraviolet radiation. This method can be used to advantage in very-high-volume applications or where cost is kept to a desired minimum.

**STIFFENER MATERIALS**

While not an integral part of the flex circuit, stiffeners are an important element of flex circuit construction. Stiffening materials are used to reinforce flex circuits when and where required. Most commonly, stiffeners are under areas where electronic components are to be attached. There they serve to support the weight of the components both through the assembly process and in the application.

Stiffeners can be made of almost any material, including metal, plastic, resin-glass laminates or even additional layers of coverlayer material. The use of coverlayer material to stiffen areas of a flex is actually a very common practice.

**SPECIAL ADHESIVELESS CONSTRUCTIONS**

As was pointed out in the earlier discussion on laminates, there is a special category of laminates referred to as *adhesiveless laminates*. These adhesiveless base materials are produced by a number of methods. Deposition of a thin seed layer onto the base film and plating copper or other metal foil directly onto the substrates is one common method. In
Flexible Circuit Technology

processing, the polymer is pretreated in an oxygen-containing plasma environment prior to metallization to clean the surface. Next a very thin (in the range of 200Å) tiecoat metal, such as nickel-chromium is sputtered, which precedes the sputtering of a thicker copper-base seed coat of about 2000Å (0.2µm) thickness. Additional copper thickness is built up to a desired thickness (e.g., 2–5 µm) by electro-deposition.

An alternative approach—casting the polymer directly onto a carrier foil—can create adhesiveless laminates. Finally, there is a type of “adhesiveless” laminate that actually employs a thin layer of high temperature adhesive, as described earlier.

Adhesiveless laminates offer special advantages in some applications, especially where high temperatures are anticipated, but also in applications where thickness matters. Another advantage is that these materials are amenable to very fine circuit feature processing.

Another area of particular advantage is in the manufacture of more reliable multilayer and rigid flex structures. The advantage is gained because the Z axis coefficient of thermal expansion of base films such as polyimide is significantly lower than most adhesives. This is an important factor in the long-term reliability of plated through holes in these more complex circuit structures.

While currently more costly than traditional laminates, the advantages of adhesiveless laminates, as has been described, make them an attractive choice in certain applications.

MATERIAL PROPERTIES OVERVIEW

Having reviewed the basic material elements of flexible circuits (base film, adhesive layer and metal foil) and having also reviewed how the materials are combined, it is possible to examine them in more depth to learn what material choices are available and what their properties are. This process will enable the designer to make informed choices by providing an understanding of the effect of each decision on the final product.

FLEXIBLE BASE FILMS

As stated in the opening of this chapter, many different materials have been used as base films or substrates for flexible circuit manufacture. Included in the list of materials are:

- Fluoropolymer films such as Teflon®
- Aramid fiber-based papers and cloths such as Nomex®
- Formable composites such as Bend/Flex®
- Various flexible epoxy-based composites
- Thermoplastic films such as polyethylene, polyvinyl chloride, polyvinyl fluoride and polyetherimide

All of these films and thin composites have been used in flex circuit
manufacture at one time or another, and many of them see some continued use in certain applications. Cost of materials can vary widely.

Presently, the most popular and most commonly specified flexible-base materials are polyester (PET) and polyimide (PI). Which of these two or any other substrate polymers to use is determined by a combination of economics, end-product application, assembly processing temperatures, and—increasingly important to satisfy—EU-legislated lead-free requirements.

Polyimide and polyester may dominate the present applications, but there are alternative film technologies that could see increased use for a number of solid reasons. Polyethylene naphthalate (PEN), for example, looks like an attractive intermediate choice in terms of cost and performance between polyester and polyimide.

Another material of increasing interest as the industry moves to higher frequency digital electronics is liquid crystal polymer (LCP). This material has a number of attractive physical and electrical properties. For example, LCP materials have inherently low moisture-absorption
Flexible Circuit Technology

Flexible Circuit Technology

properties (0.02%–0.1%), which should preclude the need for the baking that is commonly part of the polyimide manufacturing process due to its more hygroscopic nature. The low moisture uptake is also an important factor in the creation of a low signal-loss environment. With a loss tangent of 0.003 and a dielectric constant of around 2.9, LCP is very attractive for high-speed applications. Another attractive feature in LCP is that it is chemically etchable—a feature it shares with polyimide. This capability can be used to advantage in the creation of both exotic and relatively mundane constructions.

Thin fluoropolymer laminates are also candidate materials to serve future flex circuit interconnection needs. While not necessarily suited to dynamic applications, PTFE materials could find use in applications where low loss and low dielectric constant are requirements. Typical loss tangent values for PTFE materials are well under 0.001, and dielectric constant commonly comes in the 2.0–2.4 range. Companies such as Taconic, Inc. are targeting just such applications for materials they are developing for the flex circuit market. The laminate material is based on PTFE. FEP is a derivative of PTFE with a much lower melt-point of 550ºF vs. 640ºF for PTFE.

<table>
<thead>
<tr>
<th>Polyimide/Polyester Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polyimide</strong></td>
</tr>
<tr>
<td>There are several manufacturers of polyimide films. They are available from the US, Europe and Asia. Polyimide films are most popular for high reliability type (military, medical, etc.) and dynamic flex applications. Trade names include: Kapton®, Apical® and Upilex®.</td>
</tr>
<tr>
<td>Advantages</td>
</tr>
<tr>
<td>Excellent flexibility at all temperatures</td>
</tr>
<tr>
<td>Good electrical properties</td>
</tr>
<tr>
<td>Excellent chemical resistance (except hot alkaline solutions)</td>
</tr>
<tr>
<td>Very good tear resistance</td>
</tr>
<tr>
<td>Highest tensile strength</td>
</tr>
<tr>
<td>Disadvantages</td>
</tr>
<tr>
<td>Absorbs moisture (up to 3% by weight formulation dependant)</td>
</tr>
<tr>
<td>Relatively expensive compared to polyester</td>
</tr>
<tr>
<td>High-temperature performance limited by adhesive system used</td>
</tr>
</tbody>
</table>

Table 3-1 General comparison of polyester and polyimide films

Table 3-1 provides a comparison of the general properties of polyimide and polyester substrates when used for flexible circuit construction.

A more detailed chart examining some selected physical and electrical properties of a larger group of flex circuit base materials is found in Table
3-2. The table is limited in scope, however, as many other materials can potentially be used.

<table>
<thead>
<tr>
<th>Substrate Material</th>
<th>Dielectric Constant</th>
<th>Dissipation Factor</th>
<th>Dielectric Strength</th>
<th>Moisture Absorption</th>
<th>Tensile Strength</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>3.2</td>
<td>0.005</td>
<td>7000 v/mil</td>
<td>&lt; 0.08%</td>
<td>25 kpsi</td>
<td>~120%</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3.5</td>
<td>0.003</td>
<td>7000 v/mil</td>
<td>1.3 - 3.0%</td>
<td>25 kpsi</td>
<td>~60%</td>
</tr>
<tr>
<td>PEN</td>
<td>2.9</td>
<td>0.004</td>
<td>7500 v/mil</td>
<td>1.0%</td>
<td>30-35 kpsi</td>
<td>~75%</td>
</tr>
<tr>
<td>LCP</td>
<td>2.9</td>
<td>0.003</td>
<td>6000 v/mil</td>
<td>0.02 – 0.1%</td>
<td>15-25 kpsi</td>
<td>~15%</td>
</tr>
<tr>
<td>FEP</td>
<td>2.0</td>
<td>0.0002</td>
<td>5000 v/mil</td>
<td>&lt; 0.01%</td>
<td>2-3 kpsi</td>
<td>~300%</td>
</tr>
<tr>
<td>PTFE</td>
<td>2.5</td>
<td>0.0002</td>
<td>5000v/mil</td>
<td>&lt; 0.01%</td>
<td>15-25 kpsi</td>
<td>N/A</td>
</tr>
<tr>
<td>PVC</td>
<td>4.7</td>
<td>0.093</td>
<td>500 v/mil</td>
<td>&lt; 0.5%</td>
<td>5 kpsi</td>
<td>120 – 500%</td>
</tr>
<tr>
<td>Aramid Paper</td>
<td>2.0</td>
<td>0.007</td>
<td>380 v/mil</td>
<td>3.0%</td>
<td>11 kpsi</td>
<td>~10%</td>
</tr>
</tbody>
</table>

Table 3-2 Comparison of selected properties of flexible base materials

**ADHESIVES FOR FLEX CIRCUITS**

Flexible adhesives are used either to bind the metal foil to the base material to create a laminate or to bind layers of laminate material together, such as is found in multilayer constructions. Normally, the chosen adhesive is carefully matched to achieve the best mix of desirable properties for the laminate.

Following is a brief discussion of the general attributes of the adhesives most commonly used for flex circuits. A general comparison chart of the properties of different adhesives is provided in Table 3-3.

**POLYESTER ADHESIVE**

Polyester adhesives are typically used with polyester laminates; however, they have also been used occasionally with other materials, depending on the application. Chief among the advantages of polyester adhesives are low cost and the low processing temperatures required for bonding. A drawback, however, is that polyester adhesives exhibit poor high temperature performance, limiting the number of potential applications.

Other potential drawbacks are that the adhesive flow in lamination tends to be high, and bond strength tends to be relatively low. Still, they do work suitably in many applications where their temperature and physical limits will not be pushed.

**ACRYLIC ADHESIVE**

Acrylic adhesives have long been a first choice for flex circuit manufacture. They have been commonly favored for many polyimide laminates due to their excellent adhesion and ease of processing. Acrylic adhesives offer a good balance of reasonable thermal performance
(withstanding soldering temperatures), process ease and natural ability to bond reasonably well to many different materials.

On the negative side of the ledger, acrylic adhesives tend to swell in the hot alkaline processing solutions common in many electroless and electrolytic circuit board plating lines. Additionally, as was referenced briefly earlier, they have a rather high coefficient of thermal expansion, which has implicated them as a prime cause of through hole plating cracks when used extensively in multilayer and rigid flex constructions due to excessive Z-axis expansion.

**EPOXY AND MODIFIED EPOXY ADHESIVES**

Epoxies are among the most commonly used adhesives in the world, so it is no surprise that they find some application in flex circuits. Epoxies and modified versions of epoxies are near universal adhesives, capable of bonding with many different materials, including metals, ceramics and polymers.

The high temperature capabilities of epoxies are quite good, providing some of the best post solder float peel strength values. On the downside, epoxies tend by their nature to be more brittle than some of the alternative choices, however, modifications to the formula have proven successful in mitigating this issue. Epoxies are also somewhat prone to moisture uptake and thus require a bit more processing care on the part of the manufacturer.

**POLYIMIDE ADHESIVES**

Polyimide adhesives are necessarily limited to use with polyimide substrates due to the higher temperature processing required. Nevertheless, use of polyimide adhesives affords better matched—and thus improved—laminate substrate properties. They are increasing in popularity in some product applications.

Typical polyimide adhesives are thermoplastic and require relatively high lamination temperatures and pressures. The net result is that circuits made using polyimide adhesives offer the highest maximum temperature capability of any flex circuit construction. Polyimide adhesives also are seen as possibly being advantageous for multilayer and rigid flex applications due to the lower coefficient of thermal expansion (CTE).

Negative aspects of polyimide adhesives include the fact that there are a limited number of sources and experience levels—which, while increasing, are not as great as they are for other adhesives. One other concern is that the bond strengths reported for polyimide adhesives are somewhat lower than alternatives. This may not prove a large problem over time, but additional experience is required.
BUTYRAL-PHENOLIC ADHESIVES

Another adhesive type of long-standing is butyral-phenolic adhesive. This type of adhesive was actually used to create some of the first flex circuits without benefit of a base film. Butyral-phenolic adhesives have been shown to improve flexural life in some experiments.

<table>
<thead>
<tr>
<th>Adhesive Type</th>
<th>Peel Strength post-solder</th>
<th>Adhesive Flow mils/mil</th>
<th>Moisture Absorption max %</th>
<th>Surface Resistivity min MΩ</th>
<th>Dissipation Factor @ 1MHz</th>
<th>Dielectric Constant @ 1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>N/A*</td>
<td>250µm max</td>
<td>2.0</td>
<td>104</td>
<td>0.02</td>
<td>4.0 max</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1.6 N/mm</td>
<td>125 µm max</td>
<td>6.0</td>
<td>107</td>
<td>0.02</td>
<td>3.5 nom</td>
</tr>
<tr>
<td>Epoxy</td>
<td>1.4 N/mm</td>
<td>125 µm max</td>
<td>4.0</td>
<td>104</td>
<td>0.06</td>
<td>4.0 max</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1.0 N/mm</td>
<td>125 µm max</td>
<td>3.0</td>
<td>105</td>
<td>0.01</td>
<td>4.0 max</td>
</tr>
<tr>
<td>Butyral-Phenolic</td>
<td>1.0 N/mm</td>
<td>125 µm max</td>
<td>2.0</td>
<td>104</td>
<td>0.025</td>
<td>3.0 max</td>
</tr>
<tr>
<td>PTFE</td>
<td>&gt; 1 N/mm</td>
<td>125 µm max</td>
<td>0.01</td>
<td>1012</td>
<td>0.0007</td>
<td>2.2 nom</td>
</tr>
</tbody>
</table>

* Because polyester is considered unsuitable for soldering, the requirement does not apply. Nominal value for minimum peel strength of polyester adhesives is 0.9 N/mm.

Table 3-3 Comparison of selected properties of commonly used flex circuit laminate adhesives

Butyral-phenolic adhesives offer some specific advantages. Chief among them, from the perspective of the flex manufacturer, is the low flow characteristics of the adhesive during lamination. This feature lessens the concern of having adhesive flow on to interconnection lands. Excessive flow onto lands is a rejectable condition if limits are exceeded.

Other advantages of this adhesive type are that it has reasonably low moisture absorption and one of the lowest dielectric constants among commonly used adhesives. On the negative side, circuits made with this adhesive system tend to be rather stiff in comparison to some of the alternate choices.

OTHER ADHESIVES

In addition to all of the above-cited adhesives, a number of other thermoplastic materials have also been used in the past to fabricate flexible circuits. Included in this grouping are FEP and polyetherimide (PEI). These materials require processing much like polyimide adhesives, which must normally be bonded at very high temperatures and pressures.

FEP is sometimes used as low loss bonding film in multilayer microwave frequency boards and is often chosen because of the lower temperature for processing. FEP is a thermoplastic and can re-melt at extended periods above 550°C in assembly, which could, for example, cause delamination at some lead-free soldering temperatures. This concern over high-temperature soldering extends to PEI as well, so it is recommended that the materials be qualified for use in high temperature applications.
METAL FOIL AND METALLIC COATINGS

While copper is by far the most common metal used in flex construction, a wide range of other metal foils is available for use should special need arise. Virtually any metal that can be produced in foil form or that can be sputtered or plated is a candidate metal foil for flex manufacture. While many choices are possible, only a very few have seen actual volume use. Following are descriptions of a few of the many types of metallic foils available and a review of some of their actual or potential applications.

COPPER FOILS

Copper foils, as previously stated, serve the vast majority of all flexible circuit applications. Copper’s fine balance of cost and physical and electrical performance attributes makes it an excellent choice. There are actually many types of copper foil. The IPC metal foil specification IPC-4562 (formerly IPC-MF-150) identifies eight different types of copper foil for printed circuits, divided into two much broader categories—electro-deposited and wrought—each having four subtypes. (See Table 3-4.) As a result, there are several types of copper foil available for flex circuit applications to serve the varied purposes of different end-products. With most copper foil, a thin surface treatment is commonly applied to one side of the foil to improve its adhesion to the base film. (See Figure 3-4.) Following is a brief examination of some of the most common forms of copper foil.

<table>
<thead>
<tr>
<th>Copper Foil Type</th>
<th>Number</th>
<th>Designator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-deposited</td>
<td>1</td>
<td>STD - Type E</td>
<td>Standard electro-deposited</td>
</tr>
<tr>
<td>Copper Foils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>HD - Type E</td>
<td>High ductility electro-deposited</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>HTE - Type E</td>
<td>High temperature elongation electro-deposited</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>ANN - Type E</td>
<td>Annealed electro-deposited</td>
</tr>
<tr>
<td>Wrought</td>
<td>5</td>
<td>AR - Type W</td>
<td>As rolled-wrought</td>
</tr>
<tr>
<td>Copper Foils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>LCR - Type W</td>
<td>Light cold rolled-wrought</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>ANN - Type W</td>
<td>Annealed-wrought</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>LTA - Type W</td>
<td>As rolled-wrought low-temperature annealable</td>
</tr>
</tbody>
</table>

Table 3-4 A summary of current copper foil categorizations

ELECTRO-DEPOSITED COPPER (STANDARD)

Standard electro-deposited copper is recommended and used primarily for static applications due to its grain structure, which tends to be columnar (see Figure 3-4). This type of grain structure is not well suited to dynamic
flexing, owing to the fact that the vertical grain boundaries establish a short path for crack propagation.

Electro-deposited (or ED) copper foil is not commonly used for flex circuit manufacture in the US, but modifications and treatments to such foils could cause them to become more viable candidates in the future. Nevertheless, electro-deposited foils are lower in cost and still quite suitable for some applications and have been readily accepted for use in flex circuit manufacturing in many other countries.

**ELECTRO-DEPOSITED COPPER (HEAT-TREATED)**

One of the variants of standard electro-deposited copper accounted for in IPC-4562 is heat-treated electro-deposited copper foil. This foil type is treated at high temperature to modify the copper grain structure after electro-deposition to create a more ductile foil. The foil may be suitable for certain dynamic applications because of the recrystallization of the grain structure that occurs, approximating the grain structure of rolled and annealed copper.

![Figure 3-4 Cross-section and top views of low-profile treatment reveal how adhesion is improved.](image)

**WROUGHT OR ROLLED AND ANNEALED COPPER**

Wrought or rolled and annealed copper foil, also known as RA copper is produced using traditional metalworking methods. The process involves passing a copper bar through a series of metal rollers until a thin foil is produced. The foil is then heat-treated to bring the copper to a “dead” soft state. This method can create foils economically down to 18µm (1/2 oz.); specialty rollers can make even thinner foils, but the thinner foils are commonly offered only at a premium. As the most commonly used copper-foil type for flexible circuit applications, RA normally affords excellent flexural life due to grain structure.
Wrought alloys of copper can also be used in flex-laminate construction. These foils can offer greater strength and toughness, making handling in manufacture easier. They also have an advantage in low-strain/high-cycle-life flexing applications and may be a superior choice for some of these applications.

**Electroplated Copper**

With some flex materials, the copper is plated directly onto the base substrate using combinations of electroless and electrolytic plating. Electroplated copper is differentiated from electro-deposited copper by virtue of the fact that its as-plated properties can be vastly different from those produced by normal foil deposition processes. Some electroplated foils exhibit properties equivalent to RA copper and, under some conditions, give superior results. This is due, in part, to the nature of the process, which, because of the special additives used, allows the production of an amorphous or equiaxed grain structure. (See Figure 3-5.) The foil produced is much less sensitive to grain orientation effects than RA type foils.

**Sputtered Copper Films**

Another approach to getting thin copper onto flexible base materials is to sputter or vapor-deposit seed metals and plate up. The method has been in use for roughly two decades, but only in recent years has it gained the attention of a broader audience, owing to the need for finer lines and traces. One of the historical problems with the method was obtaining a foil that was consistently pinhole free and had sufficiently high peel strength.

![Figure 3-5 Copper foil grain structures vary with the process used to create the foil. Shown above are vertically ordered grain, horizontally ordered grain, and amorphous or equiaxed grain.](image)

Similar to electroplated foil, sputtered copper provides very thin (typically less than 1µm) copper film deposited directly onto base films.
over a much thinner adhesion promoting layer of nickel, chrome, nickel or Monel. The thin sputtered copper film serves as a seed layer for subsequent electroplating.

Such films are extremely useful in fabricating very fine line circuits and certain unusual constructions or applications. For example, the thin copper film is ideal for cryogenic applications where electrical conductivity is sufficient but thermal conductivity is relatively poor for the thin film. Beyond such esoteric applications, sputtered copper films are proving quite suitable for high cycle life dynamic applications such as disk drives, provided the plating process is well controlled.

**Other Thin Copper Options**

The never ending drive to reduce the size of electronic products and systems has resulted in the need for thinner copper foils to produce the finer circuit lines and traces required. Making thinner copper foils that can fulfill the requirements for flexible circuits is no mean task. The foil is expected to be pinhole free and to provide the adhesion so important for reliable manufacture and use. Some foil and material suppliers have devised and implemented a number of new and improved methods for meeting the requirements. A brief review will, hopefully, help clarify the choices.

As noted earlier, traditional rolled and annealed foils have found favor with flexible circuit material suppliers and users; however, rolling copper foils to values less than 17μm in thickness, while possible, tends to be expensive. To extend the role, foil suppliers such as the Somers division of Olin Corporation have developed technology that will allow for 3μm and 5μm copper foils to be bonded to flex circuit base materials. The “trick” is creating the thin foils on a rolled copper foil carrier of normal 35-micron thickness. The product is uniformly thick and pinhole free. The adhesion treatment, common on copper foils, is desirably low profile for flexible circuits. This attribute improves etch characteristics, allowing finer features with some (preferably minor) penalty in peel strength.

For the new Olin copper foil material, a proprietary inorganic release layer is used between the rolled foil carrier and the thin copper foil. The force required to remove the carrier foil after lamination is reportedly very low (about 1-2 grams/centimeter or approximately 0.1 oz/in), even after lamination at temperatures required for flex circuit materials. Gould and Oak Mitsui have similar ultra thin copper foil on carrier foil solutions in the market, also targeted at very fine line circuit applications.

A final option in this review is an adhesiveless tie coat-free flexible copper clad laminate from Fractal. The lack of a tie coat is made possible by an innovative micro-mechanical bonding technology, the resulting peel strength of which reaches an amazing 2-2.5 kilograms/centimeter (~ 12-17 lbs/in).
The manufacturing process reportedly involves an unusual technology in which polymer films are irradiated by heavy high-energy ions and then treated chemically to “develop out” the irradiated spots, and then plated. A photomicrographic comparison to traditional treatments is offered in the attending images. Single- and double-clad copper-polyimide flexible circuit laminates with foil thicknesses from 5-18µm are being offered. With such high peel strengths, the materials are likely to withstand the rigors of gold plating very well.

In summary, the demand for high density circuitry on flexible substrates has driven the foil manufacturing industry to develop some very innovative solutions. Those solutions are making possible leading edge products of today and securing the future for next generation opportunities. Each solution has merit, and having more than one solution is a blessing to both design and manufacturing.

<table>
<thead>
<tr>
<th>Metal Foil</th>
<th>Resistance Ω/cm x 10^6</th>
<th>Thermal Conductivity W/m*K</th>
<th>Tensile Strength psi</th>
<th>% Elongation (annealed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Rolled annealed</td>
<td>1.67</td>
<td>393</td>
<td>32,000</td>
<td>20</td>
</tr>
<tr>
<td>Copper Electro-deposited</td>
<td>1.77</td>
<td>393</td>
<td>25,000</td>
<td>12</td>
</tr>
<tr>
<td>Aluminum</td>
<td>4.33</td>
<td>225</td>
<td>16,000</td>
<td>30</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>75</td>
<td>6</td>
<td>90,000</td>
<td>40</td>
</tr>
<tr>
<td>Beryllium Copper</td>
<td>~8</td>
<td>83</td>
<td>60,000*</td>
<td>35 - 60*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200,000**</td>
<td>1 - 4**</td>
</tr>
</tbody>
</table>

* Annealed Dead Soft ** Heat-Treated Full Hard

Table 3-5 Comparison of selected properties of metal foils
**BERYLLIUM COPPER**

Beryllium copper is a useful choice when good conductivity, mechanical strength and/or spring-like qualities are simultaneously sought. While beryllium copper is not as conductive as copper (with approximately 25% the conductivity of copper), the metal is one of the standards of the electrical connector industry due to its unique blend of properties.

One of the concerns registered on occasion is the fact that beryllium is a toxic metal, but because the metal is not used in its native state but rather in an alloy, this has been shown to be a low order concern. In machining, the dust should be well controlled, but etching is not a general concern.

**ALUMINUM FOIL**

Aluminum foil has been used in special applications where reduced weight or cost is sought and the design will accommodate its use. Aluminum foils have proven particularly successful in simple flexible shielding applications. When plated with electroless nickel/gold, the terminations become both separable and/or solderable.

**IRON ALLOY FOILS**

Various iron alloys (stainless steel, Iconel, etc.) have been used and proven of value in applications where low thermal conductivity requirements were coupled with the need to pass electrical signals. A prime example is in the interconnecting of instrumentation in cryogenic devices, however, as noted earlier, very thin sputtered films of more conductive metals may also serve this function, provided that the electrical currents are not too high. Because such foils are so resistive, they have proven very useful in creating flexible heaters.

**OTHER CONDUCTOR MATERIALS**

Beyond traditional metal foils for creating conductors, other products and processes can serve to provide conductive (or resistive) pathways on flexible base laminates. Following are descriptions of some common and not so common alternative conductor materials.

**POLYMER THICK FILM FLEX CIRCUITS**

This is a special subset of flexible circuits, where specially formulated conductive and resistive inks are screen-printed onto flexible substrates to create circuit patterns. The conductive inks are normally silver filled polymers, and the resistive inks are filled with carbon or mixtures of silver and carbon.

Polymer thick film technology (PTF) is an extremely popular method for producing a range of cost effective products—from membrane switches
Flexible Circuit Technology

such as computer keyboards and touch pads to low cost calculators and disposable medical devices such as blood gas monitors. In certain cases, polymer thick film circuits can be integrated with copper foil base laminates to create novel structures that combine the benefits of PTF and copper foil, especially when there are specific requirements for higher conductivity in certain areas of a circuit.

Polymer thick film technologists have also developed SMT adhesives for mounting components on PTF circuits. This is potentially a good solution for the attachment of temperature-sensitive components and also an environmentally benign alternative to lead containing solders.

**INDIUM-TIN OXIDE**

Indium-tin oxide, or ITO as it is also commonly known, is unique among conductor materials in that it is transparent. It is one of the more important enabling technologies for liquid crystal displays but also offers a range of other possibilities. Touch screen monitors are one such example. The coatings, which are deposited in a vacuum, are very thin but reasonably tough. Normally, ITO is used on glass, but it can also be found on clear polymer films such as polyester, making it a potential candidate for solving unusual problems.

**EMBEDDED RESISTOR-MATERIAL FLEX CIRCUITS**

A unique construction technique for making flex circuits with embedded passives such as resistors, uses a specially fabricated foil supplied by Ohmega Industries (Culver City, Calif.). The foil is a combination of resistive and conductive layers. By using special design rules and a special three-step etching process, it is possible to create circuits with built-in or embedded resistors.

Though not well suited for high power applications, the material can provide an effective solution for termination resistors. This helps to reduce both assembly complexity and weight. A cross-sectional representation of a single resistor made from the material is illustrated in Figure 3-7. Alternative methods are also possible—by sputtering, for example. This is accomplished by sequentially sputtering resistive and conductive layers.
Flexible Circuit Technology

and processing in a fashion similar to the foil form. In either case, one should avoid using the resistor material in flex areas due to the potential for fracturing the resistor in the field.

Figure 3-7 A process sequence for built-in resistor manufacture

PLATABLE TONER FLEXIBLE CIRCUITS

This is another special subset of flexible circuits, patented and developed in the early 1990s by now defunct Extended Length Flex Technologies (Foster City, Calif.). The concept was interesting in that a platable toner was used to create a flex circuit pattern directly on a flexible substrate. The proprietary catalytic toners, which were electrostatically deposited by means of a modified laser printer, were subsequently processed through electroless and electrolytic copper to create the metal pattern on the surface. The result was a unique, fully additive flex circuit process. A couple of unusual features of the technology are that it allows for the production of extreme length flexible circuits and, at the same time, can enable the economical manufacture of a single circuit.

While the technology did not take hold, some of the concepts espoused by the company have been picked up on by others, and some of the manufacturing concepts and capabilities originally intended for this technology may be available in the not too distant future using other process techniques as described earlier.
SUMMARY

A wide variety of materials is used in the manufacture of flexible circuits, including films, foils and adhesives. While, presently, polyester and polyimide still dominate the base film market, newer materials continue to be examined and introduced, such as PEN and LCP—both of which may have a significant role to play in the future as an intermediate in cost (in the case of PEN) and as a higher performance option (in the case of LCP). In the same vein, thin reinforced PTFE materials could well serve an important role as well as digital signaling reaches further into the realm of RF speeds.

In addition to the base materials, a broad range of adhesives and many types of metal foils can be used in base-material construction. The choice of which materials to use is highly dependent on how and where the circuit ultimately will be assembled and used. Careful evaluation of the relative merits of the different materials may be required in order to make the best choice for a given application.
Implementing Flexible Circuit Technology

INTRODUCTION

It is highly evident that flex circuits offer unique capabilities, opportunities and options to the electronics system designer. However, to gain the advantages of flexible circuits, it is necessary to go through an implementation process, and that requires a significant amount of thought, consideration and planning. Lack of proper planning can make (and has made) the difference between either enjoying a rewarding experience or suffering through a painful one.

The process of implementation is not as difficult as it once was. Experiences of earlier users serve as guides to those who now follow, providing a map to chart a course around the most commonly encountered obstacles.

This chapter addresses the important issues of implementation by using a simple 13-step approach. The intention is to provide a basic, easy-to-follow guide to the successful incorporation of flexible circuits into new or existing products.

IMPLEMENTATION STEPS

The approach and suggested steps provided are not exhaustive, because it is not possible to anticipate and address all of the potential variations. Still, the hope is that this chapter will supply sufficient detail to help guide the user to a satisfactory end. Following is a suggested stepped approach.

STEP ONE: Define End Product Requirements

It is recommended that a market-driven approach to defining end product requirements. The product should be given as much definition as possible by end users. This assures that they will get the value and/or features they seek. At this point, it is worthwhile to determine if flex circuits are the best choice for the product. It may be that by examining alternatives, a better or more cost-effective solution can be found—for example, a thin rigid board may serve as well as a flex circuit when thinness is the only requirement.

The prospective user should also consider cost targets or requirements,
product life expectations, product size, etc., in order to make sure that the decision to use flex circuits is a sound one. In addition, he should assure himself that the materials and processes that will be used will measure up against those requirements.

**STEP TWO: Determine Reliability Requirements**

One should give early consideration to the reliability requirements for the product. What level of reliability is needed? The IPC uses a classification system for products according to their end use: Class 1 for consumer products, Class 2 for business and telecommunications, and Class 3 to meet the requirements of military aerospace and life support products.

The end product requirements will heavily influence many of the choices that must be made in terms of materials and processes. It is also worthwhile to consider product liability. What are the ramifications of product failure? While not pleasant considerations, it is very important that they be consciously addressed.

Thermal cycling is considered one of the key determinants of product life, and products from different markets must endure very different conditions. As a guide, the IPC created a chart to assess and approximate thermal cycling conditions. Table 4-1 is an abbreviated version of the chart.

**STEP THREE: Determine Operating Environment**

Product operating environment is another important factor that will influence design and manufacturing choices. Ask: “Where will the end product be used?”... In an office?... At home?... In an automobile?... In an aerospace application?

Such forward thinking will help lead the user to a determination of what the operating environment for the product is likely to be and also to bracket what temperature and relative humidity extremes are to be expected over the life of the product, as well as how often the product might be thermally cycled.

Determining what the correct material choice might be is simplified by this analysis. Still, at the same time, one must also keep in mind the assembly process. There are several descriptive tools available that define the different requirements for various use environments; these tools can serve to facilitate the decision making process. Again, Table 4-1 is a very simplified chart of operating environments for different product types.

**STEP FOUR: Define Package Configuration**

Consider the target size and shape of the package early on in the process. This is the foundation on which many other decisions will be made.
Included in this effort should be a determination of where the optimum locations are for components, I/O ports, switches and control devices for product performance, and assembly ease and usability.

A mockup of the product box will be necessary for laying out the flex circuit, facilitating conversion of the three-dimensional package requirement to the two-dimensional format needed for manufacture.

**Step Five: Define Mechanical Requirements**

Consider what mechanical requirements will be placed on the flex circuit. Will it be a static or dynamic application? If the application requires dynamic flexing, will it require continuous or intermittent operation? If dynamic, what will be the frequency of flexing? Will it be thousands of cycles per hour or only hundreds of cycles per year? The construction and material choices can be heavily influenced by the answers to these simple questions.

**Step Six: Define Electrical Requirements**

As with any electronic product, it will be necessary to determine, as early as possible, what the key electrical requirements will be. For example, what will the power requirements be? How much current will be needed and at what voltage? What is the expected maximum or peak current? Is EMI a concern, and will there be a need for shielding? If the circuit is large, is voltage drop a concern? Are commonly experienced electrical parasitics, such as capacitance and inductance, important issues relative to the performance for the design or application? Each of these items can affect both material and design choices.

There is also the matter of conflict of purpose in design. In some cases, the electronic needs of the product are at cross-purposes with mechanical requirements. For example, there may be a wish to flex a microstrip construction dynamically—a situation that is not recommended from a mechanical perspective. How might that be resolved? Such issues need to be brought out early and resolved before the design is committed to manufacture.

**Step Seven: Determine Component Locations**

In general, components, connectors, switches and other devices should rest on reinforced areas such as stiffeners and areas that are to be flexed or bent should have no components placed on them. Exceptions are possible, of course, but it is not a preferred practice in general and should never be done in areas that are to be actively flexed.

**Step Eight: Determine Assembly Method**

One should also give early consideration to which type of component assembly method is to be used. The quantity of the product, the substrate
## Thermal Excursion Expectations for Product Markets

<table>
<thead>
<tr>
<th>End Market</th>
<th>Stage in the product life</th>
<th>Temperature range potential</th>
<th>Number of thermal cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumer</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>0 to 60°C</td>
<td>365 per year</td>
</tr>
<tr>
<td><strong>Computers</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>0 to 60°C</td>
<td>1460 per year</td>
</tr>
<tr>
<td><strong>Telecom</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-40 to 85°C</td>
<td>365 per year</td>
</tr>
<tr>
<td><strong>Commercial Aircraft</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-55 to 95°C</td>
<td>3000 per year</td>
</tr>
<tr>
<td><strong>Industrial &amp; Auto (Passenger Area)</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-55 to 95°C</td>
<td>~200 per year</td>
</tr>
<tr>
<td><strong>Automotive Under Hood</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-40 to 125°C</td>
<td>1000 per year</td>
</tr>
<tr>
<td><strong>Military Land and Sea</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-40 to 85°C</td>
<td>100 per year</td>
</tr>
<tr>
<td><strong>Military Avionics</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-40 to 95°C</td>
<td>500 per year</td>
</tr>
<tr>
<td><strong>Space Low Earth Orbit</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-269 to 95°C</td>
<td>8760 per year</td>
</tr>
<tr>
<td><strong>Space Geosynchronous Orbit</strong></td>
<td>Processing</td>
<td>25 to 260°C</td>
<td>0 to 5</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>-40 to 85°C</td>
<td>Varies</td>
</tr>
<tr>
<td></td>
<td>Operational</td>
<td>-269 to 95°C</td>
<td>365 per year</td>
</tr>
</tbody>
</table>

*Certain industrial controllers and scientific instrumentation are designed for very-high-temperature environments.*

Table 4-1 Environment selection and thermal excursion projections for electronic assemblies used in various end markets (Source: IPC, Northbrook, IL)
material used, and the size of the part will all help to give this consideration some definition. Choices for electromechanical joining include soldering, the use of conductive adhesives and even mechanical fastening. Again, with the higher temperatures associated with the increased use of lead-free solders, temperature limitations of material must be fully understood.

With respect to soldering, it is possible to perform the process either by hand or machine. Relative to machines, there are several possible methods: wave solder, infrared (IR), vapor phase, convection oven, hot bar and even laser. One should keep in mind that the cost of assembly can be quite high if it requires special or individual handling. However, the cost can be better constrained by carefully considering how best to lay out the circuit to facilitate the assembly process.

**STEP NINE: Define Electrical Testing Needs**

What type and level of testing will be required? How, when and where the test will be performed is, unfortunately, often either ignored or an afterthought in the design process. Nevertheless, it is important that testing be given due consideration before embarking on a design. Some questions to raise in design are: Will testing of the bare flex be required? Will only the assembled board be tested? Are both levels of test needed? How will the test contacts be accessed? The design complexity of the flex will impact and help to steer the decision process relative to electrical-test needs.

Due to the fact that they employ relatively soft and highly flexible substrates, flex circuits have special concerns when it comes to the matter of electrical test. This is because the test probes can easily damage the circuit surfaces. On the other hand, because they are flexible, circuit test fixtures can be made smaller than normal when necessary, and the flex circuit can be shaped to fit the fixture.

**STEP TEN: Define Mechanical Testing Needs**

Mechanical testing, especially flexural endurance testing of the flex circuit, is often a requirement for flexible circuits being fabricated for dynamic flexure applications. There are several options for such testing, and it is good to be properly prepared with appropriate equipment. This topic will be reviewed in more detail later in the book.

**STEP ELEVEN: Create a Demonstration Circuit**

At some point before committing the circuit to production or even to prototyping, it is worth taking the time to verify the electronic functionality of the circuit. This can still be done through long-standing empirical methods such as bread-boarding, but it is more common to use some type of simulation software.
The objective of this activity is to avoid tooling for manufacture until the fundamental circuit is proven. This step may not prevent unforeseen incompatibilities between circuit elements in the final form, but it should reduce overall costs. That said, simulation tools are continually getting better, and it may be that in many cases this step can be satisfied by simulation.

**STEP TWELVE: MOCKUP FLEX CIRCUIT**

The use of mockups or paper doll flex circuit models has long been an important part of a successful flex circuit implementation process. A mockup of the final package should be used to provide a mandrel for the circuit layout. A simple piece of paper served well in the past in laying out circuit trace runs to meet routing requirements for all I/O points; however, present day CAD and EDA software can accomplish much of this task.

Over the years, the use of this step has helped to expose many packaging problems early, thus minimizing potential for gross and easily avoidable errors. Having a physical model also saves time and money by providing an ergonomic check for circuit access and verifying the ease of final assembly and field service. Figure 4.1 shows a simple example.

**STEP THIRTEEN: GENERATE CAD DATA PACKAGE**

As a last step, generate appropriate documentation and data packages having circuit features and circuit outline information that follow all pertinent flex design rules. Today, most manufacturers prefer to receive data in digital form. This allows them to make needed adjustments to compensate for circuit processing. The data package should be double-checked both for mechanical and electrical concerns and for accuracy to avoid a loss of time due to downstream problems.
In summary, this brief 13 step review of some of the more important considerations relevant to flex circuit implementation should provide an appreciation of the level of detail that must be addressed before entering into a flex design.

It is generally true that the simplest strategy for a flex circuit implementation is likely to be the best strategy. Historically, flex circuits are best implemented slowly, starting with simpler constructions first, the better to grasp the subtleties of flex circuit design, assembly and use. This strategy may, of course, need to be altered out of the necessities of the design challenge at hand, but this does not change the notion that simpler constructions represent a better starting point for the novice. Nevertheless, the general concepts outlined here still apply and will ease the implementation process.

**Flex Circuit Cost Factor Analysis**

It is inevitable that the matter of cost be addressed somewhere in a text on technology. No matter how great the technology, if it cannot meet cost targets, it is unlikely that there will be much chance for broad appeal and acceptance. Because flexible circuit technology is so diverse in construction and materials, the matter of cost is not an easy subject to tackle. There are, however, some generalized methods for assessing whether the technology is suitable. It must be assumed that there is or will be a breakeven point somewhere as volume increases and one technology surpasses another. This concept can be easily visualized, and Figure 4-3 is provided for that purpose.
The break-even determination chart found in Table 4-2 is also offered as an example of how a prospective user can determine what quantity of flexible circuits must be built to offset the expense of tooling up for flex circuit production. The example assumes that the flex circuit will replace a wire harness, but any other technology that might serve could be inserted with its factors in place of the wire harness.

When looking at cost, it is important to remember the many advantages flexible circuits offer. In some instances, the flex circuit may be more costly than the alternative “in the door,” but in the final analysis and at the system level, the ultimate cost is much lower. It is often found that flexible circuits are an enabling, value-add technology that can lower the overall cost of an electronic system. Lack of appreciation of the “cost in/cost out” paradigm has foiled the efforts of many price-conscious circuit purchasers in the past, and it is a mindset to avoid.

In short, while flex circuits may be more expensive than some alternatives on a cost per unit area basis, the technology is capable of solving problems in many areas of design and manufacture, thus offsetting any cost differential. Flex circuit technology can make electronic products easier to build and provide greater reliability.

Looking forward, owing to the nature of the technology, it may be possible in the future to “write” circuits directly onto polymer from roll to roll on a continuous web. Such manufacturing concepts hold great appeal in that they could well make possible flex circuit manufacture at an economical run unit of one part—an idealized objective of almost any manufacturing process. In actuality, it appears that such solutions are in the works and being evaluated at this time.
Flexible Circuit Technology

**Calculating a Breakeven Point**

*(After Sheppler, et al)*

Breakeven point $= \frac{\text{NRE (flex)}}{\text{NRE (alternative)}} - \frac{\text{RC (alternative)}}{\text{RC (flex)}}$

<table>
<thead>
<tr>
<th>Flex Circuit NRE</th>
<th>Wire Harness NRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit design &amp; artwork</td>
<td>Wiring diagrams</td>
</tr>
<tr>
<td>Documentation</td>
<td>Assembly drawings</td>
</tr>
<tr>
<td>Mock-ups</td>
<td>Harness assembly board</td>
</tr>
<tr>
<td>Hard &amp; soft tooling</td>
<td>Potting molds</td>
</tr>
<tr>
<td>Flex Circuit RC</td>
<td>Wire Harness RC</td>
</tr>
<tr>
<td>Manufactured unit price</td>
<td>Wire inventory</td>
</tr>
<tr>
<td>Inspection and test</td>
<td>Cut, strip and mark wires</td>
</tr>
<tr>
<td>Assembly</td>
<td>Lay out wires on boards</td>
</tr>
<tr>
<td>Installation</td>
<td>Solder wires to connector</td>
</tr>
<tr>
<td>Carried inventory</td>
<td>Test and correct errors</td>
</tr>
<tr>
<td></td>
<td>Pot wires in connector</td>
</tr>
<tr>
<td></td>
<td>Install</td>
</tr>
</tbody>
</table>

Factors: NRE = Non-Recurring Engineering  RC = Recurring Costs

Table 4-2 Breakeven point analysis for flex circuits versus wire harness alternatives

**SUMMARY**

Hopefully, it is clear that flexible circuit technology requires some thought prior to embarking on a new design. The technology offers some very important abilities and many advantages. Even so, while the reader has been told of numerous current and potential advantages, no technology is risk-free. Thus, it is recommended that prospective users perform their own appropriately rigorous analysis to determine whether the use of flexible circuits in any given situation is practical and makes economic sense. For example, when a thin rigid board may suit the task nicely, there may be no need to use a flexible circuit.

While we believe that the list of steps is fairly complete for the present, when viewed against the growth and expansion of flexible circuit technology, it is likely that some amplification of the list may be required over time to reflect new realities in materials, design tools and manufacturing technology.
Flexible Circuit Technology
INTRODUCTION

Flexible circuits are obviously unique among electronic packaging technologies in that they offer a wide variety of advantages unobtainable using conventional rigid interconnection technologies. Freeform integration of electronic elements through all three dimensions of space is highly liberating to the design process.

Such advantages, however, cannot be garnered without a thorough understanding of basic flex circuit design principles. Proper use of those design principles can provide a path to early success. In contrast, failure to use good design practices can result in early failure. The objective of this chapter is to provide information vital to the successful production of flexible circuit designs—ones that will consistently perform to user expectations.

DESIGN PRELIMINARIES

Before embarking on a flex circuit design, it is important that a holistic overview of the project be taken. In this overview, a circuit designer should attempt to take into account as many of the items discussed in the implementation section as are possible or relevant. This act of taking stock of the project will help the designer appreciate the broader perspective of the task, minimizing the possibility that a gross and avoidable error will be carried through the design process.

It is also important that the designer keep in mind that flexible circuit designs require a balancing of both mechanical and electrical concerns. These two competing concerns, the designer will find, often oppose each other’s requirements in a design. It will be the holistic approach that will help the designer thread the needle to make the best possible choice from given alternatives.

USE OF MOCKUPS

Let us reassert here the value of using paper doll mockups. This simple practice will help the designer prevent many errors by exposing potential
problems early and will save both time and money.

Some modern CAD systems have demonstrated the ability to execute three dimensional layouts required for flex circuit applications, but the physical model will probably always prove of some value in addressing both the ergonomic elements of assembly and the concerns of access should field repair be required.

![Normal Practice Design](image1.png) ![Copper Bias Design](image2.png)

**DESIGN WITH A BIAS FOR COPPER**

Favoring the use of copper in design is good practice for some very solid reasons, assuming that there are not important conflicts created by the practice. If all other design objectives are met, then the primary reason for maintaining extra copper is that it helps to enhance the dimensional stability of the circuit. Designing with a bias for copper is a practice especially well suited to single-layer flex circuit designs. See Figure 5-1.

As indicated before, the decision to add or leave copper should be made in light of the objectives of the circuit’s final use. For example, if a reduction in weight of the final product is a key objective, then there would be need to trade away some of the enhanced dimensional stability. Another reason for maintaining the copper is that it reduces the amount of copper etched and is thus more environmentally friendly in terms of chemical usage.

![Copper Retained Around Parts](image3.png)

**TOLERANCE SETTING FLEX CIRCUIT DESIGNS**

Proper application of tolerances of flex circuit design features is a matter that concerns both the flex circuit manufacturer and the flex circuit user.
In general, it is recommended that the largest practical tolerance be given to all features and locations to facilitate manufacture. This is because the base materials are flexible and prone to distortion, making accurate measurement over distances difficult. To compensate, it is recommended that more than one datum be used on larger circuits. Individual datums can be provided locally relative to features deemed important. (See Figure 5-3.) This will result in a more accurate measurement being taken and can preempt potential conflicts in measurement results between inspectors. To avoid confusion in design, one datum should be defined as the primary or master datum and others as secondary or slave datums.

Tight tolerances can be attained, when required, but to do so requires

<table>
<thead>
<tr>
<th>General Guidelines for Circuit Feature Sizes and Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Feature</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Hole size</td>
</tr>
<tr>
<td>Trace width</td>
</tr>
<tr>
<td>Space width</td>
</tr>
</tbody>
</table>

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Figure 5-3: The use of multiple datums, with one being the prime and the others secondary, facilitates both accurate measurement of the circuit and device placement during the assembly process.

---

Mil-Std-2118 offers the following statement regarding tolerances: “Drawing tolerances must reflect bend and fold allowances between component mounting rigid areas.”

Table 5-1 Tolerance guidelines for standard flex circuit manufacture. (Chart does not apply to leading edge products.)
special attention and good techniques. As a result, the expense of tighter tolerance circuits tends to be greater due to anticipated loss of yield. Table 5-1 provides some general guidelines for tolerancing based on different design standards.

The values offered in Table 5-1 are rather generous by today’s standards, however. To provide a global perspective on flex circuit feature capability, a 2004 survey of 20 Japanese flexible circuit manufacturers indicated that more than half of the companies were routinely producing flex circuits with traces of 110µm or less, and five companies were producing circuits with features of 70-90µm routinely. Today, a number of flex circuit manufacturers in Japan and elsewhere are producing circuits having features of 35 to 50µm and some have shown capabilities down to 25µm and even 10µm feature sizes.

**General Guidelines for Dimensioning and Tolerancing**

Proper dimensioning and tolerancing of flex circuits is vital to achieving good manufacturing yield. While it is not possible to point out every possible situation where dimensions and tolerances can be used in such a way as to confuse the interpretation of a drawing, there are certain general guidelines that, if followed, can do much to minimize the potential for confusion. Following are a few such guidelines:

- Show sufficient dimensions so that the intended sizes and shapes can be determined without requiring the distances between features to be calculated (or assumed).
- Provide individual dimensions only once and check them.
- State all dimensions clearly so they can only have a single possible interpretation.
- Show the dimensions between points, lines or surfaces, which have a necessary and specific relation to each other or which control the location of other components or mating parts.
- Check dimensions to avoid accumulations of tolerances that may permit alternative interpretations.
- Provide dimensions to features, which are shown in profile making certain that the feature’s dimensions are not ambiguous.
- Do not show dimensions to lines representing hidden surfaces.
- Do not use “off part” datums.

**Special Design Considerations**

There are some unique elements of flex circuit design that require early consideration. Mostly they address mechanical issues that could affect usability and/or long term performance. However, they will definitely affect circuit layout and so are given early consideration.
Lay Out Circuit to Conserve Material

Conservation of material in flexible circuit manufacture serves to help keep manufacturing costs down. This is important because flexible circuit materials tend to be expensive in comparison with standard rigid materials such as FR-4.

We suggest accomplishing close spacing of the circuit. The technique of optimizing the number of circuits per panel is called nesting. The term optimizing is used in place of the seemingly more logical term maximizing for a reason, that reason being that the layout of a flex circuit should be based on end use, and some uses may demand that portions of the flex circuit be properly oriented relative to the grain direction of the foil (such as is required for dynamic flexing). This may result in a less-than-maximum material use for circuit construction. However, when this is not the case, there is the opportunity to lay the circuit out in various ways to get the most out of the material.

![Diagram of circuit layouts](image)

Figure 5-4 Proper circuit nesting can greatly improve panel yield and lower overall cost. If folding can be tolerated as an assembly operation, yield can be maximized. For dynamic flex circuit designs, the grain direction requirement may impact layout.

While nesting is routinely performed by the manufacturer, the designer can aid in this process by taking advantage of the fact that flex circuits can be bent and folded. Thus, adding a small length to a circuit arm can allow a circuit to be produced more economically, provided the user doesn't mind adding a folding operation to his assembly process. (See Figure 5-4.)

Service Loops

The addition of a small amount of length to the flex circuit beyond the design requirement is advisable for most flex circuit applications. This little extra length of material is commonly referred to as the service loop length.
The purpose of the service loop is to offer sufficient length to facilitate both assembly of the product and servicing of the product once in the field, if it should ever be required. The extra length also helps to compensate for small, unforeseen variations in both the package and the flex circuit.

**Staggered Length Circuits (Bookbinder Construction)**

For ease of flexing multilayer and rigid flex designs, the use of staggered length design is commonly employed. The technique is accomplished by adding slightly to the length of each succeeding flex layer, moving away from the bend radius. (See Figure 5-5.)

A common rule of thumb is to add length equal to roughly 1.5 times the individual layer thickness. This helps defeat whatever tensor strain might have otherwise been built up in the outer metal layers of the multilayer flex and prevents buckling of the center of bend layers (see Figure 5-6).

**Conductor Sizing and Routing**

In general, flex circuit conductor width and thickness are determined by a combination of current carrying requirements, the voltage drop allowance and/or characteristic impedance control needs. When designing flex circuits for dynamic applications, the use of the thinnest possible copper is recommended. Thus, it is important that the designer opt for wider rather than thicker traces to accommodate basic electrical needs or requirements. This practice assures maximum circuit flexibility.

Table 5-2 can be used to determine maximum current and line resistance for given trace widths with both 35μm (1-oz) and 70μm (2-oz)
Flexible Circuit Technology

copper. These are relatively common foil thicknesses used in much flex circuit manufacture, although 18µm (½-oz) and even lower copper foil thicknesses are becoming increasingly important.

A number of different nomographs for determining other electrical values for copper have been developed to simplify copper trace-requirement specification. The IPC’s flex circuit design specification is a good source for such nomographs for those who have interest. There is an effort underway to revise these graphs, which have long been in use, to reflect more practical values.

<table>
<thead>
<tr>
<th>Conductor Width</th>
<th>Maximum Current for 10° C rise 1 oz copper</th>
<th>Conductor Resistance milliohms/ft 1 oz copper</th>
<th>Maximum Current for 10° C rise 2 oz copper</th>
<th>Conductor Resistance milliohms/ft 2 oz copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>.25</td>
<td>1280</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>0.010</td>
<td>.6</td>
<td>640</td>
<td>1.0</td>
<td>320</td>
</tr>
<tr>
<td>0.015</td>
<td>1.1</td>
<td>400</td>
<td>1.8</td>
<td>200</td>
</tr>
<tr>
<td>0.020</td>
<td>1.3</td>
<td>320</td>
<td>2.0</td>
<td>160</td>
</tr>
<tr>
<td>0.025</td>
<td>1.5</td>
<td>250</td>
<td>2.5</td>
<td>125</td>
</tr>
<tr>
<td>0.030</td>
<td>1.8</td>
<td>200</td>
<td>2.9</td>
<td>100</td>
</tr>
<tr>
<td>0.050</td>
<td>2.5</td>
<td>120</td>
<td>4.0</td>
<td>60</td>
</tr>
<tr>
<td>0.070</td>
<td>3.2</td>
<td>90</td>
<td>5.0</td>
<td>45</td>
</tr>
<tr>
<td>0.100</td>
<td>4.0</td>
<td>60</td>
<td>6.9</td>
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<td>5.9</td>
<td>40</td>
<td>9.8</td>
<td>20</td>
</tr>
<tr>
<td>0.200</td>
<td>6.9</td>
<td>30</td>
<td>12.0</td>
<td>15</td>
</tr>
<tr>
<td>0.250</td>
<td>8.6</td>
<td>25</td>
<td>13.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Table 5-2 Current Carrying Capacity of Conductors. Conductor width and copper thickness have a direct impact on the current carrying capacity of a flexible circuit. The above table provides a means of determining the conductor width for a 10° C rise.

Trace Width Minimums

The minimum practical trace width for a flex circuit varies from vendor to vendor. Flex circuits with traces 250µm (0.010”) and greater are fairly easy to obtain; however, line widths 125µm (0.005”) and lower are increasingly common. Flex circuits having features in the range of 50µm (0.002”) and lower are available in volume production from a limited number of vendors, but the number of such vendors is growing to keep pace with the demand for ever smaller electronic products.

The type of technology used in circuit feature manufacture also heavily influences trace width minimums. For example, plated up copper sputtered polyimide base circuits are basically limited in feature size only by the
photolithographic capabilities of the manufacturer. Thus, very small circuit features can be made. For etched circuit traces, however, the trace width and pitch are influenced primarily by the thickness of the base copper foil.

Typically, the trace pitch limit is nearly linear with copper thickness within a narrow range. 18µm (½-oz) copper will yield circuit features at a 125µm (0.005”) pitch, while with 35µm (1-oz) copper, etching becomes more difficult under 175µm (0.007”) pitch. While some manufacturers can successfully produce 25µm (0.001”) features with 18µm copper, vendor capabilities vary widely. It is best to check with the fabricator before attempting to design very fine line features.

**Controlled Impedance Lines**

Controlled impedance transmission cabling is a popular application for flex circuits, and the value of such product is increasing as digital data signaling speeds continue to rise.

Tighter tolerances for etched features are possible with flex circuits because of the lower profile adhesion treatment or “tooth” of the copper. The use of thicker flexible dielectric substrates, if the design allows, can ease somewhat the etching challenge because thicker substrates allow for wider signal lines, which can be fabricated more easily to meet the tight tolerances needed for controlled impedance circuits. This topic will be discussed in more detail later in this chapter.

**Etch Factors**

An etch factor is a tool used by the manufacturer to compensate for isotropic etching process effects. It is recommended that the designer check with the vendor to determine if they want inclusion of an etch factor. Usually it is best if the manufacturer makes this adjustment, as they will be most familiar with their process and its capability.

![Figure 5-7 The etching process works laterally as well as down, at a ratio of roughly 1:2 laterally to down](image)

The typical line width loss (measured at the top of the trace) due to the etching process is approximately 2x copper foil thickness, although copper type, conductor pitch, etch mask, process chemistry and equipment can all influence the results.
**Conductor Routing Concerns**

There are a few general issues related to conductor routing of a flex circuit. The first item of concern is keeping to a minimum the number of crossovers in the layout. This will help to keep the layer count down and lower the cost. Newer CAD systems can respond to such a requirement, but the results may need to be massaged or optimized to make certain that the smallest possible area has been consumed in the process.

Routing of conductors on a flexible circuit perpendicular to bend and fold is the recommended design practice. The purpose is to facilitate the bending or folding process and to minimize stress through the area. In addition, circuitry should be routed on a single copper layer through bend and fold areas whenever possible.

![Routing options for flex circuit trace corners](image)

*Figure 5-8 Routing options for flex circuit trace corners. Avoid sharp corners if possible. A radius is best as it provides a smooth transition and mitigates potential issues related to stress risers.*

It is also recommended that designs avoid having right or acute angles (≤ 90°) in circuit routing. This is because they tend to trap solution and may over etch in process. They are also more difficult to clean after processing, so best practice dictates that corners should be provided with a radius if possible. The radius also improves signal propagation, as the reflections at turns are reduced.

With double-sided flex, when and where the conductors must be routed through bend and fold areas and when copper traces are on both sides, the circuit designer should design spaces to be approximately 2-2.5x the trace width.

Preferably, the designer should also stagger traces from side to side. The purpose of this practice is to avoid the I-beam effect. This can be a critical concern in dynamic applications. (See Figure 5-9.)
Finally, placement of vias within the bend area is highly discouraged as they will adversely affect bend formation and create unwanted points of stress and potential crack propagation.

**GROUND PLANE DESIGN**

Ground areas should be crosshatched if electrical consideration of the design will allow for such. The practice helps both to reduce weight and improve circuit flexibility. The size of the openings in the ground plane may be critical depending on the end product requirements for shielding or controlling of characteristic impedance. If openings are too large, some shielding effects may be lost, depending on frequency. Also, ground connections for components should be thermally relieved to reduce heat sinking and assure formation of a good solder joint. This is accomplished by etching a clearance area around the pad while maintaining electrical connection. Figure 5-10 illustrates the technique.
POLYMER THICK FILM DESIGN GUIDELINES

Due to their unique nature, polymer thick film (PTF) circuits have their own very specific design rules. As a screen printing based technology, the limits of design are tied to two main factors: (1) the conductivity of the ink chosen and the limits of the screen-printing materials, and (2) the processes used. Much of the latter factor is tied to the former. That is, the particle size of the included conductor material and the polymer carrier will help establish the limits of screen printing. Emerging nanoparticle technologies could boost conductivity significantly, possibly opening the door for broader use of polymer thick film technology. While PTF circuits are not generally considered for dynamic applications, they can actually perform quite well in certain dynamic applications. Some experimenters have reported increases in conductivity with cycling. PTF membrane switches also stand as witnesses to the efficacy of PTF as a flexing technology.

CONDUCTOR WIDTH AND SPACING FOR PTF

Generally, minimum conductor width and spacing is considered to be in the range of 375µm (0.015”). It is possible to produce finer lines and spaces using PTF inks, but conductivity can become more of a design performance concern.

CURRENT CARRYING CAPACITY OF PTF

Silver-based polymer thick film inks, under normal conditions, can be expected to carry approximately 25% of the current of copper circuits for equivalent line widths and nominal PTF ink thickness. Care should be used, however, in attempting to maximize conductor current-carrying capability under this premise. Hot spots within the conductor matrix can cause rapid degradation of the conductor and possible failure.

SCREEN-PRINTED PTF RESISTORS

Screen-printed resistors are fairly commonly incorporated into PTF circuit designs. If used in a design, the resistors should be kept to a minimum of one or two values to facilitate processing. Generally, the resistors can be printed to ± 20% of value without trimming. Laser or mechanical trimming of the resistor can be used if tighter tolerances are required.

TERMINATION DESIGN CONCERNS FOR PTF CIRCUITS

The design rules for circuit pads or lands for PTF circuits are similar to those used for rigid printed wiring boards; however, the termination features should be discussed with the manufacturer. While polymer thick film inks are not directly solderable, conductive adhesives can be used to surface mount components. Again, land design for surface mounting is similar to PCBs.
INTERCONNECTION DESIGN FEATURES

This chapter section deals with interconnection design features, including both through holes and lands for making interconnections and the design criteria for making those access points more reliable.

HOLE SIZES FOR COMPONENT LEADS

While surface mount technology has become the dominant interconnection technology for electronic component assembly, through hole components are still used in many applications. As a result, proper sizing of the hole remains an important design checkpoint.

Finished hole diameter for through hole mounted components in flex circuits for most applications should be nominally 200-250µm (0.008-0.010”) larger than component lead to meet best practice design requirements for automated component placement. However, this is not always possible or practical. One key advantage of flex circuits is that, because of the thinness of the circuit, smaller gaps between the component and the through hole can be reliably soldered—but the devices are more difficult to insert.

Best or preferred case flex design practice suggests that all lands or pads should be made 2-2.5x the hole diameter. Holding this value is primarily a concern with single-sided flex, where maximum solderable area is sought to ensure that a reliable connection can be made.

Again, as with drilled through holes, this ratio will not always be practical, as is the case with miniature connectors. In those cases where very small lands are mandated and pin in hole assembly is required, a plated through hole may be required to enhance solder joint reliability.

VIA HOLE SIZING

Vias can be designed as small as is practical for the manufacturer’s yield. Small vias offer great advantage for circuit layout, but circuit cost may be affected if they are designed too small, depending on what technologies are available for making holes in the base material. Current generation punching and laser techniques are capable of economically mass producing interconnection vias as small as 25-50µm (0.001-0.002”). In contrast, drilling, because of the higher cost of small drills, becomes more expensive.
as the holes get smaller. Because flexible circuit base materials are thin, it is fairly easy to plate small through holes reliably. The small plated holes are also highly reliable in flex circuits. This is due in large part to the thinness of the base material, which results in a total material expansion that is low and less of a concern with respect to thermal cycling.

**Filleting of Lands and Pads**
Termination lands and pads on flexible circuits should be filleted. This process increases pad area and helps to distribute stresses local to the coverlayer openings better, effectively relieving a stress riser condition that commonly causes failure if the fillet is not supplied or ignored. Earlier CAD systems had difficulty in producing these features, but today’s more advanced systems can more reliably address the requirement for fillets without difficulty. See Figure 5-12.

**Pad or Land Hold downs for Single-Sided Flex**
Termination pads on single conductor layer circuits and surface mount lands on flex circuits of any layer count may require special land hold down techniques. With single-sided flex circuits, the use of special features variously referred to as tie down tabs, anchoring spurs, or rabbit ears may be employed to prevent the land from lifting during soldering processes in cases where excessive heat is used. With new lead-free solders, this may become more important.

An important note on this subject is that features such as tie down tabs could well cause problems as the industry moves to higher data rate signaling, and they should be used with caution. The stubs associated with some tie down features are capable of acting like antenna and can broadcast noise within the package when higher frequencies are used. Thus, an evaluation of the approach may be warranted, depending on the nature of the design. Figure 5-13 shows typical hold down tab features and alternative designs.
**Surface Mounting Lands for Flex**

Surface mount in combination with flex circuit technology is now very popular as the world’s flex circuit designers look to the success of Japanese products, which often employ flex circuits with surface mounted components. Surface mounting lands, however, often require a slight modification of standard design rules when applied to flex circuit applications.

The use of holes or slots drilled or routed into the coverlayer before lamination is a common way for flex circuit manufacturers to access solder lands. However, if traces are routed straight into the land, misregistration of the coverlayer could result in the creation of a stress riser, as shown in Figure 5-12. The same concerns regarding through hole components hold true for surface mount land features. In Figure 5-14 (A), the potential stress riser condition is again shown. Side or corner entry to the land is more tolerant to misregistration (Fig 5-14 [B]). Laser-cut or mechanically punched or routed coverlayer openings can be made rectangular (Fig 5-14 [C]).

**Figure 5-13** Various pad designs to help facilitate their capture by the coverlayer. (A) Standard filleted pad with full pad capture (B) Standard filleted pad with hold down tab (C) Overlapping pad design (D) Oval pad design (E) Corner entry to square pad (F) Plated through holes normally require only filleting.

**Figure 5-14** Coverlayer openings for discrete SMT components create special design concerns.
Rectangular openings can also be achieved by using photoimageable cover films in place of a coverlayer. When accessing component lands for device assembly, it is recommended that solder lands extend beneath the coverlayer, as shown in Figure 5-15.

SMT device lands for both discrete and leaded devices should be extended to allow capture by the coverlayer. Normally, lands should be 250-375µm (0.010 to 0.015") larger to facilitate land capture and prevent undesired lifting of the land during assembly or repair.

As with single-sided through hole lands for flex circuits, the objective is to prevent land lift during soldering operations and to provide extra strength against component pull-away in operation. This is of greater importance with components of greater mass. Figures 5-15 and 5-16 provide examples of common approaches used to access surface mount features in flexible circuits.
circuit design applications while maintaining hold down capability.

**LANDS FOR PLATED THROUGH HOLES**

Except for the shared need for filleting, double-sided flex with plated through holes does not require tie-downs, due to the rivet effect from the plated through hole. This inherent feature of the plated through hole serves effectively in preventing the pad from lifting away from the surface of the flexible circuit during soldering processes, should excessive temperatures be used in the assembly operation. Plated through holes are especially advisable if very small pads are required by the design to ensure formation of a reliable solder joint. This may require the addition of a second layer of copper, thus making a single-sided design a double-sided one. But, ease of processing and increases in reliability should, hopefully, offset any increases in cost.

**BUTTON PLATING**

An alternative plated through hole construction can be created using a process called button plating. The process can best be characterized as one where through holes and vias are selectively plated with copper. A finished structure can be seen in Figure 5-17.

The basic idea is relatively simple, however, success requires reasonable care in the manufacturing process. In practice, the manufacturer first drills and makes conductive the hole walls of the flex circuit using a suitable technology (electroless copper or graphite coating). The manufacturer next takes the panel in for imaging, where the panel is coated with a photoimageable plating resist, and the holes and vias to be plated are exposed and developed. A copper pattern plating step follows, and the hole walls and annuli of the holes are plated to the specified thickness. That resist is stripped away, and a second plating resist is applied and exposed to create a positive circuit image, which can then be etched to create a metal circuit pattern. The holes and vias are tented over in this process. This action prevents the metal etching chemistry from entering the vias and etching out the holes, thus creating electrical opens.

**COVERLAYER AND COVERCOAT CONCERNS**

As mentioned earlier in the section on flex circuit materials, there are several types of flexible covercoating systems available. Each has its own special applications and advantages. Included among them are the following:
Adhesive-backed films
Adhesive-backed polymer films are the type of coverlayer most frequently specified and used by flex circuit designers and manufacturers. It is also the flex circuit covering method best suited to dynamic flex circuit applications because of the balanced material properties from side to side.

Screen-printable liquid covercoats
Applied and cured by simple means, screen-printable liquid covercoats are the least expensive covercoat type and the one most often used with polymer thick film and simple single-sided copper constructions.

Photoimageable liquid and film polymers
Newer methods for covercoating flex circuits involve the use of photoimageable polymers. The results have been very promising. In process, the flex circuit is coated with a polymer film, which can then be imaged and developed to access termination features. This method, which looks quite good for many applications, could help put an end to many of the coverlayer misregistration problems manufacturers have had with small features and, in addition, quell concerns over adhesive squeeze-out onto lands.

In most flex circuit designs, the coverlayer or covercoat serves more than one purpose. For example, covercoats commonly function as a solder mask, helping to prevent solder from shorting circuit traces together, and serve to isolate electrically and protect physically the circuit from damage. In addition, as described earlier, coverlayers serve to help restrain the pads physically and hold them in place during soldering, preventing pad lift. The coverlayer (or possibly a covercoat) also allows conductors to be placed in the neutral axis for improved flex and bending performance. This subject will be covered in more detail later in the chapter.

Given the diversity of the roles flex circuits play in electronics packaging, it is understandable that it has been difficult for suppliers to come up with a universal solution that is at once low cost, high performing and easy to apply. Nevertheless, steady progress is being made by material suppliers, and new solutions are regularly being developed and offered to the industry.

Sizing Coverlayer Openings
As was seen in the discussions on surface mount land design, the sizing of coverlayer openings varies according to pad design features and with the
number of metal layers. Again, the key area of concern is with single-metal-layer flex circuits, where potential pad lift demands special care in design. Table 5-3 provides general guidelines for sizing of coverlayer openings.

**TRACE-TO-CUT LINE CONCERNS**

Best current practice for flex circuit design generally recommends that the edge of the part to the edge of conductor spacing be >1.25mm (0.050”). It has been shown, however, that circuits can be made reliably with edge-to-conductor spacing of ≤ 250µm (0.010”), although this normally comes at increased cost, which will vary depending on the tooling system used. Refer to Table 5-1 on page 77.

<table>
<thead>
<tr>
<th>Flex Circuit Type</th>
<th>Coverlayer Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single metal layer flex circuit with land hold down features</td>
<td>Coverlayer opening can be roughly equal to pad diameter.</td>
</tr>
<tr>
<td>Single metal layer flex without land hold down features or filleting</td>
<td>Openings in coverlayer should be 250µm (0.010”) less than pad diameter.</td>
</tr>
<tr>
<td>Double-sided flex PCBs and multilayer flex with plated through holes and filleted lands</td>
<td>Coverlayer opening can be equal to or slightly larger than pad. This minimizes squeeze out.</td>
</tr>
<tr>
<td>Non-component plated through hole vias</td>
<td>No opening unless needed for electrical test purposes</td>
</tr>
</tbody>
</table>

Table 5-3 Coverlayer opening guidelines vary with the nature of the design.

**TEAR-RESISTANCE FEATURES IN FLEX DESIGN**

All flex circuit designs should be made as tear-resistant as possible. While the material may not be intrinsically tear-resistant, tear-resistance can be improved by employing certain features in the design. There are several possible methods, described below and illustrated in Figure 5-18.

All of the following techniques have been successfully used to help prevent tearing. One or more of the following techniques can be used:

**Radius All Internal Corners**

The first line of defense against tearing is to make certain that all internal corners are provided with as generous a radius as possible. This design practice is the most important and simplest of all methods used to prevent tearing of the flex circuit material.

**Leave Metal in Corners**

The circuit design should, if possible, have small areas of copper provided for at internal corners to serve as tear stops at the inside of corner radii. This serves to prevent further or imminent propagation
of a tear through the polymer, should a tear in the material start.

**Laminate Glass Fabric in Corners**
Glass cloths can be laminated into corners during the fabrication process. Though not flexible, this method has been shown to provide a very robust corner construction and has been favored in the past by military product designers. It is an expensive solution, however, because of the type of preparation required and should be used only after careful consideration of the alternatives. (See Figure 5-19.)

**Use Fluoropolymer Coverlayer**
The use of fluoroplastics such as Teflon® as coverlayers helps to improve tear resistance by virtue of the high tear resistance of the polymer itself. This is due to the fact that fluoropolymer tends to stretch rather than tear, adding toughness to the substrate. An additional benefit of using fluoropolymer coverlayers for those involved in high frequency design is that the dielectric constant of the coverlayer is much lower.

**Use of Radiused Slots**
The use of slots with ends that have a radius to access relieved circuit features also can serve to provide tear resistance. Normally, such features can easily be provided for during the punching operation or other circuit fabrication process.

**Drilled Holes at Corners or Ends of Slits**
Drilled or punched holes in corners or at the ends of access slits have been used with success when flexible appendages must be spaced close together. This method allows the greatest use of material, but the hole size chosen will impact tear resistance. If the hole is very small, the overall robustness will be reduced.

**Aramid Fibers Inside Cut Line**
As an alternative to glass cloth, the use of aramid fibers routed through corners or along the entire outline of the flex circuit is a unique method to stop tearing of flex circuits. The thin polymer fibers have very high strength and are very pliable, minimally affecting flexibility. However, this is a labor intensive method and should only be specified with the knowledge of cost impact.

Ultimately, the choice of which method to use to restrain or prevent tearing of the flex circuit is not of overriding importance. What is very important is that the designer makes certain that some suitable method to protect against tearing is used.

To summarize, all internal corners should be provided with radii, and it
is here reemphasized that square or sharp internal corners are an invitation to trouble and should be studiously avoided. If the area of the corner is to be permanently bonded to a rigid base, then it is less important but still recommended that a radius be used.

**Stiffeners and Reinforcements for Flex**

Stiffeners or reinforcements are commonly used to support components on flex circuits. These important “add-ons” can be fabricated from a wide range of materials, depending on design need. The choice of material is predicated on what objectives are sought (low weight, best heat sinking, lowest cost, best spring qualities, etc.). The materials referenced in Table 5-4 have all been successfully employed to reinforce flexible circuits.

In addition to materials mentioned in the table, the package or box...
into which the circuit is to be placed can also be used as the stiffener if the design allows. Beyond simple component support, this technique allows the package or box itself to be used for heat dissipation. While a potentially attractive solution for a number of applications, the difficulty of this method comes to light if repair is required, because removal can damage the circuit.

<table>
<thead>
<tr>
<th>RESIN-GLASS LAMINATES</th>
<th>EXTRA LAYER OF COVERLAYER</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMOPLASTIC SHEET</td>
<td>BERYLLIUM COPPER</td>
</tr>
<tr>
<td>STAINLESS STEEL</td>
<td>ANODIZED ALUMINUM</td>
</tr>
<tr>
<td>INJECTION-MOLDED BASES</td>
<td>QUARTZ GLASS</td>
</tr>
</tbody>
</table>

Table 5-4 Stiffener Material Choice for Flex Circuits. A wide range of materials, both conductive and insulating, can be used to provide stiffness to a flex circuit where required. The table above notes some of the materials that have been used for different applications and needs.

**Special Techniques for Stiffeners**

Special design techniques allow stiffeners to serve more than the function of component support. For example, while the primary purpose is to support components, stiffeners can be so designed as to aid assembly by enabling the flex to be assembled as virtually a rigid board. This can be accomplished by using one of the following techniques.

Figure 5-20 Gang assembly or mass application of stiffeners in panelized form facilitates both the application of the flex circuit to the stiffener and subsequent component assembly. When the flex circuit and stiffener are bonded together, the resulting flex circuit panel can be processed much like a rigid board. Note that the adhesive is applied oversized and cut to dimension before the routing step is performed.
**ROUT-AND-RETAIN STIFFENERS**

Rout-and-retain stiffeners are produced by CNC routing of the substrate so as to leave it attached in certain locations for easy removal later. Such constructions allow the stiffener to be snapped or cut off after assembly. (See Figure 5-20.)

While routers are pervasively used in circuit manufacturing, lasers and water-jet cutters are other potential manufacturing choices for preparing or pre-cutting stiffeners.

**RETURN TO WEB PUNCHING**

Return to web punching (also referred to as “punch out, punch in”) of the stiffener requires special punch tooling wherein the rigid material is punched out of the panel and then immediately pushed or punched back into its original position in the panel. The method is commonly used for inexpensive rigid boards and allows mass assembly with relatively simple assembly fixture requirements.

**SCORING OR DICING OF STIFFENERS**

If features of the flex circuit design allow the use of scoring or dicing tools to prepare the stiffener panel is potentially possible. With respect to the scoring process, the circuit and/or the stiffener is cut partially through, using special tools which cut a controlled-depth straight path through the rigid circuit material. The cut can be made through the rigid material alone or through both flex circuit and rigid base. After component mounting and assembly, the circuits can be snapped apart along the score lines.

In contrast to the routing concept shown, the other alternative—dicing—requires cutting completely through the circuit and stiffener. Because of the nature of the tools used, all material cuts must be made in a straight line and orthogonal to the major (X&Y) dimensions of the panel.

**ADHESIVES FOR BONDING OF STIFFENERS**

All of the bonding adhesives used in the creation of flex circuit laminates are candidates for attaching a flex circuit to a stiffener. The choice of which adhesive to use is most often a function of performance requirements.

It is worth checking with the flex circuit vendor for his recommendations. Beyond those adhesives used in normal flex circuit construction, there are other types of adhesives that can be used as well. Following are some of the more commonly used adhesives for stiffener attachment.

**PRESSURE-SENSITIVE ADHESIVES**

Pressure-sensitive adhesives are very commonly used to attach stiffeners. They are perhaps the most versatile and easiest to use. They exhibit very good bond strength, which in some cases actually improves
with age. These adhesives are not generally designed for extended use at high temperatures but are for the most part limited to enduring only short excursions at high temperatures (soldering temperatures). Again, with lead-free solder technology moving ahead, there is need to check capabilities when using higher-temperature lead-free solders.

One particular advantage PSAs offer over other adhesive choices is that, when applied directly to the flex circuit, they allow for the flex circuit to be bonded to virtually any surface, thus effectively making anything in the package a potential stiffener.

**Thermosetting Adhesive Films**

Thermosetting adhesive bonding films (cast-acrylic films or flex circuit bondplies) can also be used to bond flex circuits to stiffeners, but they require the time and expense of an additional lamination step. Even so, thermosetting film adhesives can offer very high bond strength of the flex to the stiffener.

**Liquid Adhesives**

One and two part liquid epoxy type adhesives have been used for bonding stiffeners to flex circuits. They are difficult to apply uniformly and thus do not enjoy wide popularity. Such adhesive materials are well suited for—and can be well applied in—the creation of strain relief at the transition edge of the flex and stiffener by creating a bead of epoxy along the entire edge of the transition.

**Thermoplastic Adhesive Films**

The use of thermoplastic-based adhesive films for bonding flex circuits to stiffeners is another common option. Thermoplastic films have some unique advantages among adhesives in that they are low-stress, fully-polymerized polymer resins that require no cure. With properties that include adhesion to a wide variety of surfaces and materials, and the reported ability to be reworked easily, these adhesive materials may see expanded service in the future.

**UV Curable Adhesives**

Ultraviolet curable adhesives are another potential adhesive choice for stiffener attachment. With some screen-printable formulations, the UV “activates” the polymer, creating a tacky adhesive with PSA qualities. In addition, because they can be rapidly cured, these adhesives are also an attractive choice for relieving strain on the flex circuit at the transition point from rigid to flex.

**Holes for Stiffeners**

The diameter and relative sizing of mounting holes for components,
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and those for final flex circuit assembly mounting, have different purposes and often somewhat oppositional requirements. The result is that the design rules can vary considerably, depending on the application. Explanations as to how to determine the appropriate size follow. Figure 5-21 illustrates the concept.

**Component Holes in Stiffener**

Holes in the stiffener for through hole mounting of electronic components, such as dual in-line packages (DIPS), should be 250µm-375µm (0.010-0.015") larger than the through holes in the flex circuit (which, in turn, are by design rule 250µm [0.010"] larger than the lead). This is to allow for any movement and misregistration between flex and stiffener that might occur during the stiffener lamination or bonding process. This technique also helps to assure the greatest opportunity of accessing the through hole with the component lead without interference from the stiffener.

**Assembly Mounting Holes**

Holes in the stiffener for mounting the assembly should be equal to or slightly smaller in diameter than the holes in the flex. This assures that the stresses are placed on the rigid portion of the assembly and not on the flex circuit. This is not an ironclad rule, as it is possible to mount the flex circuit directly to a carrier without a stiffener, using common mounting hardware if necessary.

**Unsupported Mounting Holes**

Mounting holes that are not supported by a stiffener should be designed to maintain copper around the hole for added strength. (See Figure 5-22.) This practice is of value with regular mounting holes, as well, if the design will permit. Such features are also a convenient means of making a connection to ground.

**Strain Relief for Flex Circuits**

The provision of strain relief at the edges of stiffeners helps to prevent stress risers from occurring at transition areas from flex to rigid. Tearing
of the circuit or breaking of the copper at the transition point can more easily occur if the procedure is omitted from the design or manufacturing process. One or both of the following techniques should be used.

**Rounded Stiffener Edges at Transition**

The stiffener edges in areas where the flex circuit egresses from the perimeter of the stiffener should be rounded or provided with a radius at the edge to prevent a point of focused stress. Alternatively, breaking the rigid stiffener with a file or sandpaper at the transition edge before assembly can provide a similar benefit.

**Fillet Transition Edge of Stiffener**

Filleting of the transition edge of a stiffener with a resilient adhesive or epoxy is another common method of strain relieving circuits. The small bead of a suitable polymer will provide a simple means of transitioning strain from the stiffener to the flex circuit. Figure 5-23 illustrates the two approaches.

**Strain Relief for Unsupported Flex Circuits**

Strain relief should also be provided when mounting the finished circuit or assembly. The following methods can be used for this purpose:

1) Break or radius sharp edges of any retaining bars or clamps may be used to hold the flexible circuit in place.
2) Use a low modulus, elastomeric material between restraining bars and the flex circuit.
3) Bond the circuit to the assembly housing, using a double backed adhesive foam material or simple pressure-sensitive adhesive.
METHODS OF CONNECTING FLEX CIRCUITS

Connecting a flexible circuit to other elements of an electronic system is a vitally important element in system design, manufacture and assembly. There are numerous methods of making connection to flexible circuits. Virtually all connector manufacturers have connectors either specially built for, or readily adaptable to, flex circuit designs.

One innovative connector manufacturer of record, Beta Phase, Inc. (Menlo Park, Calif.), actually made its connectors out of flexible circuits, producing high-performance connectors with very high pin count equivalents. The concept was much ahead of its time and did not get much use outside of extreme performance applications, such as the Cray supercomputer, but the technology was purchased by Molex, and some elements of the earlier concepts are now available. As well, other connector manufacturers now have comparable product in the market.

FLEXIBLE CIRCUIT CONNECTOR TYPES

Some basic connectors are relatively simple devices. Examples include insulation displacement and crimp-type connectors. These have proven popular in applications where cost is important. They are not generally considered suitable for high-reliability applications, however.

To make both male and female pin in socket type connectors, swaged or brazed pins can be attached directly to the flex circuits. These have also brought some success in certain low-end product areas where performance is not a key concern.
The Sculptured® flex circuit technology described earlier has the ability to integrate the connector directly into the flex circuit itself. The method is suitable for a number of different electronic applications, due to the fact that no discrete joining of pins to the flexible circuit is required. By using this technology approach, it is possible to have edge contacts that extend, unsupported, beyond the edge of the flex circuit. It is then possible to simply post-form the leads as required to create a viable male pin connector for mating with a compatible socket.

In addition, or as an alternative to the sculpturing method described, edge card contact constructions can be created by folding the contact area of a flexible circuit around a stiffener. This is a simple and relatively inexpensive way to interconnect a flex circuit. It is directly analogous to edge card contacts on rigid boards, for which there are numerous types of mating connector solutions available. Because the flex circuit itself is thin, it is possible to accommodate a wide range of connector designs simply by altering the thickness of the stiffener (see Figure 5-26).

Surface mounted connectors are an increasingly important and common connector choice for use with flexible circuits, for obvious reasons. With size reduction a common objective...
of flexible circuit technologies, it comes without surprise that low-profile connectors are well-suited to the needs and abilities of flex circuits.

A number of low-profile connectors are presently in the market. These miniature connectors are very nicely suited to many space-constrained flexible circuit applications. Low-profile connectors known as low-insertion-force (LIF) and zero-insertion-force (ZIF) connectors that can handle contact pitches down to 0.30mm (.012") have been produced by commercial manufacturers. The profile height for such connectors can be as low as 0.60mm (.24").

Another option for low profile interconnection of flexible circuits is lapped connections. Solder, conductive polymers and adhesives have all
been used to make lapped connections between a flex circuit and a mating interconnection structure. It is a reasonably common method; for example, a large percentage of flat panel displays are connected using anisotropic adhesives.

Another unusual design approach to making flex circuit interconnections is one wherein the connections are made directly between chips, using anisotropic adhesives or lap soldered connections. This approach has been proven, both by modeling and manufactured prototypes, to be capable of providing very high speed and low power.

To summarize the topic, connecting the flexible circuit to a next level or associated interconnection device or system can be accomplished using one of many options. The choice is predicated on the cost and performance requirements of the end product. The examples provided are not exhaustive in terms of options, but they are representative.

**Bending and Flexing Design Concerns**

![Diagram of flex circuit connections](image)

While flex circuits typically are employed simply to allow the user to form the circuit to fit the shape of the package (flex to install applications), there are still many applications that require some dynamic flexing. In fact, in most applications, the very act of placing the flex circuit into the assembly requires that the circuit be bent or folded. In some applications this can occur several times. Flexible circuits are capable of enduring many millions or even billions of flexural cycles, provided the design is properly matched to the task.

Those not involved in dynamic flex design should also take to heart the
lessons of this process. For example, it is important to remember that even static flex circuits can be dynamically cycled by virtue of their application and design. Such events are common occurrences in circuits designed for any type of mobile equipment, such as automobiles and planes.

For example, shock and vibration encountered by a vehicle can cause a flex circuit to endure millions of low amplitude, high frequency flex cycles. If dynamic flex design rules are not taken into account or are simply ignored, the potential for unexpected cyclic fatigue failure of an application subjected to shock and vibration exists. Attention to the few simple rules for dynamic flex provided here can benefit many flex circuit applications. They are, arguably, good practice for all flex circuit designs.

**BENDING AND FLEXING TECHNIQUES**

A number of clever approaches and techniques have been developed by engineers over the years to achieve the desired bending or flexing motion in a flexible circuit. The types of motions employed range from linear extension and contraction to rotational flexing through various small angles of 5° or 10° to more than 360°. Figure 5-29 provides conceptual examples.

**AVOID PLACEMENT OF THROUGH HOLES IN BEND AREAS**

An important design practice that is sometimes overlooked or ignored is the avoidance of placing plated through holes in the bend areas. This is of particularly great importance in dynamic applications. For static applications, it may be possible to place vias through a bend successfully if they have a coverlayer and if the bend radius is large enough. That said, it is still a practice that should be avoided.
**ROUTE TRACES AT 90° THROUGH BEND AND FOLD AREAS**

Conductor traces should be routed through bending and flexing areas at 90° (perpendicular) to the bend line. This is an intuitively natural routing scheme and serves the purpose of bending well. However, the rule is somewhat fungible and seems to be violated regularly for matters of convenience. For example, in some hinge circuits (see Figure 5-33), the traces may be bent in more than one direction to achieve the design purpose.

**ROUTE CONDUCTORS ON A SINGLE LAYER THROUGH BEND**

Whenever possible, conductors should be routed on a single metal layer through bend and fold areas to enhance flexibility. When not possible, the conductor should be staggered from side to side to avoid the I-beam effect discussed earlier.

**DESIGN TO KEEP COPPER IN NEUTRAL AXIS**

The concept of neutral axis is very important to flexible circuits. In theory, the center of any item being bent is nearly immobile, with stress being absorbed by the outer layers of material. Therefore, if the copper (or other metal) foil is kept to the center of the design, the flexing life should be enhanced. (See Figure 5-31.)

Many experiments have verified this theory. Data provided in the graph in Figure 5-32 dramatically illustrate the effect that neutral axis placement can have on the flexing life of a flex circuit.

**FLEX DYNAMIC AREAS WITH THE COPPER GRAIN DIRECTION**

The orientation of the grain of the copper foil has a definite effect on flexural life of a design. Grain direction is of greatest importance with flex circuit designs fabricated using rolled and annealed (RA) or traditional...
Flexible Circuit Technology

Electro-deposited (ED) copper foil. With vendor-electroplated copper on sputtered film, orientation is not as critical, as there is no specific grain direction. The effects of grain direction on flexural life can be very significant, as the data found in the graph in Figure 5-32 indicate.

**Figure 5-32** Data show construction influence on flexural endurance.

**Notes:**

1) The unbalanced construction consisted of 25µm polyimide with 25µm adhesive on a base of 50µm polyimide with 25µm adhesive and one-ounce copper.

2) The semi-balanced construction used adhesive to achieve the desired balance (25µm polyimide with 50µm adhesive). The base was the same as above.

3) The balanced construction had a coverlay makeup that matched the base material exactly (50µm polyimide with 25µm adhesive).

**Keep Flexural Arc Small**

For maximum flex life, it is best to keep the range of the flexural arc or total angle of flexure of the circuit for dynamic designs as small as possible (that is, flex the circuit over the smallest possible distance). This is a key technique used in later-model disk drive applications to allow them to achieve their present high-flex-life cycling.

**Provide the Largest Bend Radius Possible**

The designer is advised always to provide the largest practical radius through bend areas. This design approach is especially important for dynamic flex, but, as has been previously noted, it can also be
important in flex applications that are apparently static in nature.

The graphic and simple equation in Figure 5-34 illustrate the effect of bend-radius diameter on the copper foil. As can be concluded by calculation, the elongation requirements for the copper foil rise significantly as bend radii decrease.

**GUIDELINES FOR MINIMUM BEND RADIUS**

While finite element modeling can provide excellent predictive data for suggesting bend limits, there are some common guidelines that have long served to keep the design inside the limits. For normal bending of flexible circuits, those guidelines can be found in Table 5-5. For very high flex life dynamic flex circuit designs, fabrication and testing of prototypes commonly remains the preferred method of design verification.

<table>
<thead>
<tr>
<th>Flex Circuit Type</th>
<th>Minimum Bend Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Metal Layer</td>
<td>3-6 x circuit thickness</td>
</tr>
<tr>
<td>Double-sided Flex</td>
<td>6-10x circuit thickness</td>
</tr>
<tr>
<td>Multilayer Flex</td>
<td>10-15x circuit thickness (or more)</td>
</tr>
<tr>
<td>Dynamic Application (Only single-sided recommended)</td>
<td>20-40x circuit thickness (increase in bend radius increases life)</td>
</tr>
</tbody>
</table>

Table 5-5 Minimum bend radii design guidelines for flex circuits

**CREASING AND FOLDING FLEX CIRCUITS**

Creasing and hard folding of flex, while not a preferred practice, can be successfully accomplished with some attention to certain details. When required, circuit should be bonded to prevent it from bending back at the crease or fold line. Strain relief is also recommended. As noted earlier, it is important to keep the construction balanced for best flexural endurance life. The ideal copper for such strain-bending applications will be a low strength, high-elongation copper. Fully annealed soft copper is normally a good choice for applications requiring a small radius bend.

**BENDING FLEX CIRCUITS TO HOLD SHAPE**

When bending flex circuit products for static, form-to-fit applications, holding shape is a desirable condition. However, flex circuits sometimes have some elastic memory. The following principles for shaping flexible
circuits to fit permanently in their application will help to overcome the condition. The first principle is maximizing the metal area. Copper, or any other metal one might use for the conductors, will permanently deform plastically when bent beyond its elastic limit.

Many polymers (elastomers are generally excluded, although they can take a set over time) will also permanently deform if their elastic limit is exceeded; their limit, however, is many times greater than that of metal. Thus, when the composite structure that we now call a flex circuit is bent, the metal has plastically deformed, while the polymer is still likely to be in its elastic range.

**Provide for Metal Dominance in Bend Area**

In order for the copper (or other metal) to prevent the polymer from snapping back, it must overwhelm the elastic memory of the polymer. Copper is stronger and higher in elastic modulus, but if the traces are small or the copper is a low percentage of the local area, the remnant elastic strain in the polymer may cause the flex circuit to regress to its original flat shape. This method is in keeping with the practices used by flexible circuit manufacturers to help maintain dimensional stability.

**Figure 5-35 Very small bends in the flex circuit are possible, as demonstrated in this figure (from a disc drive application).**

**Widened Circuit Traces Through Bending Zone**

If circuit weight is a concern, the area of extra copper can be localized. In such cases, the circuit features are widened in the area of the bend and then reduced in width again as they enter and exit (see Figure 5-36). Circuit traces should taper to the new width in both directions.

**Determining Bend Area Length**

As to the potential question, Through what length of the bend area should the traces be widened? A simple method to get a first order approximation is to determine the circumference of an imaginary circle having the desired bend radius, and multiply that result by the bend angle divided by 360 (the degrees in a circle). This should ensure that a sufficient
amount of the bend area is filled with the wider copper traces. However, a little extra length may be required, depending on the construction.

**Use Thicker Copper in Bend Area**

If widening the traces alone does not help sufficiently, then one of two analogous methods can be used. One can either use a thicker metal foil or use a thinner flexible base material. The objective remains the same: Make certain that the metal can overwhelm the polymer in order to hold the final shape. There are advantages and disadvantages to both paths. Making the copper thicker may make etching a bit more difficult; it will also take longer to etch and will use more chemistry. On the other hand, making the polymer thinner could make handling a bit more difficult, and the strength of the final assembly will not be as great as with the alternative method.

**Permanent Shaping Alternatives**

Slight over-driving of the bend to create a stable, more permanent shape can be used to advantage, with the caveat that the minimum bend radius for the flex construction not be violated. Note that when permanently bent and plastically deformed, the copper is normally thinned in the area of the bend, and is thus weakened. If a truly accurate predictive solution is desired, one can use finite element modeling methods.

**Heat Forming**

Another way to get the flex circuit to hold shape is to form it (usually using a mandrel of some sort), bend the circuit into shape, and then apply heat to the fixture, allowing it to cool in place. The objective is to relieve all of the remnant elastic strain in the polymer by allowing it to deform plastically to the final shape with the addition of heat. This approach works easiest with polymers and/or adhesives that have relatively low melting points. It is a very common method for making dome switches in polymer thick film circuits using polyester base materials.
In contrast, polyimide has a very high melting temperature, making it a less attractive candidate. In this method, one must normally rely on the ability to get above the glass transition temperature of the adhesive and allow the circuit to cool back below that temperature before releasing it from the mandrel.

**USE OF LOW-MODULUS POLYMERS**

A final choice for permanent shaping is to use nontraditional base materials. These would be materials of low strength and having little if any elastic strength. Unreinforced FEP or PTFE [Teflon], for example, falls into this category. This combination will allow the user to deform the circuit permanently into the desired shape. There are other options that are variations on one or more of these themes, but these are the basics.

Summarizing this topic, keeping and holding flex circuits in shape is not that difficult, but it does take some attention. The method of choice relative to those mentioned above will, obviously, depend on the demands of the design and its application.

**FINITE ELEMENT MODELING OF FLEX**

Over the years, with increases in computing power and increased availability of memory, there has been a significant improvement in finite element modeling tools, in terms of both cost and performance. Thus, it is not surprising that—given the importance of the mechanical requirements to the long-term performance of a flexible circuit assembly—many companies are beginning to perform finite-element modeling of the circuits to validate the design before committing the product to manufacture. This can be much more cost effective than iterating through a number of prototype runs, provided the modeling parameters are properly selected.

FEA tools are widely available and many can accept data directly from many types of design software and the user need only input

![Figure 5-37](image.png) Finite element modeling can significantly improve the chances of first-pass success in design for application by providing valuable information about the location and magnitude
material properties. Meshing is automatic. Figures 5-37 and 5-38 illustrate where the strain is located and dislocation in a simple bend and also re-emphasize the importance of coverlayer in reducing strain on the copper foil.

**Shielding Flex Circuits**

With the proliferation of wirelessly operated electronic products, there is increasing concern around the world about electromagnetic interference or EMI. Shielding of flex circuits may be required to block out unwanted electronic interference or noise. There is, in addition, the converse need to minimize emissions emanating from the circuit as well. Shielding can be accomplished by using the electronic system in a shielded room, but this obviously is not practical for most of today’s electronics. Alternative methods, therefore, are necessary.

Following are some techniques developed for flexible circuits:

**Integral Foil Shields**

The use of laminated copper (or other metal) foil on the outer surfaces of the circuit can provide excellent shielding. Such approaches should be carefully weighed to assess their cost-effectiveness, however. If only simple shielding is required, lower-cost screened-on coating may serve. All metal foils also tend to be stiffer and heavier than the alternatives.

**Thin Metal Shielding**

Vacuum sputtering of metal, and other dry metallization processes such as vapor deposition, have been used successfully to metallize the outer surface of the circuit, providing the required shielding. Such shielding is very lightweight and has been successfully employed in satellite applications. The process requires the use of expensive equipment and may not be suitable for cost-sensitive applications.
**SCREEN-PRINTED CONDUCTIVE POLYMER SHIELDING**

Screen-printing the surface with conductive polymers is a technique that has been used with great success in many applications. To use this technique, access to ground must be provided through the coverlayer. This allows the conductive ink to be screen-printed down into the opening and make contact. No openings are required when a floating ground is satisfactory for the application. (See ground plane section.)

**GRAPHITE COATINGS**

Depending on the level of signal attenuation sought or required by the application, lower-conductivity coatings such as graphite or carbon films may also serve the user's needs. Graphite coatings can be easily applied by spraying.

**MEMBRANE SWITCHES**

Membrane switches are ubiquitous. Any time one physically interfaces with the world of electronics, the odds are that he is doing so through a membrane switch of some type. As common as they are, membrane switches are also perhaps one of the more unsung and least visible members of the flex circuit family. As switches are fundamental elements of the electronic interconnection hierarchy, it is worthwhile to look more deeply into this important component.

Basically, a membrane switch is—as its name implies—an electrical switch created on a thin film or membrane. They are typically of low power, with maximum current ratings of around one-tenth of an amp. The circuitry for these devices is often somewhat elaborate since they frequently provide connections for a host of different input functions. Perhaps the most common application for membrane switches is in a keyboard of some type. While not all keyboards are made of flexible materials, a great many are. The most common layouts are matrix type (rows and columns) and common line connections (a common trace plus some number of switches). Other structures are possible depending on the needs of the user, such as integration of electronic circuits (including passive devices such as resistors) and land patterns for component mounting.

**CONDUCTOR MATERIALS FOR MEMBRANE SWITCHES**

The conductor material used for membrane switches varies by application. Copper and polymer thick film (PTF) inks are the most common choices. Cost is usually a key factor when making the choice. Because of this, a substantial number of membrane switches have screen-printed PTF conductors consisting of metal-filled ink. Obviously, the typically lower conductivity of printed inks limits the conductivity, but they
Flexible Circuit Technology

are not normally meant to carry current. Rather, they are designed to send a simple signal pulse. Copper is employed when there is need to solder devices to the membrane or when higher conductivity is needed; however, conductive adhesives have proven quite acceptable in most applications.

The switch-life of a membrane contact can vary significantly, from several thousand to many millions. The life-determining factors include such matters as materials of construction, contact design, switch travel, and operating conditions, among many others.

TACTILE FEEDBACK

While some membrane switches do not provide for tactile feedback, which some suppliers call a Type 1 structure, it is arguable that one of the key elements of membrane-switch design involves providing for tactile feedback. This is commonly a small snap or click that can be felt when a switch is pressed and released. Determining the right amount of force to be applied (the actuation pressure) is both an art and a science. Some customers are very adamant about “feel,” which, unfortunately, can be subjective.

There are basically two approaches to getting tactile feedback: polymer dome contacts (sometimes called a Type 2 structure) and metal dome contacts (sometimes referred to as a Type 3 structure). Metal-dome tactile switches have spring metal dome over the contact area. When pressed, it snaps down to complete a circuit and snaps back when released. The shape and thickness of the metal (commonly spring stainless steel) will determine actuation force. They offer a long life but are not well suited for use with flex circuits.

In contrast, polymer dome switches are embossed into the plastic film overlaying the circuit. It is possible to get a good tactile feel from such contact, and though their life expectation is heavily influenced by their use environment, they can endure millions of cycles if designed right. Furthermore, they have the advantage when it comes to cost, since they reduce the number of parts—thus reduced assembly time and complexity. Of course, one can opt to not use tactile feedback. To this end, an auditory response method is employed, such as a small beep. Because of their extreme simplicity, these tend to be the lowest-cost contacts of all.

CONTACT DESIGN

The contact area design is another important and interesting element of a membrane switch. Contact finish can vary. Gold, nickel, silver and even graphite have been used. The layout will vary with the type of contact used. For example, for a shorting contact, interdigitated fingers are often used. However, when a metal dome contact is employed, a central contact with a surrounding ring is frequently seen (Figure 5-39). Much time and
effort has been expended over the years to define the ideal contact.

![Dome snap contact and Shorting contact](image)

**Figure 5-39 Basic membrane-switch contact designs are shown without an overlayer. The shorting contact on the right normally is attached to a resilient material that holds it off the surface when it is not pressed down.**

**CONNECTING TO MEMBRANE SWITCHES**

Perhaps the element most recognizable as a flex circuit in a membrane switch is the tail element, commonly made to serve as half of a mated pair connector. In such constructions, graphite is commonly applied over the circuits as the contact finish. In such cases, the circuit traces are simply plugged into a ZIF-type connector of a sort described earlier in this chapter.

This brief review of membrane switches is by no means complete. It serves only as an introduction to the technology and was meant to provide some appreciation for this important use of flex circuit technology.

**CONTROLLED-IMPEDANCE CONSTRUCTIONS**

Controlled-impedance electronicsignal-transmissioncable applications are one of the applications best suited to the capabilities of flexible circuits. Because of the rapid increase in the growth of high-speed, high-performance electronic products, the use of controlled-impedance interconnections is expected to grow. Following are some of the construction types available using flex circuits. Figure 5-40 shows examples of each type.

**COPLANAR STRIPLINE**

In this very simple method of creating a controlled impedance cable, the circuit is produced with one metal layer by alternating ground and power. Such constructions are well suited to higher-characteristic impedance designs. A drawback of these designs is that they are susceptible to EMI noise.

**MICROSTRIP CIRCUITS**

Microstrip circuit designs are two-layer flex constructions, of which one metal layer is devoted to ground. Such circuits have been successfully employed in transmission line applications, are normally targeted for a 50Ω characteristic impedance, and are often used for single-ended
interconnections. Higher-characteristic impedance designs can be built, but flexibility usually suffers.

**STRIPLINE CIRCUITS**

Stripline circuits and transmission line cables are also excellent applications for flex circuits. With ground layers on both sides, great signal integrity can be achieved. However, such constructions tend not to be very flexible due to the extra dielectric and metal foil used. Stripline circuits are often designed to 100 ohms and are frequently used for differential pair interconnections.

**360° SHIELDED STRIPLINE**

360° shielded stripline constructions attempt to replicate coaxial cable constructions by virtue of the fact that the signal line is surrounded on four sides by ground. Such applications are of interest where crosstalk is a concern and where maximum signal integrity is required. Like stripline flexible circuit, these constructions tend to be rather stiff.

**PSEUDO COAXIAL CABLE**

Some researchers have taken 360° stripline constructions a bit further and used either plated through holes at points along the length of the flex circuit or plated trenches along the length of the copper ground to improve the shielding between the signal lines.

**CAD TOOLS**

Designing flexible circuits is, clearly, no mean task. There are many special design elements that must be attended to in order for a design to move easily through the manufacturing process. One important family of enabling technologies can be found in computer-aided design (CAD) tools. Newer CAD solutions are being adapted specially to meet the needs of flexible circuit designers.
In fact, with the increasing emphasis on the use of flexible circuits in all manner of electronic products, CAD tool suppliers, such as Mentor Graphics, are creating new tools to address the growing need for rapid learning in this important technology sector. These new tools not only help to make certain that the appropriate connections are made but also now address the various mechanical needs for curved trace routes to prevent stress risers. An example of a computer aided flex circuit design having one such solution applied can be seen in Figure 5-41.

**SUMMARY**

This chapter has provided an overview of some basic, yet very important, design practices required for successful implementation of flex circuit technology. As stated earlier, there are many other design requirements for PCBs in general, many of which are common to both flex and rigid circuit designs. Many concerns of flex circuits are created by the mechanical demands placed upon them. The reason is simple: What was formerly a simple replacement for a standard PCB has become a much more complex and highly mechanical, multifunctional interconnection device.

This simple reality forces the electronics designer to give proper consideration to mechanical concerns that could normally be ignored in rigid board design, but which are vital in the designing of flex circuits.
**INTRODUCTION**

Many different materials and processes can be used to fabricate flexible circuits. For very simple circuits, such as those produced for polymer thick film applications, only a few processing steps are required. However, for more complex flex circuit constructions, such as rigid flex circuits, the number of processing steps can be quite numerous and the processing methods very intricate.

The degree of complexity depends on such factors as: layer count, the number of different breakouts, whether a bookbinder construction is required, whether or not there are multilayer subassemblies as a part of the final circuit, etc. As a result, it is very difficult to describe, except in the most general fashion, how each type of product is fabricated.

That challenge acknowledged, this chapter will attempt to provide the reader with sufficient information on how flex circuits are built and to help him or her understand and appreciate some of the complexities of the manufacturing process. Hopefully, the designer/user will utilize this understanding to design flex products with manufacturing in mind, thus assuring the mutual success of both design and manufacturer.

**SINGLE CONDUCTOR LAYER MANUFACTURING**

Single conductor layer or single-sided flex are the simplest representative form of flex circuit technology. Logically, they are also the least expensive type of flexible circuit. These two factors combine to cause single-sided flex circuits to be the volume leader of flex circuit construction types.

A large part of the success and expansion of the flex circuit industry is the result of efficiencies achieved in the manufacture of single-sided flex. Because single-sided flex is readily adaptable to roll-to-roll fabrication processing, a number of flex circuit companies use such processing to take advantage of the great manufacturing economies for volume production.

With the numerous manufacturing options and material choices available to the prospective single-sided flex circuit user, the choices are many. Following are descriptions of some of the techniques employed to
produce these relatively simple yet highly useful circuits.

Additive, semi-additive, semi-subtractive, and subtractive comprises the basic list of methods for creating copper circuits for flexible circuits. While previous chapters have touched on the different types of copper foil used to produce flex circuits (wrought foil versus plated foil) and discussed their relative merits, understanding the methods of circuit creation using the different offerings is important. Of the four choices given, the first and last options are fairly self-explanatory. However, the subtler differences between semi-additive and semi-subtractive are illustrated in Figure 6-1.

**Copper Processing Options**

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**ADDITIVE PROCESSING**

While fully additive processing is very rare in flex circuit processing, it is a potential option, and there are a few ways to accomplish it. The most familiar method (a) involves use of a catalyzed laminate, onto which negative images of the circuit patterns are created. The exposed laminate can then be plated upon, to build up the desired circuit patterns. To control the deposit, the plating process is quite long, taking several hours to build the required thickness of approx. 25Km.

A variation on the additive process (b) was developed for making flex circuits in the early 1990s. Here, a catalytic toner is printed onto a continuous web of material and the circuit pattern fused in place. The circuits can then be plated up using a combination of traditional processes.

Transfer lamination of circuits can also be classified as an additive
Flexible Circuit Technology

process (c). In this process, the circuits are plated onto a mandrel of some type and then transferred to a base material in a lamination process.

**Semi-Additive Processing**

As the name implies, this method is not fully additive. The basic process normally involves the use of a base material, which is coated with a very thin layer of metal, most often copper. The thin metal layer can be additively plated to the entire surface using an electroless copper plating process, or by means of a sputtering process. When sputtering is employed, the copper film typically is preceded by a thin adhesion-improvement layer of chrome or nickel. This film is then imaged with a negative circuit pattern, just like in the additive process, and the circuits are electroplated to the desired thickness. After plating, the resist is removed and the circuits are “flash”-etched to remove the background copper and adhesion film (d).

There are potential variations on this process as well. One such variation is to place the circuit pattern down first, and then to sputter into the openings to bond to the base film. As the walls usually are very poorly coated, it is possible to strip the resist with its thin coating of metal after the plating process. This process is aptly called the “lift off” process (e).

**Semi-Subtractive**

While there are no hard and fast definitions for semi-subtractive, the distinction (for our purposes here) is best seen in terms of the thickness of the base copper. Base copper for semi-subtractive is much thinner than foils used for subtractive circuits; the copper foils for semi-subtractive tend to be two to three times thicker than semi-additive base metal (4-5Km versus 0.5-2Km). It is a seemingly small but significant difference. The processing methods are not very different from semi-additive, with the exception that circuits plated on semi-subtractive circuits likely will require an overplate to protect them in the etching process in order to maintain circuit feature accuracy (f). It is also possible that a simple print-and-etch process, using the thin metal clad, can be used as well to create the circuit of this group (g).

**Subtractive Processing**

Subtractive processing by means of etching is the most common method used for flexible circuits (h). The foils are typically 17µm or greater in thickness. For flex circuits, they are also most commonly rolled and annealed copper. In processing, the positive circuit patterns of etch resist, which directly represent the circuit, are imaged onto the copper foil and then etched to create the circuit. There are variations, however. One process variation involves embossing the foil and grinding off the copper that sits above the relief circuit pattern created by the embossing process (i).

Another subtractive-process option is by direct laser ablation of the
copper, as demonstrated by LPKF Laser & Electronics AG in Germany. The process allows a 40mm wide web to run at 30 meters per minute while ablating circuit patterns from thin copper on polymer films.

Clearly, there are several options available. Each method has its own place in the greater scheme of circuit manufacturing; however, one should be careful to make certain that the choice is consistent with the needs of the design. In general, additive processes tend to allow one to produce circuits with the finest, most accurate features, but the processing costs can be a bit more. Subtractive processes are straightforward and are the method of choice for most flex circuit manufacturers. This method does, however, produce circuits with trapezoidal cross-section due to the effects of isotropic etching. Nevertheless, it is still a highly popular choice.

**Subtractive or Print and Etch Fabrication**

Print and etch or subtractive processing is one of the most commonly used methods for producing flex circuits. The circuits are manufactured by printing the circuit image on the metal surface of a metal-foil-clad dielectric using a suitable etch-resistant polymer, and then etching the unprotected copper.

When required, holes for component mounting usually are generated by either drilling or punching. The holes can be created at the beginning, middle or end of the process, but it is most common to put the holes in at the beginning of the manufacturing cycle.

Following the etch process, a flexible coverlayer or polymer covercoat is applied. The protective covering has openings in it to provide access to component mounting holes, mounting lands for surface mounted devices, or other contact surfaces or important features.

While this process is commonly used for processing panels, it is extremely important technology for roll-to-roll processing of flex circuits. Many manufacturers of single-sided flex rely on roll-to-roll processing for high-volume production runs.

**Die Cut Process**

A clever but unusual technique used in the past to make flex circuits involved the use of specially fabricated rotary dies, which punched the circuit patterns out of a roll of copper foil on
a release film and subsequently stripped away the excess copper. The process utilized a differential bond-strength approach by creating a bond to the base material that was greater in the circuit pattern area than it was in the background copper area. The machine also applied a base film/cover-layer to the foil and had the capability to provide an integral adhesive for bonding the circuit to an assembly.

This approach has seen greatest success when used in applications where very coarse circuit features are a design requirement. Examples would include power bus circuits and simpler automobile instrument cluster circuits. In such applications, where volumes are very high, the approach has proven of great practical and economical value. An early example of such a process tool is shown in Figure 6-2.

**BACK-BARED (DOUBLE-SIDE ACCESS) FLEXIBLE CIRCUITS**

Back-bared—also known variously as double-side access, double-access or back-side access—flexible circuits are, most typically, single-conductor-layer circuits that have their metal conductors accessed or accessible from both sides.

The back-access technique typically is employed when component soldering or another interconnection method is required on two sides of the circuit. This circuit design and manufacture approach preempts the need for plated through holes and the extra processing steps that the plated through hole process entails.

There are several methods for creating a back-bared, single-conductor-layer circuit. Following are some of the more commonly used approaches:

**PRE-PUNCHED BASE FILM LAMINATION**

Pre-punched base film lamination is the most common method for producing back-bared circuits. This is primarily because the method offers the best use of widely available technology. This manufacturing approach is commonly used in the manufacture of TAB tape and flexible circuit interposers for IC packaging.
The circuit is created by first pre-drilling or punching access holes in the flexible laminate film before the film is laminated to the metal foil that is then etched to create the circuit paths. A top coverlayer having holes over other termination areas is then laminated to the etched circuit. Holes in the metal foil are generated by drilling or punching or by etching during the same etching process used to create the circuit pattern. In the last of these cases, it is possible to create odd-shaped holes such as rectangles or crosshairs that can improve the solder joint formation.

**Chemical Etching of Polyimide**

This method is specifically for use with circuits fabricated using polyimide films. Polyimide films, while normally very chemically-inert substrates, are subject to dissolution in hot, strongly alkaline solutions. The technique involves the masking of the circuit with an appropriate etch resistant image, which may be either metallic or organic, and then immersing the circuit in a hot caustic solution to dissolve the polyimide in the desired areas. Often this is done through a series of etch-and-rinse steps.

**Single-Sided Flex Manufacture**

1. Single-sided flex laminate
2. Drill or punch holes
3. Image with circuit pattern
4. Etch background copper
5. Strip resist
6. Apply covercoat or overlay

*Figure 6-4 Print-and-etch-process for single-sided flex circuit manufacture*

**Mechanical Skiving**

Although no longer commonly used due to the advent of ubiquitous laser availability, mechanical skiving is another method of record for accessing features from both sides of a single-metal-layer flex circuit. The method is performed by mechanically removing polymer film from the top (or bottom) of the circuit feature of interest on a single-sided flex circuit. Techniques employed for this purpose have included the use of a fiberglass rod, filed to a point of the correct size, as a spinning abrasion tool in a drill press to remove polymer film from the copper.

Another skiving method used is that of end-mill machining. Here a flat-faced, fluted end-mill bit of appropriate size is chucked in a drill press and used to cut away the covering film, exposing the base metal feature. Mechanical skiving is not the most cost-effective way to double-access a flex
Flexible Circuit Technology

circuit design for volume production, but it can be an effective technique for small quantity prototypes or engineering change orders.

Figure 6-5 Nonstandard interconnections are possible if the features can be etched rather than machined by drilling. From left to right: a breakable tab to enlarge solderable area, a rectangular opening to match pin shape, a star washer opening for press-fitting pins to ease wave solder assembly.

**Laser Machining**

Lasers of virtually every type are capable of skiving polyimide material. CO₂, YAG and excimer lasers have all been used to access metal features through the cover film or coverlayer. Each of the technologies has its own advantages and drawbacks. Lasers are fast and powerful, but they can also easily damage the flex circuit if care is not taken. Lasers also commonly leave a carbon charring of material at the edges of the cut. Still, newer lasers are vastly improved over earlier models and have proved to be very cost-effective alternatives. Excimer lasers are slower, relatively less powerful, and they generally require more maintenance, but they can produce sharp, well-defined features.

Figure 6-6 Examples of laser (left) and plasma-etched (right) openings through polyimide film. Laser holes may have a slight taper, while two-sided plasma-etched holes have the characteristic “hourglass” shape shown. (Courtesy Lumonics and Dyconex)

Regardless of which type is chosen, lasers are superior to mechanical skiving. Presently they are on a par with mechanical drilling techniques for cost-effectiveness. Lasers are highly valued for microvia creation, a technology that is directly analogous to providing backside access. Laser drilling rates are impressive. Within a small area, drill rates of 10,000 holes per minute have been reported.
**PLASMA ETCHING OF HOLES**

Plasma etching of flex material to achieve back baring is the least common method among those being discussed here. This is due, in part, to the relative slowness of plasma etching when compared to the other methods. While plasma is not well suited to one-at-a-time and individual hole formation, it can be very cost-effective for bulk or mass-quantity hole formation. The preparation of a panel for back baring by plasma etching involves the use of a metal mask that protects all surfaces but the areas of interest from attack by the plasma.

One method used to accomplish this is to coat the surface of the cover film with a thin metal layer and then etch openings above the desired interconnect point. Another method is to pre-etch a metal mask and pin it to the flex panel or part before processing. The latter method will not, however, provide quite as good an edge definition. A unique advantage of plasma processing is that features can be created with unusual shapes, such as square holes, because the lithographic pattern defines the feature shape.

**ADDITIVE AND SEMI-ADDITIVE PROCESSES**

At present, additively- and semi-additively processed flex circuits are a relatively uncommon subset of flex circuit manufacture. This is because most flex circuit designers opt for traditional subtractive copper methods to create their designs. Nevertheless, there are presently large numbers of what can be called flexible circuits produced by additive technology, and the numbers are expected to grow as finer lines and spaces become more common. Figure 6-7 shows an example of a semi-additive process.

Following are more detailed descriptions of some additive and semi-additive flex circuit manufacturing processes.

**ELECTROLYTIC PLATE-up (SEMI-ADDITIVE) PROCESSING**

Advances in sputtered-film processing technology have led semi-additive flex circuit technology. Such micro-thin coatings have gained favor for fine-line flex circuit applications because simple, light etching of few-micrometers-thick copper is all that is required to create the very fine features. The photolithography systems used must, of course, be capable of resolving such features. Circuit traces down to less than 10µm (0.4 mil) line and space can be produced with such thin-film clad laminates. Another area of advantage for these materials is in dynamic flex applications. Data gathered to date indicate that superior flex life can be achieved with flex circuits fabricated using this material, provided the manufacturer has good control of the copper plating process.

Additionally, adhesiveless structures have been shown to perform in
superior fashion in rigid flex constructions. This is because they allow for a large reduction in the amount of adhesive. This factor is important because adhesives have much higher coefficients of expansion, meaning they can exert higher strain on the plated through hole, reducing the plated through hole's reliability. Cast-polymer forms of flex laminate can also provide similar benefits, provided their dimensional stability is satisfactory.

Semi-additive processing, sometimes called semi-subtractive processing, is similar in many respects to the conventional pattern plate processing (described later). The major difference is that the laminate is coated with only a very thin layer of copper, to which additional copper is added by electroplating.

The extra copper is added to the conductor paths by the application of a photoresist coating that defines the circuit paths in copper, allowing additional copper to plate only into the openings. When plating is complete, the plating-resistant coating is removed and the thin background coating of copper is differentially etched away. This means that some of the electroplated copper is also etched, but the amount lost is not significant to the performance of the circuit.

**Figure 6-7** Semi-additive methods are very useful in producing fine-line circuits. To use the process shown, the features must be designed slightly oversized to compensate for etch losses that will occur.

**Polymer Thick-film (PTF) Technology**

The area of additively-processed flexible circuits has been largely dominated by PTF technology. Though long in use for calculator keyboards, displays, etc., recent advances in ink technology have resulted in increases in conductivity that make PTF an attractive alternative to etched metal flex in some applications.
The processes used in polymer thick film flex circuit manufacture are rather straightforward. The circuit pattern of conductive ink is screen-printed onto the surface of a flexible polymer using a screen of suitable mesh, and the conductive metal-filled ink is cured using either UV radiation or heat.

The pattern is then normally protected either by a screen-printed covercoat or, alternatively, by a pre-machined (drilled or punched) coverlayer. Frequently, polymer thick film flex circuit product incorporates
screen-printed resistors as well. The graphite inks used are also commonly employed as a contact finish for switches. Because polyester films are usually used, a heat-forming step can be introduced to cause the circuit to take and hold a certain shape. Low-cost dome switches are produced in such a fashion.

**Plateable Toner Technology (PTT)**

Another previously explored candidate for additive flex circuit manufacture was a technology based on use and deposition of a catalytic and plateable toner. The catalytic toner was deposited using a modified laser printer directly on the surfaces of a flexible polymer, and the circuit patterns were subsequently plated with electroless/electrolytic copper.

A unique attribute of the technology was that it allows a part to be dropped directly into manufacture via computer with no intermediate steps. This would offer the potential to build circuits economically at a run quantity of one. In addition, the technology would allow for the manufacture of circuits of virtually unlimited length.

A variation on this concept is being introduced at the time of writing. The basic ideas are similar, but the processes differ in that the newer method uses an inkjet printer to print the circuit pattern with a catalytic ink.

**Protective Coatings for Flexible Circuits**

Coverlayers and covercoats have been reviewed and discussed a few times in earlier chapters. However, it is an important subject and worthy of some further discussion. Flexible circuits almost always require a coating of some fashion over the finished circuits. (At the same time, openings are nearly always required to provide access to circuit features for interconnection to components or connectors.) This coating is generally referred to as a covercoat, a coverlayer or a cover film. In all cases, a common feature of the finished protective layer is that it is flexible.

The differing terms, used to define products that serve a common function, gives away the fact that the products are likely to be different not only in name but also in process. What is not clear from their names is that these products typically serve different purposes in terms of the application. Some explanation of the technologies and their rationale should help make this a bit clearer.

The first category is covercoats. Typically, these are liquid coatings, most often applied by screen printing. However, other methods can also be used. Depending on the type of covercoat used, the screen-printing process can involve a pattern that leaves open the circuit features if it is a UV or thermal cure material, or it can completely cover all features for later exposure and development if it is a photoimageable material. The process
Flexible Circuit Technology

can be very cost-effective with the former case, and is best suited to use with coarser features. These materials are commonly used in applications where the assemblies do not see much repeat flexing; however, they can serve well in some dynamic applications.

The second category is coverlayers. This term has historically been reserved for polymer films that have an adhesive layer on one side, used to bond to the flex circuit. In process, the coverlayer is commonly machined in some fashion, most often by drilling, routing or punching to provide openings for the circuit features. After providing the openings, the coverlayer is aligned and laminated to the flex circuit using heat and pressure.

While they are more time-consuming to produce, and more costly than screen printing, laminated coverlayers have historically been the primary choice for use with circuits requiring high-cycle-life, dynamic flexing. This is because the properties of the base film and its thickness can be made identical by placing the circuits in the desired neutral axis of the bend radius.

The third type of coating in this review is coverfilms. These are most similar to dry film solder mask in form and use in that they are laminated, exposed and developed to access circuit features. These have become increasingly popular for their ability to define openings and access very fine circuit features. While cover films are not ideal for all dynamic applications, they can be quite serviceable in many. Figure 6-9 provides a general idea of the processes.

There are, of course, variations on processing that can extend one technology over into other areas. For example, as discussed earlier, lasers can be used with coverlayers to access fine features, and chemical or plasma etching of polymer films can be used to access features when combined with certain other processing methods, such as the use of integral metal masks.

Thus, there are several viable options for protectively coating flex circuits when required. Which method to use depends on a number of factors, including application and cost. It can be difficult at times to make the decision, but it is at least nice to have a choice. The basic processes are illustrated in Figure 6-9.

Looking to coverlayer lamination, while it may seem rather mundane, lamination of machined, adhesive-backed coverlayer is one of the more important process steps to be mastered in flex circuit manufacture. The process includes a number of steps and a variety of materials that make it possible. Following is a review of some of the more important process steps in successful coverlayer lamination.
The first area of interest and concern is the lay-up area itself. A clean working environment is an important prerequisite. Dust and dirt can easily be attracted to the work due to electrostatic charges created in separating the coverlayer from the film that protects the coverlayer’s adhesive surface. A clean area fitted with antistatic devices, similar to the environment provided for imaging, is recommended.

Maintaining the alignment of the access holes with the circuit features is critical to the creation of reliable interconnection and test features. To accomplish this, flex circuit manufacturers have developed, over time, a number of methods. One is to use tooling holes internal to the panel and parts. Another commonly used technique is to heat-tack the coverlayer to the circuit panel during the lay-up process. This has proven very effective and allows the technician to compensate for some of the dimensional instability associated with these unreinforced films.

The next area of interest is in the stack-up of materials used in the lamination process. Many materials have been used over the years. In general, there are the following:

1) Thermal lagging material to control or moderate the rate of temperature rise in the laminate stack. Materials that have been used for this purpose include construction/craft paper and silicone rubber pads.

2) Conformal material, used to ensure that the coverlayer adhesive uniformly fills the spaces between the circuits in order to preclude the potential for air entrapment. Materials that have been used for this purpose include fluoropolymer sheet, polyethylene film, silicone rubber pads, and liquid crystal polymers.

3) Release film, as the name implies, is used to ensure that these materials do not bond permanently together. Materials that have been used include fluoropolymer films such as FEP or PTFE.
There are also several interesting specialty materials on the market that provide the properties of the lamination materials described into a single material. Some of these materials are designed to be used once as process consumables; however, newer materials have been designed for multiple uses. One interesting, relatively new, material of this latter class consists of a central core of glass material covered with a relatively thick coating of high-temperature silicone rubber and having a fluoropolymer film bonded to both outer surfaces. The release surface facing the circuit becomes distorted as it conforms to the circuit in lamination. However, in the next lamination, the material is flipped over so that the distorted side is facing the flat separator plate, where it is returned to flatness while the opposing side is distorted. This allows the material to be used hundreds of times, according to the manufacturer, thus eliminating much of the waste associated with the lamination process. This is an attractive feature as we move to create more environmentally-friendly manufacturing methods.

While there are some limits on the material just described, it is possible, depending on the materials used and their order in the lay-up process, to stack and laminate a number of circuits in between carrier plates by using separator plates between the panels. In some cases, the separator plate may even be omitted.

When it comes to actual lamination, the lamination pressure and
temperature should normally be performed in accordance with the recommendations of the material supplier. Vacuum lamination has some particularly attractive capabilities, especially when it comes to air removal, but traditional lamination presses can still be very effective.

In short, there are several important process steps and facilities issues that should be addressed in the manufacture of flex circuits, especially when it comes time for lamination of coverlayers. Attention to each seemingly small detail is vital to sustained success.

All of the foregoing discussion is applicable to two-metal-layer flexible circuits or inner layers for multilayer and rigid flex constructions.

**SINGULATION METHODS FOR FLEXIBLE CIRCUITS**

Several methods are available for singulating or extricating individual flexible circuits from a processed panel; this discussion of the topic applies to all types of flexible circuits. In general, the methods for singulating flex circuits can be branched along two main lines: dynamic, vector-based cutting methods, represented by routers, lasers, water jet cutters and numerically controlled blade cutters, and punching methods, which include Class-A tools, steel rule dies and a “new” category of etched cutting dies. The choice of which technology to use is often a trade-off where convenience, tolerance requirements, and product volume must be factored into the equation.

The first of the methods—dynamic, vector-based cutting—uses a computer program to move the flex circuit panel relative to the means of cutting. This can be accomplished by moving the table with a stationary cutter, or by moving the cutter while the panel is held in place. The former method is the one most commonly employed in circuit manufacture. A prime example is a printed circuit router. It is a convenient tool because most flex circuit manufacturers have routers in-house for making rigid parts such as stiffeners. Among the advantages of this method is that a number of panels can be routed at one time, because routers often have more than one head and the circuits themselves can be stacked to improve productivity.

Moreover, because a router is “soft tooled” by CAD data, there is no wait for tooling. On the downside, if the circuit outline is complex, routers can be slow, and edge quality may suffer if good processing control is not exercised. While routers have been singled out as an example, water jets and lasers can also be used to cut flex circuits from their panels. With all methods, stacking generally is possible. The results can vary quite a bit between processes, however. Water jets are clean and can cut through a variety of materials, and their cutting rates are quite good. The method
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was considered exotic at one time but is finding more use. Still, it is not as common as more traditional methods. On the other hand, lasers are seeing increased use in circuit manufacture, especially in drilling microvias. With lasers, one must be careful in the selection and use. For example, under most circumstances, CO$_2$ laser energy is reflected by copper. Thus, if copper is to be cut, a potential problem exists. There are ways to overcome the problem, but they require some nonstandard preparation steps. Still, CO$_2$ lasers can provide highly accurate cuts when copper is used as a conformal mask.

The other branch of singulation methods, punching, is accomplished by the use of one of two general types of tools: two-part punch and die sets; and single-part patterned blade cutters. The former method, punch and die, has been employed for punching shapes from flat materials for hundreds of years. Modern Class-A punch and die tools are among the most accurate available and can last for hundreds of thousands to millions of hits without resharpening if properly cared for. However, they are relatively expensive, and lead times can be very long.

An option for Class A tool punch is the patterned blade cutter or steel rule die. Here, a sharp blade of spring steel is placed into a channel cut into a base of plywood or other material. A shoe die press or clicker press is then used to press down on the flex circuit, pushing it into the blade and through into a cutting board. A foam-rubber piece, slightly thicker than the blade, serves to help push the circuits back up from the blade cavity after punching. These tools can be very accurate, depending on the method used to manufacture channels, and the material used for blade support, cost and turnaround time are usually fairly low.

The final method for this discussion is the etched blade pattern. This method has been used for many years to manufacture roll cutters, but it has only recently been made available as an alternative to standard rule die. The features are produced photolithographically and thus can accurately recreate the outline pattern. The dimensional stability is excellent. A rare-earth magnet is used to hold the cutting pattern in place and to provide mechanical support. This method has gained some favor with the flex circuit manufacturing and user community.
Thus, there are several possible methods for singulating flexible circuits from the panel. The method choice is predicated on a number of factors, including volume, time and tolerance. The “right” method will vary with the requirements of the individual product.

**TWO-CONDUCTOR-LAYER FLEX MANUFACTURE**

While single-metal-layer flex circuits are broadly used, two-conductor layer, two-metal or double-sided flex have become much more popular as packaging densities increase. Two-metal-layer constructions are very popular in a wide range of applications, from camera and cell phones to medical equipment and IC packaging. As with single-sided flex circuits, a number of different methods can be used to create double-sided flex circuits. Two-metal-layer flex circuits are not as readily adapted to roll-to-roll processing as single-sided flex; however, double-sided flex circuits can be produced in roll-to-roll fashion. Following are descriptions of methods for producing double-sided flex that are either in use or under study.

**THE PANEL PLATE PROCESS**

Panel plating of flex circuits is a method of long standing. Like other methods, it has advantages and disadvantages. From a processing perspective, it is easier to electroplate a non-patterned panel; the extra thickness works against the cause of flexibility and makes fine-feature definition more difficult. A typical manufacturing sequence for this process
is as follows:

1) Metal-clad laminate is drilled with the desired hole pattern and the holes metallized using an electroless copper process or a suitable alternative such as a graphite coating.

2) The laminate is then electroplated with copper to build the plating in the hole to meet requirements.

3) A dry-film resist image of the circuit pattern is then applied to the laminate on both sides, making certain that the through holes are “tented” reliably to cover and protect against the etching process.

4) The resist clad laminates are then etched to create circuit patterns on both sides.

5) Next, the resist is stripped and coverlayers are laminated to the top and bottom as required.

Except for the plated through hole portion of the process, the procedure is nearly identical to that used for the manufacture of single-sided flex. Figure 6-14 illustrates the typical manufacturing steps required to produce a double-sided flex circuit as just described. The flow chart in Figure 6-16 provides greater detail as to the circuit processing steps.

**Double-Sided Flex Manufacture**

1. Double sided flex material
2. Drill or punch holes
3. Metallize holes and panel plate
4. Resist coat and image pattern
5. Etch exposed copper
6. Strip resist
7. Apply coverlay or covercoat

![Diagram of Double-Sided Flex Manufacture](image)

Figure 6-14 A graphic representation of the process steps in the manufacture of a panel-plated flexible double-sided circuit

**The Pattern Plate Process**

Pattern plating is a common variation for producing two-metal flex circuits with plated through holes. It differs from the panel plating process...
Flexible Circuit Technology

in that a negative image of the circuit pattern is used, which exposes through holes for plating along with the conductors. The copper circuits then are commonly overplated with an etch-chemistry-resistant metal such as tin, solder or gold. Such metals will protect the circuit pattern and through holes during the etching process, depending on the type of chemistry used. After plating the metals, the plating resist is stripped and the circuit etched in an etchant that does not attack protective metal deposits. Ammonical or sulfuric acid-peroxide etchant are commonly used as they preferentially attack copper. Following etching, the protective metal normally is stripped from the circuit, leaving a bare copper circuit identical to the one produced by the first process.

The greatest advantage of the pattern-plating process is realized when features are fine and there is very little annular ring present in a design, and the risk is high of the resist being undercut and etching out the copper from plated through holes. This technique is also of value when finer circuit features are required. This is because a lesser amount of copper needs to be etched through to create the circuit image. This reduces undercut and results in a more accurate final circuit pattern.

**ALTERNATIVE TWO METAL INTERconnexion METHODS**

Interconnection of the two sides of a double-sided flexible circuit can also be accomplished mechanically. Over the years, several methods have been developed. While all of the methods have demonstrated functionality, the individual methods are limited to applications where specifications will permit their use. Following are some of the many methods that can be and have been used over the years to create mechanical connections:

**Z Wire Interconnection**

An early precursor of the plated through hole, the Z wire is simply a wire bent in the shape of a Z and carefully soldered to interconnect both sides of the circuit. This technique is normally used for vias only, as other through hole connections are accomplished by the component leads themselves.

• **Eyeletting**

Another early alternative to the plated through hole, eyelets are the equivalent of small rivets with holes at their centers, like those found around shoelace holes. Like Z wires, eyelets can make interconnection possible between sides of a two-sided circuit.

• **Cold Welding**

An interesting technique for interconnecting the two sides of a double-sided flexible circuit is cold welding. The method, developed by inventor
Flexible Circuit Technology

Robert Lomerson, requires that special tools be fabricated and that the circuit be manufactured in a prescribed fashion. Permanent interconnection is obtained by pressing copper into copper through openings in the flexible laminate and forming a metallurgical joint by cold welding using the special etched or machined tools.

![Conductive ink, Z wire, Cold weld, Eyelet](image)

Figure 6-15 Examples of various alternative methods for interconnecting two-metal-layer flex circuits

**Polymer Thick-film Process for Double-Sided Flex**

The polymer thick-film process has also been used successfully for producing very cost-effective two-sided flex circuits. As with single-sided flex, screen-printing of the circuit pattern is required. Through hole connection is made by screening the conductive inks through the hole in the base polymer film. This is often done with the assistance of a vacuum. Fully automated web-printing machines have been developed for producing polymer thick film circuits in a reel-to-reel fashion.

**PTF Copper Hybrid Process**

A sequential, hybridized process has also been used for double-sided flex manufacture. The process draws from both PTF and standard print-and-etch technologies. In manufacture, a circuit pattern is first printed and etched on a single-metal-layer flexible laminate. The opposite side is then printed with conductive polymer ink.

The ink passes through the holes to make contact with the opposite side. In such products, the copper is used for higher-power circuits and the PTF traces for certain low-level, low-current signals and the higher voltage levels. While the number of suppliers of such technology is small at present, the method holds some promise as a solution for a number of low- to mid-range products.
**Double-Sided Flex Manufacture**

Roll to roll processing of flexible circuits is highly automated and a very cost-effective method of one and two metal layer flex circuit manufacture. Because there are different approaches to such processing, the equipment is often customized to meet the needs of the customer. Both horizontal and vertical web handling equipment is available. An example of a piece of vertical processing equipment is shown in Figure 6-17.

**Figure 6-16 Double-sided flex circuit manufacturing options**

**Roll to Roll Processing**

Roll to roll processing of flexible circuits is highly automated and a very cost-effective method of one and two metal layer flex circuit manufacture. Because there are different approaches to such processing, the equipment is often customized to meet the needs of the customer. Both horizontal and vertical web handling equipment is available. An example of a piece of vertical processing equipment is shown in Figure 6-17.
Multilayer Flex Circuit Manufacture

Multilayer flexible circuits have three or more layers of metal conductors. Over the years, they have become more popular as a packaging scheme in some applications in spite of their higher relative cost. They are, however, very complex, engineering-intensive and demanding both in design layout and manufacture. Often, it is possible to lay out a design on paper, which, though it has apparent logic and order to it, cannot be easily manufactured or even manufactured at all.

Even so, the fact that multilayer flex circuit structures allow the designer to create very unusual high density and high performance electronic packages keeps them on the list of options for many designers. In fact, many packaging engineers feel that they are a bargain for the many benefits they bring, particularly in complicated wiring situations.

Processing of these often highly complex interconnection structures is extremely demanding and requires an exceptional command of manufacturing operations. Unlike single-sided and double-sided flex circuits, which can be processed in a reel-to-reel fashion, multilayer circuits are typically only fabricated in panel form. (A multiple conductor layer construction is possible using PTF in a web format, but this is not considered a common multilayer flex technique.)

Along with rigid flex circuits, multilayer flex circuits are among the most expensive types of electronic interconnection structures; however, they can also be among the most cost-effective. Thus, designing and laying out a multilayer flex circuit is best carried out in close coordination with the flex circuit manufacturer. Most manufacturers are eager to provide assistance because it normally facilitates entry of the design into manufacture and yields better results. Following are descriptions of some methods of multilayer flex construction that have been explored to date.
MULTILAYER FLEXIBLE CIRCUITS

Very little about multilayer flex-circuit processing is truly conventional. Each new design brings with it a host of new challenges. Multilayer circuits tend to be very engineering-intensive and normally require well-thought-out and skilled planning. Because each design is unique, it is difficult to describe a typical processing sequence, however, there are some fundamentally common themes. The following descriptions are offered to provide some sense of the intricacies involved in the manufacture of multilayer flexible circuits.

BASIC MULTILAYER FLEX CIRCUIT MANUFACTURING

There are many similarities between multilayer flexible circuits and standard rigid PCBs, but the actual processing of multilayer flex is often much more challenging. In flex MLB (multilayer board) processing, flexible laminates that are to be the circuit layers are provided with tooling holes. Drilling of holes in what will be flexible appendages or breakouts may also occur at this time. The layers are then imaged and etched and possibly plated through, depending on the design needs. Coverlayers are typically laminated to the etched patterns while providing access to interconnect points on tentacle ends through openings in the coverlayer.

The covercoated flex circuit layers are then laminated together using flexible bondplies, leaving the tentacles unbonded where design requires. The outermost layers are commonly still coated fully with copper foil. The panel is drilled using the same tooling system that was used for image transfer. This is to assure to the degree possible that internal lands will be in register with the drilled holes.

The holes are next cleaned using a plasma process or other suitable method and then metallized by electroless copper deposition or other acceptable technique, then electroplated with additional copper, either to meet requirements for full plating or simply to “lock” the electroless plating on.

For a subtractive process, a negative image of the outer circuit pattern is next applied to the copper foil. The open area or circuit pattern is plated with an etch-resistant metal such as tin or tin-lead. The resist image is then stripped and the pattern etched from the background foil. The metal etch resist is stripped from the circuit and the surfaces cleaned, providing a bare copper surface.

Next, an outer coverlayer is laminated to the circuits, providing openings to the interconnection features of interest. A solder coating process may be prescribed at this time. If not soldered, the circuit is punched, routed or
Flexible Circuit Technology

cut from the laminate and the tentacle ends are freed for component and connector installation, if required.

This highly simplified look at a basic approach to multilayer flex circuit fabrication is offered as an indication only of the complexity entailed in manufacturing these interconnection structures. If one refers back to the description of single- and double-sided flex circuit processing, it is easier to appreciate what difficulties are entailed in multilayer constructions and why they can be so costly. The balance of this section gives brief descriptions of some alternative methods and approaches for producing multilayer flex circuits.

**SEQUENTIAL LAMINATION PROCESSING**

In sequential lamination manufacture, the conductor layers are individually fabricated, and the resulting substructures are then laminated together layer by layer (or substructure by substructure) until the multilayer interconnection structure is complete. The panel is then drilled and the holes plated through to make connection to the various layers. The process can be time-consuming but does allow for some unique design freedom. On the negative side, such constructions demand near-perfect yield at every process step. Failure to achieve such will result in a very poor final yield. Such methods have been used with some success by certain Japanese manufacturers to build rigid multilayer circuits for cell phones and the like.

A variation on this method, briefly described earlier, allows for the electrical interconnections between layers to be made during the lamination process itself. The process is a cross between those processes
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Multilayer Flex Manufacture

Figure 6-19 Manufacturing flow diagram for a multilayer flex circuit

used for creating ceramic hybrid structures and those used to create anisotropically-interconnected multilayer flexible circuits.

Plated Post Interconnect (Sequential) Multilayers

Plated post interconnect multilayer flex circuits are fabricated by a nonstandard manufacturing process, which is similar to processes used
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in producing multichip modules (MCMs). With this method, the circuit layers are interconnected by means of solid plated metal posts that pass through from layer to layer. The posts may continuously stack on top of themselves or may be moved aside to make connection only to one other layer. This technology best serves multilayer flex circuit constructions that must be bonded to a reinforcing base. A brief process example follows:

1) A specially prepared substrate is coated with a flexible film; holes are opened to provide interconnect points in the finished product.

2) The surface is next metallized, imaged and plated up with the appropriate circuit pattern.

3) The surface is recoated with a flexible film layer and, again, holes are generated in the film and the surface is metallized and imaged. This time, however, only the interconnects or posts are patterned on the board. The posts are then plated to thickness.

4) Next, the resist mask is stripped off and the micro-thin surface metallization is etched away. The surface may or may not be planarized at this time.

5) Another layer of dielectric film is then laid down, and the cycle starts anew and continues until all layers are processed. The circuit is finally separated from its base when complete.

This technique allows for very dense structures to be fabricated, but the number of vendors capable of producing this type of product is small. As with the sequential lamination process described earlier, near-perfect yields are required at each processing step to obtain acceptable final yields.

Vertically Interconnected Flex Multilayers

Another technique for creating multilayer flex circuits involves the use of vertical interconnection by means of another co-laminated structure process. In one type of such a structure, anisotropic conductive bonding films are used to make numerous short Z-axis interconnections in place of the standard plated through hole. The interconnections are made during the lamination, providing a much-simplified process. Other structures use dielectric bondplies with programmed joining points of metal or conductive adhesive. An example is provided in Figure 6-21.

These structures are playing an increasingly important role in electronic interconnection for high density applications. They could possibly replace rigid PCBs in some applications owing to their ability to avoid redistribution wiring, especially for area array interconnections. This makes them ideal candidates for high density structures that use high-pin-count ball grid arrays (BGA) and chip scale packages (CSP).

Multilayer flex circuits are much less common than their rigid laminate
Figure 6-20 Multilayer-flex circuit can be visually simple but structurally quite complex, as the construction below the circuit image illustrates.

ABBREVIATED RIGID FLEX CIRCUIT MANUFACTURING PROCESS

1. Double-sided flex is built with coverlayer but no holes

2. Rigid caps are scored for later removal and laminated to flex using bondply or pre-preg

3. Circuit is drilled and processed like standard multilayer circuit. After routing the scored areas are removed to allow circuit to flex

Base film
Adhesive
Plated copper
Copper foil
Rigid laminate
Counterparts. There are a number of reasons why this has remained the case for many years. Cost of materials, handling concerns, and a general lack of experienced vendors are near the top of the list of reasons. However, as the line between flex and rigid continues to blur with the thinner reinforced core materials becoming more common and newer composite materials being introduced, it appears that the gap between the two sibling technologies is slowly being bridged.

While they are not yet common, multilayer circuits constructed using flexible circuit laminate materials have some intrinsic features that provide compelling reasons for their increased use. For example, flexible base materials are largely non-reinforced and are thus pure polymer substrates rather than composites. This feature results in a material that is consistent in electrical properties and, by general agreement, makes it a preferable choice for highest-performance applications. Moreover, when contrasted with less homogeneous glass-fiber-reinforced materials, wherein the dielectric constant and loss tangent can vary on a localized basis as the signal is transmitted through the material. This makes the control of signal characteristics at higher frequencies (the domain where skin effects kick in) more difficult.

Flex circuit materials also have the advantage of being homogenous. This is a significant advantage where one seeks to drill or punch holes in very close proximity to one another to conserve space or boost performance. The benefit is that the structure is immune to the so-called “conductive anodic filament phenomenon,” where ionic migration along glass fibers causes shorting between adjacent plated through holes.

Many methods for making multilayer flex circuits have been described over the years. Most descriptions follow traditional methods used in the manufacture of rigid multilayer PCBs. Other methods, however, have departed from the mainstream to explore alternatives. Dyconex (Switzerland), for example, was among the first to use flex circuit materials
Flexible Circuit Technology

to create high-reliability multilayer flex circuits with microvias using their innovative plasma processing methods. Other companies have also proposed flexible circuit options for multilayer flex. Tessera Technologies, for example, has described a number of ways to create such interconnection structures. Their original concept was a structure wherein simple two-metal-layer flex circuits were bonded and interconnected during the lamination process by means of special interposer material.

While the original electrical interconnection and joining medium was a silver-filled conductive resin in a flex circuit bondply, later concepts included the use of deformable plated metal features that deformed, mated and joined the interconnection points during the lamination process (Figure 6-22).

During development, the driving premise was to create high density multilayer structures using high-yielding double-sided circuits with low aspect ratio plated through holes. These layers would then be joined and interconnected using a high-yielding lamination process. Test data from early experiments were encouraging, but commercialization has, thus far, been slow to occur.

Other companies also have technologies designed to

Figure 6-22 Traditional approaches to multilayer circuits, both rigid and flex, can be complex in processing. Alternative methods could potentially provide simpler manufacturing solutions. Equivalent structures in terms of circuit layout, as shown above, vary significantly in processing steps.

Figure 6-23 Process steps for a two-metal circuit using the Toshiba B2IT method. For a multilayer, the process steps are repeated.
provide a similar solution (where interconnection between layers is made during the lamination process)—for example, Toshiba’s B2IT technology, Matsushita’s ALIVH technology, and a more recent offering, also out of Japan, the NeoManhattan bump process from North Corporation. The first two methods have been fairly well developed, while the third is following the other approaches into the market.

Yamaichi in Japan is in production of the B2IT technology; the company has developed specific design rules for prospective users of YFLEX and has specially adapted the technology for use with LCP for higher performance. The design rules can be reviewed in Table 6-1. While all of the technologies described are potentially capable of being used in the construction of all flex multilayer circuits, it may be that hybrid constructions will find some application as well. Use of rigid and flexible materials together in a common construction could provide some unique opportunities for high performance applications.

<table>
<thead>
<tr>
<th>Design Feature</th>
<th>Standard</th>
<th>Advanced</th>
<th>Leading edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line width/space</td>
<td>60/60μm</td>
<td>25/35μm</td>
<td>20/25μm</td>
</tr>
<tr>
<td>Bump diameter</td>
<td>250μm</td>
<td>150μm</td>
<td>100μm</td>
</tr>
<tr>
<td>Land diameter</td>
<td>400μm</td>
<td>250μm</td>
<td>200μm</td>
</tr>
<tr>
<td>Maximum current</td>
<td>0.1A /bump</td>
<td>0.05A /bump</td>
<td>0.05A /bump</td>
</tr>
<tr>
<td>Surface treatments</td>
<td>Au: flash</td>
<td>Au: flash</td>
<td>Au: flash</td>
</tr>
<tr>
<td></td>
<td>Au: bondable</td>
<td>Au: bondable</td>
<td>Au: bonding</td>
</tr>
</tbody>
</table>

Table 6-1 Capabilities for B2IT technology (Courtesy Yamaichi)

The continuing evolution of electronic interconnection technology over the last several years has been fascinating to watch. Conventional notions as to what is desirable or possible in the manufacture of interconnection structures continue to be challenged. We are likely to see more of the same in the months and years to come. Will there be a single solution in the future, suitable for all interconnections? It’s not very likely; however, the innovations that have been introduced to date will surely spark new ideas relative to what directions and forms interconnection technologies might take in the future.

**Rigid Flex Circuit Manufacture**

Rigid flex circuits are perhaps the most complex interconnection structures in production today. Having elements of both rigid and flexible circuit technologies, these circuit constructions bring with them both the best and the worst each technology has to offer. To their credit, rigid flex circuits provide an excellent method for interconnecting complex electronic systems. They also are capable of offering cost and weight savings as well as
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increases in reliability over conventional wiring harnesses while significantly reducing or even eliminating rework and repair. The counterpoint to the advantages is that rigid flex circuits represent some of the most demanding technical challenges a flex circuit manufacturer is likely to experience and are, like multilayer flex circuits, extremely engineering-intensive and thus expensive on an up front basis. Even so, on a system-level basis, rigid flex circuit can provide a very cost-effective solution.

Although rigid flex circuits are most often thought of in a military product context, more commercial applications are being developed, often with great success. In simplest terms, rigid flex circuits are hybridized constructions of rigid material laminated to flexible material and interconnected by means of plated through holes. As with multilayer flex, there is no such thing as a typical rigid flex circuit. Each construction offers its own unique challenges and requirements. While rigid flex has origins in the US, high tech flex suppliers of complex rigid flex circuits can be found in a few locations around the world, a notable supplier is Eltek in Israel.

In its simplest form, a rigid flex circuit may be limited to two conductive layers, one rigid, one flexible. In more complex constructions there may be six, 10, 20 or more layers of flexible interconnects sandwiched between rigid outer layers. Internal to such constructions might be several of the simpler constructions such as single- and double-sided flex circuits, which serve as interconnect tentacles.

Rigid flex circuits commonly serve as formable backplanes for electronic system interconnections and buses. These constructions, though normally fairly linear, often require the use of a technique described earlier called bookbinder construction, where each successive layer is lengthened in bend areas in anticipation of, and to mitigate, the strain-related damage to the outer conductor layers or buckling of circuits that will occur if the technique is not used. The term comes from recognition that such measures are required to keep pages flush on a closed book.

Rigid flex circuits can be especially difficult to manufacture because of the requirement to mate materials of different composition and dimensional stability, hold them in good registration and reliably plate the through holes. On page 143 can be found an illustration highlighting the most basic manufacturing steps. Following is a brief description of a somewhat typical rigid flex manufacturing process:

Rigid flex Manufacturing

As in the construction of multilayer flex circuits, there is no typical approach to building a rigid flex circuit construction. As a result, the sequence described previously for multilayer flex circuit manufacture
Flexible Circuit Technology

approximates the ones used for rigid flex, with the exception that rigid outer layers are used and more pre-machining of rigid materials is required in order to access flexible elements of the finished product freely. Route and retain techniques are not uncommon with rigid flex manufacture, as they facilitate assembly. Successful manufacture of rigid flex is heavily dependent on the tooling and fixturing used in fabrication.

One significant problem area in the manufacture of military-qualified rigid flex circuits has been meeting the requirements for thermal stress testing and thermal cycling. These tests, while demanding enough for standard rigid boards, can be doubly difficult for rigid flex constructions. This is because a very large percentage of a rigid flex construction is unsupported adhesives, traditionally used in rigid flex manufacture.

Unsupported adhesives are known to have large coefficients of thermal expansion (CTE), which translates to excessive strain being exerted on the plated through holes during thermal processes. The result of excessive expansion is manifest as cracking of copper plating at the corners and in the barrels of the plated through holes.

Material vendors and circuit manufacturers have worked diligently to solve the problem. Two general approaches have been developed to address this important issue. The first approach is to use new materials such as adhesiveless flexible laminates, which ameliorate the problem by eliminating the adhesive. Use of glass-reinforced polyimide prepreg bondplies in place of unsupported adhesive films can augment PTH protection. The overall expansion is considerably reduced by the combined use of lower coefficient of thermal expansion materials and higher glass transition temperature (Tg) of glass-reinforced prepregs. Another approach to the problem has been through the use of new or modified construction techniques. For example, heavily plated copper through holes have been recommended as a method for improving reliability of rigid flex circuits.

The objective is to create an extremely robust interconnect that will withstand the rigors of thermal stress and thermal cycle testing. Two things to note here are that: (1) Good control of the copper plating operation is imperative. Thick copper of poor quality does not solve the problem. (2) The design may require modification in order to accept the additional

Figure 6-24 Example of a rigid-flex board with folded wraparound layers. The circuit actually has five sections, with two sections folded over a metal core (shown at lower right).
copper thickness. That is, oversized holes will be required, mandating the need for larger internal and external lands if minimum annular ring requirements are to be met while accommodating the excess copper.

**Finishes for Flexible Circuits**

Over the last few years, circuit finishes have become increasingly important for several reasons. Some relate to attempts to reduce cost. Other reasons relate to functional concerns such as when the finish must serve more than a single purpose (both a solderable surface and a contact surface). Still others relate to the looming imposition of lead-free regulations by the European Union (EU). As a result, the industry has seen a number of different final coatings for PCB contacts and land patterns trot into the lineup in a race to “the finish.” In truth, we are not likely ever to see a single finish capable of meeting the diverse needs and requirements of each unique circuit design. With flexible circuits, the issues are the same but the impact might well be even greater. That aside, a quick examination of some of the many solutions offered is in order.

**Tin-Lead**

First on the list of considered finishes must be tin-lead. While this venerable alloy is a candidate for much reduced usage due to ill-conceived legislation from the EU, it still stands tall as an overall more environmentally-friendly solution from a scientific point of view than lead-free solders. Perhaps more important is that with its long history, its solderability and reliability are much better understood. For those demanding high-reliability, such as the military, aerospace and medical fields, it may well continue to have its selected users. 63/37 tin-lead solder is the most commonly used and is typically applied by the use of Hot Air Solder Leveling (HASL). Difficulty in controlling thickness, which can affect planarity and solderability if the finish is too thin, is a drawback.

**Tin**

Tin is another potential candidate as a solderable finish for application in flexible circuits. Like the others that will follow in this review, tin has the advantage of being acceptable in the eyes of the European Union legislative parliament.

Tin can be electroplated, immersion-coated or applied as a molten metal. The third method is not common because of the extreme temperatures. Immersion coatings are among the most common. The limited thickness of immersion coating (~0.25mm) makes it immune to concerns of tin whiskers, but its thinness causes concern because the CuSn intermetallic that quickly forms is not highly solderable.
Still, at least one formulation appears to have achieved thickness values of up to 1.0mm and claims excellent long-term solderability. The finish shares with some others the advantage of providing a planar surface and a processing temperature that is not damaging to the circuit. Still, some questions remain about the ability of the finish to maintain solderability through multiple assembly cycles.
IMMERSION SILVER

Immersion silver is another finish candidate. Silver is one of the most conductive elements. Even its oxides are highly conductive but are, unfortunately, not readily solderable. There are also long-standing concerns over silver migration. Strides appear to have been made in recent years to address both concerns. Immersion finishes as thin as 0.3mm appear to be capable of maintaining solderability and have the added advantage of being wire-bondable using aluminum wire ultrasonic bonding methods.

ELECTROLESS NICKEL IMMERSION GOLD (ENIG)

Electroless nickel immersion gold finishes (ENIG) have been the subject of countless research papers in recent years. They have been postured as a panacea of sorts, offering in a single finish planarity, solderability, wire bondability and a corrosion-resistant contact finish, so all the effort to make them work reliably comes without surprise. What has been troublesome has been the sporadic occurrence of the “black pad” phenomenon, wherein solder leads lift away from what was the nickel-gold interface. However, a recent study suggested that a higher percentage of phosphorous in the nickel could alleviate the problem.

Immersion gold using the ENIG process is generally 0.1-0.2mm thick and not well suited to gold ball bonding or multiple insertion connections. Electrolytic gold is another option. For gold ball bonding, a thickness of ~1.0mm has generally proven suitable. Soft gold with a hardness of approximately 90 Knoop is preferred. For contacts, hard gold plating is preferred. Electrolytic gold requires that electrical connections be present; therefore, shorting bars are often used to this end.

DIRECT IMMERSION GOLD (DIG)

At the time of writing, another finish that is gaining attention is direct immersion gold (DIG). It has the advantage that there is no nickel plating required, making it a simpler process. Immersion coating of gold directly over copper is a fairly simple process owing to the fact that the two metals are far apart in the electromotive series. Gold will easily replace copper, but the thickness is limited by diffusion to less than a micrometer.

ORGANIC SOLDERABILITY PROTECTIVE COATINGS (OSP)

The final category is that of organic solderability protective coatings or OSPs. While the history of such coatings is long, going back to near the beginning of the PCB industry, the current class of finishes is much superior to the early materials. Newer finishes are quick and easy to apply and have been formulated to survive several passes through assembly while protecting and maintaining the solderability of the copper they coat. They have been successful for traditional solders, but some concern has
been expressed about their ability to survive as many passes in lead-free
processing.

Obviously, finish choices abound to meet the many different needs
of the myriad of applications that flexible circuits now serve. However,
with no single solution in the mix, the choice must be made based on the
assembly and use criteria of the design.

**FUTURE DIRECTIONS FOR FLEX MANUFACTURE**

Flexible circuit manufacturing technology continues to evolve. New
solutions are presently in development and evolving. For example, roll-
to-roll processing of flexible circuits is evolving to include the printing of
active devices. Recent events indicate that the electronics industry may well
be crossing such a threshold. While concepts induced by ELF Technologies
in the early 1990s demonstrated that it was possible to produce flexible
circuits in roll-to-roll fashion on a continuous web by raster-printing
catalytic material onto flexible film, which was then electrolessly and
electrolytically plated (the developers considered printing conductive inks,
but the conductivity was not good enough at that time), newer printing
technologies offer significant improvements. Presently, roll-to-roll flexible
circuit production is no longer simply concerned with printing conductors.
Evolving solutions are expected to offer printed transistors and passive
devices. This opens the door to operational circuits being produced
additively on polymer films. By way of example, Fraunhofer Institute for
Reliability and Microintegration has demonstrated the production of an
all-polymer ring oscillator on a 200mm-wide roll of PET film. The process
involves the creation of flexible polymer transistors and logic circuits having
drain-source structures with channel lengths of 20 microns. The steps are as
follows: The first step is to structure the copper metal pattern; next, polymer
semiconductor materials are deposited, and then a polymer gate dielectric.
After the screen-printing of the gate electrode and the application of an
intermediate dielectric, the vias are opened through the layers. In the last
step, silver conducting paste is applied through a screen-printing process
followed by inspection and test to ensure proper function.

Given the propensity of the electronics industry to want to make
everything not only electronic but also inexpensive, the prospect of
microchips made of plastic and manufactured inexpensively using large-
area printing processes is compelling for low-cost electronics applications
for the mass market. The range of potential products is seemingly unlimited.
Developers have suggested intelligent tickets, paper toys, ID tags, electronic
postage stamps, speakers and smart bandages, just for starters.

Another company that has been on this path is Rolltronics of Menlo
Park, Calif. After years of effort, the company demonstrated a printed flexible display. The product, called FASwitch, is based on two thin layers of plastic with copper plates and paths activated by row and column circuitry. When activated, the flexible layer bends slightly until it closes a contact on the other layer and changes intensity, allowing four levels of gray.

The subject of printed electronics is now trying to establish its own base of support. At a recent industry event/conference sponsored by IDTechEx, the organizers stated: “The future electronic fabrication plants will be printing presses.” The organizers also suggested that the market for organic and printable electronics could reach $300 billion in 2025. That number is almost twice the size of the silicon industry today. Validating the market size of a technology 20 years hence is much too daunting, but it is hard to argue with their observation that there are significant potential markets waiting. If the technology catches hold and can deliver on the promises its champions are making, we will certainly see many new applications of electronics in our lives. What remains to be seen is when the technology will be rolled out onto a manufacturing floor.

**SUMMARY**

There are numerous ways to manufacture flexible circuits. In fact, there are many more ways to build flex circuits than there are flexible circuit types. The correct choice of manufacturing method is highly dependent on the objectives sought of the end-product and what can be traded off, if necessary, with the least impact on the finished product. Because of the diversity of flex circuit manufacturing approaches, the capacity to provide a solution to such challenges is well within the capabilities of flex circuit technology. Still, a close working relationship between designer and manufacturer should be maintained to assure that the right balance between design objectives and manufacturing choices is achieved.
Flexible Circuit Technology

Flexible Circuit Assembly

INTRODUCTION

Flexible circuits offer some unique challenges to the assembly process. The assembly materials and processes for populating and interconnecting components to a flexible circuit range are essentially identical to those used for standard rigid boards, but there are some twists required, as will be shown. The assembly processes range from very simple methods, such as manual component insertion and hand-soldering, which requires little or no fixturing, to fully automated methods, which normally require specially developed design-specific and dedicated fixtures.

How, then, does one choose an assembly process and method for flex circuits? To begin appropriately, it is necessary to consider a number of important factors: What is the flex circuit base material? What types of components will be used? How many assemblies will be built? These and other important questions must be addressed before one can make the proper decisions regarding assembly. These seemingly simple matters can greatly influence the assembly choice. For example, it is commonly assumed that polyester circuits cannot be used in applications where soldering is required. The reason for this assumption is that polyester films have a low melt-point and will be grossly distorted by the tin-lead soldering process. However, when properly fixtured, soldering can be used for joining components to polyester. A number of major OEMs have been doing just that for many years. They have developed methods that provide proper shielding to the body of the polyester circuit in process. The distortion of the material can be localized to areas adjacent to the point of connection. With the advent of well-intentioned but misguided legislation mandating the use of lead-free solders, there are significant challenges ahead, as lead-free solders have a roughly 30-40ºC higher melting temperature than traditional tin-lead solders. Sadly, it appears that traditional tin-lead solders are actually more environmentally–friendly, so the law does double damage. One alternative is to use lower-temperature solders, or conductive adhesives can also be employed. The important thing is not to limit oneself
Flexible Circuit Technology

As was indicated earlier, the assembly process for flex circuits follows a path similar to rigid boards but with some important points of departure. It is of value to understand the traditional flow of assembly as a point of common reference.

There are but a few simple elements associated with and required for assembly: interconnecting substrates (PCBs or flex circuits), components (ICs, discrete components and connectors) and a method for joining them. The challenge comes in bringing these elements together in a cost-effective and highly reliable way. This normally means that a high degree of automation and capital expenditure is required. A simple flow diagram of the assembly process, illustrating how and when the various elements are brought together to create an assembly, is provided in Figure 7-1. A brief examination of the assembly process follows, based on the flow diagram provided.

**Assembly Overview**

**Flex Circuit and Component Preparation**

As the principle elements of a flex circuit assembly, the flex circuit and components should be properly prepared. One thing that most plastic components and flex circuits have in common is that they take up moisture. This means that they must be protected from humid environments. Otherwise, they must be pre-baked to prevent explosive outgassing of trapped moisture and the creation of defective conditions such as cracked components or blistering and delamination of the coverlayer.

For component preparation, it has been suggested that the optimum component lead angle for leaded surface mounted components is 60° ± 5°. That angle can be opened up to 45°-65° for existing designs where the component body has been reduced in width. The purpose of the 55°-65° lead angle is to provide added strain relief in the x-, y-, and Z-axis during thermal cycling beyond what the flex circuit can offer intrinsically. To achieve high-reliability, the heel fillet of the solder joint should be adequate. Component lead angles of greater than 65°-70° improve the chances of this. While component lead co-planarity is important to good assembly,
one shouldn’t force leads into co-planarity by using a thermode or other method to drive component leads into the solder. It is better to reform the leads off line.

**Assembly Process Fixtures and Tools**

A range of fixtures and tools is required for normal assembly. The requirements of these elements will vary with the assembly process chose. For example, through hole assembly fixtures for wave soldering are quite different from those required for surface mount assembly. A brief discussion of each process is warranted.

**Wave Solder Fixturing**

Wave solder fixtures are designed to carry the flex assembly over a molten solder wave while keeping the flex circuit and components stable. There are several possible solutions to this problem. For example, the flex circuits can be left attached to the stiffener assembly in panel form, as illustrated in Figure 7-2. This method is relatively common. It can be a cost-effective solution, provided there is not an excessive number of defective parts in the panel.

Another possible method for fixturing flex circuits for wave solder is illustrated in Figure 7-3. Here, either individual holes are drilled or much larger openings are provided in a carrier plate that allows the component leads and plated through holes to be properly accessed by the solder wave.
Surface Mount Fixturing Surface mount assembly of flexible circuits is extremely difficult without proper tooling and fixturing. Many different tools and fixtures are required. A solder stencil is commonly used to place solder paste on the surface mount lands; however, new solder paste jetting technology is also an option.

Typically, a vacuum system is used to hold the circuit flat during the screen-printing of solder paste. This is frequently used in combination with special fixtures such as were described earlier. The fixtures themselves can be made from a variety of materials, such as glass epoxy or anodized aluminum. The fixture provides a stable base for processing, thus allowing more common soldering-process profiles to be run. An example of a fixture for surface mounting a flex circuit can be seen in Figure 7-4.

Component Placement

Placement of components onto a flexible circuit board is best performed automatically, although manual placement can be used for prototype or low volume, depending on complexity. The efficacy of modern automated equipment and manufacturing management practices continues to reduce the low-volume crossover point. Component density is another factor requiring consideration, for, as component densities increase, manual placement becomes more difficult.

Nonconductive, high-temperature adhesives are useful in holding components in place while the soldering operation takes place. Only small dots of adhesive are required. They can be applied by point dispensing, stenciling or pin transfer.
INTERCONNECTING & JOINING PROCESSES

There are several process options available for making electrical interconnection between the component and the flex circuit. The choice of joining method is linked hierarchically first to the electrical performance and reliability expectations of the finished product and secondly to the materials used in making the flex circuit. Following are some of the most common methods in use:

**CONDUCTIVE ADHESIVE ATTACH**

Conductive adhesives are a popular method of assembling components to certain types of PCBs. The adhesives normally consist of UV- or thermally cured epoxies, which are filled with silver particles. The material can be stenciled or dispensed point by point onto the selected component lands prior to assembly.

**SOLDER-JOINING**

Tin-lead-based solder has long been the most common method for interconnecting components to flex circuits. Of the many types of tin-
Flexible Circuit Technology

lead solder available, Eutectic Sn63Pb37 solder (M.P. 183°C) is perhaps the most commonly used solder. Other solders are of value for flex circuit assembly, especially where lower-melting-point base materials, such as polyester, are used in the flex circuit construction. Indium-tin solder (In52Sn48 [M.P. 117°C]) and bismuth-tin solder (Bi57Sn43 [M.P. 138°C]) have both been employed for such purposes.

In process, the solder is melted using a reflow oven. IR, forced-air convention and vapor phase are all candidate processes. Care should be taken in profiling any flex circuit assembly processes because of their much lower thermal mass. An example of an assembly profile for a flex circuit assembly using lead-free solder can be seen in Figure 7-8.

Lead-free solders pose special challenges for electronics due to their higher melting temperatures. While no risk of harm or demonstrable link of risk related to lead in electronic products has ever been shown, the industry must try to meet EU mandates slated for introduction in July 2006.

![Figure 7-7 Example of a flex circuit SMT assembly (Courtesy Interconnect Systems, Inc.)](image)

**REEL-TO-REEL ASSEMBLY**

There have been numerous efforts to assemble flexible circuit using reel-to-reel (or roll-to-roll) assembly methods. Conceptually, the approach is very attractive, especially for flexible circuits processed in a reel-to-reel. One concern for such assembly is that if there is need for a line shutdown, a significant amount of product may be at risk, and reworking in web form is somewhat problematic. Still, it remains an attractive approach for certain types of high-volume products that are small and have few components.

![Figure 7-8 Three-probe lead-free soldering profile for a flex circuit assembly using a carrier (Courtesy Bob Willis)](image)
Examples of such products include smart-card assemblies and RFID devices, which typically have only one or two components. Such devices can be assembled using more traditional soldering methods, conductive adhesives or wire bonding technology. Sheldahl (Multek) and Phillips Corp. co-developed a piece of equipment in the 1990s, wherein the reflow oven was placed on rails, allowing it to be moved back and forth over the web in case of a web shutdown and thus allowing the operator to prevent local overheating by moving the oven back and forth over the web and preventing hot spots.

An example of a prospective piece of reel to reel assembly equipment is shown in Figure 7-9.

**Wire Bonding**

Wire bonding is a very useful interconnection technology long employed in IC die assembly when interconnecting the chip to a leadframe or package. The technology has also been successfully employed in direct assembly of IC chips to flex circuits. Wire bonding is performed by one of two major methods: thermosonic bonding and ultrasonic or wedge bonding. The choice of wire bonding process is highly influenced by the materials used and reliability requirements of the finished product. For example, wedge bonding with aluminum wire can be performed at room temperature, so it is a good choice when lower-temperature laminate materials are used. In contrast, thermosonic bonding of gold wire requires a heat-bonding stage that is commonly operated at 150º C. Of these two primary methods, thermosonic offers greater versatility in terms of design and termination placement as the second bond can be made at any angle after the first bond is complete. Wedge bonding is much more constrained and more directional.

As an interconnection technology, wire bonding also offers some unique design advantages owing to its allowing the assembly process
to provide jumpers proximate to the die, if desired.

**Summary**

Assembly of flexible circuits requires special knowledge, special tooling and a great deal of care. This chapter has attempted to highlight some of the most important points. But it has not been exhaustive. A great number of excellent books have been published on the subject of component assembly and soldering technology. It would be well worth the while for the reader to consider obtaining one of these books to get a more detailed understanding of the assembly process.
Inspection and Test of Flex Circuits

INTRODUCTION

Testing and inspection are among the most important (and frustrating) elements of any manufacturing operation—important because they provide valuable feedback as to the health of the manufacturing operation and (hopefully) prevent the escape of defective parts. They can also be frustrating because the process seems not to add value to the product but rather to take value from it by seeing the faults and relegating the labors of those who participated in its manufacture to the waste bin. But it is the value of inspection and test that one needs to focus on: Inspection and test are really friends, not enemies, of the manufacturing process.

Testing of any product, if it is to be performed economically, is normally done on a sample basis. This is no less true for flexible circuits than it is for any other product. With flexible circuits, there are two levels of interest for inspection and test: the raw material level and the finished product level.

Raw materials are inspected and tested to assure that they will meet the normally self-imposed requirements of their industry. Such testing provides a level of assurance that only acceptable product will be committed to manufacture, thus eliminating, to the degree possible, its potential contribution to final product defects.

In like fashion, the final product is also tested to make certain that it holds to the requirements of its specifications of performance, assuring the end-user, again to the degree possible, that the final product will reliably fulfill its commitment to the customer for the expected life of the product.

Sample products submitted to a testing program assume roles of typical product. Manufactured by the same process line, all product off the line should be nearly identical (subject to the condition that the process is under control). Variance in the process is monitored, and testing is performed on a statistically valid basis to verify that the process is continuing to produce acceptable product.

Testing should not be confused with inspection. Inspection is frequently a sorting process for separating the good from the bad and/or
the potentially bad. This is not meant to undermine the value of inspection, for inspection can be a valuable tool in feeding back specific information to manufacturers regarding the general health of the product being built—and thus, regarding the manufacturing process. Inspection must also be used to assess the quality of the product and assure that it conforms to requirements.

**RAW MATERIAL TESTING**

Raw materials are tested to assure that the end-product will not be limited in performance by nonconforming basic materials of construction. To enhance the user’s sense of reliability, raw materials used in flex circuit manufacture (base materials, adhesives, foil-clad laminates, etc.) are tested to verify their ability to meet specified requirements. Material performance is evaluated in several categories (physical, chemical, electrical and environmental), which reasonably represent the spectrum of potential areas of concern for a product. Following, in abbreviated form, is a review of tests that may be required for flexible raw materials.

**Physical Performance Tests**

The physical performance of the raw material is checked to ascertain that certain minimum physical properties are present relative to the specified requirements. Included among physical tests to be performed are the following:

- **TENSILE STRENGTH AND ELONGATION**

  These common mechanical tests are performed to determine the values of two key physical properties of the flexible base material. The ultimate strength of the base film and the degree to which the material can be stretched before failure are important mechanical considerations and are useful in predicting the suitability of a material for a given application. They are also important values used in modeling.
• **INITIATION TEAR STRENGTH**

This test is used to determine how much force is required to initiate tearing in a material. It is a measure of the toughness of the base material—an important factor for flex circuits, given the somewhat delicate nature of thin materials.

• **PROPAGATION TEAR STRENGTH**

Propagation tear strength is another important measure, suggestive of the toughness of the material. This test is designed to measure the force required to propagate a tear in a material after a tear has been initiated and can be a vital determinant in the ultimate reliability of a product. The lower this value is, the more important it is that tear-stop features be added to the flex circuit design.

• **LOW TEMPERATURE FLEXIBILITY**

Low-temperature flexibility testing is performed to evaluate material resistance to embrittlement and possible fracture at low-temperature conditions, as might be encountered by flex circuit end-products in some applications.

• **DIMENSIONAL STABILITY**

Characterizing dimensional stability is of significant importance to both the designer and the manufacturer. The test verifies that flex material meets requirements for overall shrinkage or growth after etching of the metal foil. The more dimensionally stable the material, the easier it is to predict the locations of design features after manufacture.

Figure 8-2 Example of a peel strength tester (Photo courtesy of LPFK)

• **PEEL STRENGTH**

Peel strength is measured to assure minimum bond strength. It is normally applied to the measure of copper foil, but it can be applied to other combinations as well. Tests are run under different conditions to assure that
adequate peel strength is retained after exposure to different conditions:

1. As received, to check for minimum bond strength of copper to the flexible dielectric base.
2. After floating the sample on 289°C solder for 10 seconds to check for degradation after simulated assembly and rework.
3. After exposure to five cycles of -50°C, +150°C with one half hour dwell at each extreme, with a 15-minute intermediate dwell at room temperature between exposures at extremes. Simulating accelerated aging effect on bond strength.

**Volatile Content**

Volatile content is a potential source of outgassing and delamination. The test is employed to determine the weight percentage of volatile elements in flexible laminates.

**Chemical Performance Tests**

Chemical performance testing requirements for flexible circuits are very limited. There are just two major items of concern in the area of chemical performance of flexible raw materials used in flex circuit manufacture.

**Chemical Resistance**

Chemical resistance testing is performed to verify that no damage occurs to the laminate during exposure to chemicals commonly used in processing flexible circuits.

**Flammability**

Flammability testing is performed to determine what minimum level of oxygen is required to sustain combustion of the laminate. For printed circuitry, a commonly required rating is Underwriters Laboratories’ UL 94 V-0, which indicates that the material is nonflammable. While, in the past, UL 94 V-0 ratings for flex laminates were uncommon, advances in flex circuit materials have resulted in a number of materials having 94 V-0 ratings.

**Electrical Performance Tests**

The electrical performance of a flex circuit is often a function of the electrical properties of the material itself. This is increasingly the case for high-speed circuits. The electrical properties are verified by checking material samples and determining values for all of the following attributes.

**Dielectric Constant**

Determination of the unitless value known as the dielectric constant (Dk) of the material is an important determinant in many predictive calculations of electronic performance. A low Dk is especially important
in high-speed applications. It is fundamentally the ratio of the capacitance of the material to the capacitance of air.

**Dissipation Factor**

The determination of the relationship between the material’s permittivity (capacitance) and its conductivity, when measured at a given frequency, the dissipation factor is another important determinant to assist the circuit designer in making calculations of the electronic performance of the end-product. Moisture uptake is a common contributor to increase of dissipation factor and signals loss, and it will become increasingly important as signal speeds continue to rise.

**Dielectric Strength**

Dielectric strength is determined to establish the minimum breakdown voltage of the material. It is of particular interest and importance in the fabrication of high-voltage circuits as well as circuits that are to operate at high altitudes and are prone to electrical arcing.

**Surface and Volume Resistivity**

Surface and volume resistivity values are measured and established to provide the minimum values for volume and surface electrical resistance of the base material under damp heat conditions (such as might be encountered by exposure to highly humid environments), which can alter electronic circuit performance. The test provides a measure of a material’s propensity for current leakage under such conditions.

**Environmental Performance Testing**

Environmental performance testing is undertaken to evaluate certain physical and electrical attributes of the material that may change as a result of exposure to the environment over product life.

**Moisture Absorption**

Moisture absorption is a determination of how much moisture the base material will absorb under humid conditions. Moisture absorption is relevant to electrical considerations, as moisture absorption will alter the dielectric constant of the material. However, it is also a potential concern in assembly, as excessive moisture absorption can cause explosive outgassing of absorbed moisture and delamination of coverlayers.

**Moisture and Insulation Resistance**

This testing is performed to determine the effects of exposure to moisture on the insulation resistance of the raw material, verifying that electrical properties do not degrade beyond established limits for the material under test conditions.
• **FUNGUS RESISTANCE**

This test is performed to determine if the material is a nutrient for fungi or other biological material that might be capable of degrading the electrical properties of the flex circuit.

**FLEXIBLE CIRCUIT EVALUATION**

The testing of finished flex circuits duplicates many of the tests performed on the raw material. This is to assure that the manufacturing process has not degraded the material beyond acceptable limits. As with the raw materials, testing requirements have been established in several key areas to ascertain that the product is acceptable for its intended purpose.

Major categories for testing the finished flex circuit include: visual inspection, metal finish solderability, physical dimensions, physical properties, circuit construction integrity, plated through hole quality both before and after thermal stress, electrical properties, environmental properties and cleanliness. Testing requirements for each of the above-mentioned categories are reviewed here in brief fashion. IPC documents describing the precise test methods are available and should be read if more detail is sought or if one wishes to perform the actual testing.

**Visual Inspection Requirements**

Visual inspections are performed as part of the testing process to assure conformance to requirements not readily captured by other test techniques. Following are key attributes that are determined visually:

• **DELAMINATION**

Any separation of the material from itself, of conductors from laminate, or of cover films from conductors constitutes evidence of delamination. It is generally seen as an indicator of improper processing, lack of cleanliness or possibly thermal stress excesses. In nearly all cases, delamination is considered a rejectable condition.

• **EDGE CONDITION**

Flex circuits are inspected to check for nicks or tears that could be sites for tear propagation and failure of the circuit. This is of great importance in dynamic flex circuit applications, where nicks along the edges of a flex circuit can act as sites for tear initiation. However, it is of importance for static applications as well, since circuits could be inadvertently stressed and torn during assembly.

• **STIFFENER ATTACHMENT**

Stiffeners normally perform vital mechanical component-support functions. As a result, the attachment is checked to assure integrity of the bond on the flex circuit to the chosen stiffener substrate. If filleting of
stiffener edges or an edge break is specified, this inspection step will also verify their presence.

- **Solder Wicking**
  
  Evidence of solder wicking along the surfaces of traces away from openings in the coverlayer may be either an indication of improper lamination of the coverlayer or possibly excessive exposure to molten solder. The condition is not preferred but is generally considered to be acceptable if it is within specified or agreed-upon limits. (See Figure 8-3.)

- **Marking**
  
  Marking of the circuit is checked to verify compliance to the master drawing and to prevent mislocation or misorientation of components either during assembly or later, when or if field repair of the circuit is required. Serialization of the circuit (if used) can also be checked at this time.

- **Plated Through Hole Voids**
  
  Plated through holes with voids of unacceptable size or quantity are inspected in order to avoid possible soldering or reliability problems with the copper-plated through hole. Ring voids are a major concern and definite cause for rejection. If not discovered in inspection during assembly, the problem of voiding in plated through holes is frequently manifested as an outgassing condition or blow hole in the solder joint.

- **Workmanship**
  
  This general “catchall”-category inspection covers miscellaneous items
such as the presence or absence of dirt, oils, fingerprints, wrinkles, bends or creases, and other nonspecific indicators of the workmanship of the circuit's manufacturer. While such inspection may occasionally be subjective, it can provide an indication of the quality of the circuit manufacturer's process.

**DIMENSIONAL MEASUREMENT REQUIREMENTS**

Dimensional measurements of the finished flex circuit are taken to assure the form and fit of the circuit, because dimensional accuracy is often important to actual function and ultimate reliability of the circuit. Following are some key points of inspection and measurement:

**ANNULAR RING**

**MINIMUM ANNULAR RING DETERMINATION**

The lack of sufficient annular ring can affect both the solderability and the reliability of an interconnect. Requirements differ greatly for plated and nonplated through holes, with nonplated through holes in single-sided flex normally requiring a much greater solderable area to assure a reliable joint. Thus, annular ring is checked to assure that minimum requirements are met.

**HOLE PATTERN ACCURACY**

Hole pattern accuracy is checked to assure that through holes are in their proper locations. This is obviously an important issue for circuit assembly, especially when automated plated-through-hole assembly procedures are employed, but it is also important when the holes are to be used as tooling holes for surface mount assembly.

**COVERLAYER REGISTRATION**

Coverlayer registration has a net effect similar to that of the annular ring. This is because coverlay misregistration can encroach on the solderable area, making for a less reliable connection. The coverlayer should register on the pad to meet the minimum specified requirements (see Figure 8-6). Registration requirements can vary with pad design features, with some approaches being more forgiving. With single-sided flex circuit designs, where the coverlayer serves to prevent pad lift, registration can be a very
important concern. A minimum of 270° of land capture is normally recommended.

**ADHESIVE SQUEEZE-OUT**

Adhesive squeeze-out onto pads is a fairly common by-product of manufacturing during coverlayer lamination due to adhesive flow under heat and pressure. (See Figures 8-6 and 8-7.) There are standard allowances for squeeze-out onto lands, but the amount of squeeze-out may need to be negotiated. Good process technique and materials can minimize the effects by damming off the adhesive with conforming press-pad materials. With newer photoimageable coverlayers, this factor generally is not a concern.

**SODA-STRAWING**

Air entrapment along the edges of flex circuit traces, commonly referred to as “soda-strawing,” can occur in dense closely-packed circuit designs or when very thick copper is called out by design. Not harmful in all applications, acceptability is often based on application of end product. Still, capillary wicking of moisture is a possibility if the effect runs to the edge of the circuit or land. Limits should be agreed upon between user and manufacturer. (See Figure 8-6.)

**FOREIGN ENTRAPMENTS**

Foreign entrapments are sometimes present either in the raw material, under the coverlayer of flex circuits, or both. They are considered acceptable in various applications, provided they do not bridge conductors or reduce spacing between conductors to less than acceptable limits. They may also be a concern if located in a critical bend area. (See Figure 8-5.)

**HOLE SIZES**

Hole sizes are checked to verify conformance to print requirements and to preempt potential assembly problems. Circuit hole sizes, if made too small, may make insertion of component leads difficult. If, on the other hand, the hole size is too large, it may be difficult to form solder joints of preferred quality in the assembly process. For tooling holes, hole size inaccuracy is a concern because loss of positional accuracy is a possibility.

**CONDUCTOR PATTERN**

The finished conductor pattern on the flex circuit should accurately represent the master drawing. While allowances exist for localized reductions of up to 20% in conductor trace width due to nicks or “mouse bites” (see Figure 8-6), an excessively large number of occurrences is likely to be indicative of problems in the manufacturing process.
**CONDUCTOR WIDTH AND SPACING**

Conductor width and spacing may be critical and often must meet minimum size or spacing requirements to assure proper electrical and/or electronic performance. Evaluation requirements should be controlled by and defined on the master drawing.

**PHYSICAL TESTING REQUIREMENTS**

Physical testing is a key part of flex circuit testing. It helps to verify the physical appropriateness of the product for the application. The following tests are performed to assure product quality and reliability. The flex testing sections are especially important in dynamic flex circuit applications.

**PLATING ADHESION**

Plating adhesion or “tape” tests are performed to assure a good metallurgical bond of plated metals to the base laminate copper foil. Low bond strength could result in latent failure of the circuit due to conductor lift or shorting.

**UNSUPPORTED HOLE BOND STRENGTH**

Unsupported hole bond strength is examined to assure that the circuit can endure assembly and repair without excessive damage. The land must endure five cycles of soldering and desoldering in accordance with common specification.

**CONDUCTOR PATTERN BOND STRENGTH**

This test is performed to assure that the circuit manufacturing process has not reduced foil bond strength to unacceptable levels. Test conditions are essentially identical to those described for raw materials.
**FOLDING FLEXIBILITY**

Folding flexibility tests are performed to assure that the circuit can be successfully formed to meet the requirements of the master drawing without delaminating or breaking conductors. Information required for proper testing of folding flexibility includes: location of bend, radius of bend, angle of bend, direction of bend, and number of cycles.

**FLEXIBILITY ENDURANCE**

This form of testing is most important for dynamic flex applications. Testing apparatus can vary with customer requirements. Standard test methods using equipment such as the fatigue ductility (a.k.a. Englemaier) flex tester may require only minutes or hours to perform. However, many disk drive manufacturers opt to test circuits under simulated operating conditions. Such testing can take weeks or even months to complete, but in such cases the manufacturer is seeking the comfort of hard statistical-reliability data. Examples of some of the most-often used flexibility-endurance test concepts are provided in Figure 8-7.

**CONSTRUCTION INTEGRITY REQUIREMENTS**

The construction integrity of a flex circuit normally is best evaluated by performing a microscopic evaluation of a cross-section of the product both before and after thermal stress testing. This type of inspection is used to reveal the presence of microscopic defects that may impact the reliability of the finished flex circuit. As just stated, inspections are performed both as received (pre-stressed) and after various thermal stress tests have been performed (post-thermal stress). The tests are performed to assure that product quality and reliability are not degraded by the thermal exposure.

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**Coverlayer Concerns**

![Coverlayer Concerns Diagram](image)

Figure 8-7. Points of inspection for flex circuit cover layers.

173
endured during solder assembly and solder rework operations. Following are the major points of inspection:

**Pre-Stress Evaluation Requirements**

The following points are evaluated before exposure to solder stress, to screen product for the presence of defects in the as-received product. Major faults detected here may preempt the need for further testing.

**Lifted Lands**

These are checked to assure that land or pads have good adhesion to the substrate before stress testing. Land lifting is usually the result of thermal stress, where expansion of the heated laminate can cause lands to lose adhesion and to lift from the surface of the circuit. (See Figure 8-8.)

**Plating Integrity**

Plating integrity is evaluated to assure that plating quality, uniformity and thickness all meet specification requirements and that no cracks are present in the through hole in order to assure through-hole plating reliability. Major points of inspection are illustrated in Figure 8-7.

**Layer to Layer Misregistration**

Layer to layer registration is checked to assure that minimum requirements for the given class of product are met. This is primarily a concern for multilayer and rigid flex constructions, though it can be a concern with double-sided flex as well. (See Figure 8-7.)

**Post-Stress Evaluation Requirements**

The following checks are performed after required thermal tests. Microscopic evaluation of plated through hole cross-sections after thermal stress testing is the approved method for determining ultimate plated through hole quality.
THERMAL STRESS

Thermal stress or “solder float” testing, as the test is commonly called, is performed to determine if the plated through holes can successfully survive assembly. The test—exposure to molten solder for 10 seconds at 289°C (550°F)—is more punishing than typical assembly, but it is used to screen the product and prevent marginal product from entering manufacture. The samples are mounted and evaluated in cross section for attributes illustrated in Figure 8-10.

REWORK SIMULATION

Soldering and desoldering of a component lead five times in the plated through hole is a test performed to simulate field repair and evaluate its...
effects on the flex circuit’s plated through hole integrity. The test needs to be performed by a skilled operator, as an uncontrolled soldering iron could cause significant damage. The samples are evaluated in cross section for attributes illustrated in Figure 8-10.

**Lifted Lands**

Product is evaluated again for lifted lands after thermal stress. Limits for degree of lift are established to provide a measure of assurance that lands will not lift off the surface of the circuit while it is in service. (See Figure 8-10.)

**Electrical Requirements**

Electrical requirements of the flex circuit are specified to assure proper electrical performance of the finished product. While the tests outlined below are ones most often called out for circuit acceptance, other tests such as time domain reflectometry (TDR) testing of controlled-impedance circuits may also be required under contract provisions:

**Circuit Continuity and Shorting**

The circuits should be electrically tested to make certain that no opens or shorts are present in the board. This testing will assure conformance to design, and, just as important, proper circuit performance in the field. Test conditions such as test voltage and minimum resistance between conductors should be called out on the master drawing.

**Insulation Resistance**

Insulation resistance testing duplicates the raw material test and verifies that circuit manufacture processing has not degraded the insulation resistance of the material beyond customer-specified requirements.

**Environmental Requirements**

Environmental tests are performed to simulate, in a practical fashion, the effects of various environmental conditions on flex circuit quality, performance and reliability:

**Moisture and Insulation Resistance**

In this test, circuits are cyclically exposed to hot, moist air (from 80% relative humidity at 25°C to 98% relative humidity at 65°C). This is to assure that no damaging effects occur in the laminate and that undesirable degradation of the insulation resistance of the flex circuit has not occurred. Some variations to the test exist.

**Thermal Shock and Thermal Cycling**

Several tests and test conditions are embraced under the terms thermal shock and thermal cycling. Most tests consist of exposing the device to temperature extremes to induce thermal-cycle strain-related failures.
Thermal cycling is meant to be representative of the temperature extremes a circuit might be exposed to during its lifetime. Cycling conditions range from -65°C to +150°C, with prescribed dwells at temperature anywhere from 10 minutes to one hour. Shock testing normally employs short dwell times. The most common temperature conditions for bare-board test are −55°C to +125°C; however, with the introduction of the “product-specific reliability” testing concept by some manufacturers, several new thermal-cycling tests are becoming more common.

CLEANING REQUIREMENTS

Finished flex circuits must also be tested to assure that the circuits do not carry an excessive amount of ionic or organic contaminants with them. Such contaminants have been shown to have a negative effect on long term reliability.

IONIC CONTAMINANTS (SOLVENT EXTRACT RESISTIVITY)

Ionic contamination testing is performed to determine the level of ionic material left on the board by washing the board using a pure alcohol-water solvent, collecting the solvent and measuring its change in resistance. Such contaminants, if left on the board, are capable of causing latent failures due to corrosion and current leakage or shorting.

ORGANIC CONTAMINANTS

Organic contaminants are another potential source of problems and are looked for on the circuit. The contamination can be detected by flushing the surface of a small sample of the circuit with chemically pure acetonitrile onto a clean glass surface and allowing the solvent to evaporate. Residue on the slide may indicate the presence of organic contaminants.

SOLDERABILITY REQUIREMENTS

Tests for solderability of the finished circuit are performed to ascertain that the flexible circuit will not experience or create problems in assembly operations due to a non-wetting condition. This is normally accomplished by checking to make certain that proper wetting of solderable surfaces is present after testing in accordance with an approved test method.

The IPC-S-804 has long been a commonly called-out specification for solderability. However, it is being replaced by EIA/IPC-J-Standard-001, which is now the common standard for all electronic applications across the industry and around the globe.

SUMMARY

There are, clearly, a great many tests and inspection steps employed to assure the reliability of a flexible circuit. It is important to note that not all tests are required for every lot. Testing is typically split into two
levels: those tests required for qualification and those tests required for acceptance. Of these two, acceptance testing is more limited in scope, thus helping to reduce some of the testing requirements.

The reader is reminded that an effectively run manufacturing operation is normally one that rigorously employs statistical process-control (SPC) methods. Use of such process-control methods can significantly reduce the need for formal inspection operations by keeping the processes under constant control. Through the use of statistical process control, it is possible to achieve desired levels of performance and reliability at no extra cost, or even, perhaps, at a reduced cost. Employment of SPC methods is quickly becoming a customer requirement for an increasing number of flex circuit users and is a key conceptual foundation for the ISO-9000 certification program, which is becoming a de facto standard for the world market.
Documentation Needs for Flex Circuits

INTRODUCTION

The documentation package for a flexible circuit is the means by which the needs and requirements of the user are communicated to the manufacturer. If the information presented is clear and easily understandable, the chances of getting the product you want on the first pass is greatly enhanced. Some manufacturers have reported that as many as 75% of documentation packages they receive require some sort of clarification. This translates to countless man-hours lost pursuing very important information to meet manufacturing targets—a task that does little to improve productivity.

At a bare minimum, the circuit manufacturer needs to be given the following information in order to complete his manufacturing task properly:

- Class of product
- Materials to be used for construction
  - Base material and coverlayer type
  - Metal foil type and thickness
- Hole count for each hole size called out
- Data to define hole locations (hard/digital copy)
- Conductor layer count
- Circuit artwork defining signal runs for each layer
- Cross-sectional view of circuit construction
- Coverlayer or covercoat opening locations
- Circuit outline with dimensions and datums
- Marking requirements, materials and locations
- Bend and flex locations and direction of bend
- Stiffener location and bonding requirements
- Special processes and/or finish requirements
- Tolerances for manufacturing
  - Hole tolerances
  - Physical dimension tolerances
  - Critical dimensions, if any
- Test point locations
- Special electrical testing requirements
GENERAL DOCUMENTATION REQUIREMENTS

Following is a more detailed discussion of each of the above topics, along with some more general requirements commonly used for documentation purposes. The list is representative and not exhaustive.

DEFINE CLASS OF PRODUCT

There are three generally-accepted classes of product as defined by IPC standards: Class 1, consumer products, Class 2, telecommunications, computers and general industrial, and Class 3, high-reliability. The definition of class will serve to provide guidelines as to how the product must be fabricated and inspected as well as provide performance requirements.

DEFINE MATERIALS TO BE USED FOR CONSTRUCTION

The materials to be used in construction of the circuit need to be defined to inform the manufacturer of which material the circuit should be made from. This includes issues of base polymer choice, adhesive type and copper foil type, along with the thickness of each of the above.

PREPARE HOLE COUNT FOR EACH HOLE SIZE CALLED OUT

There is a need to define a hole count for each different hole size called out. This can usually be most easily accomplished by simply extracting data from digital files. The data are commonly used to help define the manufactured cost of the circuit.

PROVIDE DATA TO DEFINE HOLE LOCATIONS

While the sales department may be interested in the hole count, manufacturing is vitally interested in hole location in order to verify that holes and artwork are properly aligned. Hardcopy or digital information will work. These data can be extracted from drill files.

PROVIDE CONDUCTOR LAYER COUNT

This information serves the needs of both manufacturing and sales. The layer count provides an indication of circuit complexity to sales and a key descriptor of the product to manufacturing.

PROVIDE CIRCUIT ARTWORK THAT DEFINES CIRCUIT RUNS FOR EACH LAYER

Ideally, artwork is supplied in digital form, such as a CAD file. The CAD artwork provides the final definition of what the circuit will look like, where terminations will be located, and how they will be shaped. Depending on the feature size, this information may also serve the needs of sales as a means of predicting or estimating yield based on complexity.

PROVIDE CROSS-SECTIONAL VIEW OF CIRCUIT CONSTRUCTION

A cross-sectional view of the circuit is required to provide a visual cue as to what the designer expects his finished product to look like on
Flexible Circuit Technology

edge. It is a helpful means of predicting overall thickness. Figure 1-4 in Chapter 1 provides examples of cross-sectional views of various flex circuit constructions, though the addition of a perspective view, as illustrated, is not required.

**Provide Coverlayer or Covercoat Opening Locations**

The documentation package should also define the location of access points through the coverlayer or covercoat. In many cases, these will match the hole locations defined earlier; however, when surface mount devices are used, many other locations on the circuit will require access.

**Provide Circuit Outline with Dimensions and Datums**

The final circuit outline is necessary to define the periphery of the circuit relative to the circuitry itself. These data are used to create the tooling required to remove the part from the panel, whether soft (such as a routing program), semi-hard (such as steel rule die technology), or hard (such as Class A die technology).

The datums are important reference points to facilitate measurement. It is best if datums are called out based on features within the part rather than external to it. This allows the inspector to baseline his measurements on a real feature as opposed to an imaginary point outside the part. In addition, when features are distant from each other in a flex circuit, it is best to have a second or even third datum to facilitate measurement. This is because the length between features of a typical flex circuit may shrink or grow, making precise location of features difficult over long distances. Locally, however, the effects are not so great, and the part can more easily meet requirements. This scheme does not require the sacrifice of any tolerances but is merely a means of recognizing and accounting for the common realities of flex circuit manufacture. Figure 9-1 provides an example of such an approach.

![Figure 9-1 The use of multiple datums facilitates both accurate measurement and device placement.](image-url)
**Marking Requirements, Materials and Locations**

Marking requirements must be defined to provide the circuit manufacturer the information needed to locate accurately and mark properly specific locations on the circuit. The choice of type and color of marking ink must also be defined at this time.

**Bend, Flex and Crease Locations**

It is helpful to define the location of bend and flex areas as well as where crease lines may be required. This can be accomplished by placing special indicating features in the circuit artwork, or while marking is applied, and can also facilitate the assembly process by providing information as to which direction a bend must take. For example, dotted lines could be used to indicate bends in one direction, and solid lines could then indicate bends in the opposite direction. (See Figure 9-2.)

**Etched Metal Feature Bend Locators**

![Etched Metal Feature Bend Locators](image)

**Screen Printed Ink Bend Locators**

![Screen Printed Ink Bend Locators](image)

**Stiffener Location and Bonding Requirements**

Location of flex circuit stiffeners and special bonding requirements or instructions should be provided in the documentation package. Requirements for special strain-relief techniques such as an epoxy bead along flex-to-rigid transformations should also be cited here.

**Special Processing and/or Finish Requirements**

If special processes are required—such as the addition of special tear restraints or special finishes on the flex circuit—they should be called out. This includes calls for solder plating, nickel or gold plating, and the use of special, organic, solderable, protective coatings, such as benzotriazole and alkylimidazole. Organic, solderable, protective (OSP) coatings in particular are gaining in popularity as a means of bypassing molten solder coat finishes, which can damage the flex circuit.
TOLERANCES FOR MANUFACTURING

Manufacturing tolerances should be called out on the print. Most print formats provide a tolerance block near the title block for the drawing. Keep in mind that by nature of the product, flex circuit tolerances are or should be less stringent than those applied to rigid board constructions. As a result, the tolerance block should accurately reflect the capabilities of the finished flex product.

TEST POINT LOCATIONS

Test point locations should be defined either in the print or—more preferably—in a digital data format. The use of test nodes in place of 100% testing of all points on a circuit can help reduce testing cost by limiting test points only to those required.

It is important to remember that test probes will likely leave physical indentations on the metal surface due to the softness of the flex circuit base material. If this will be cause for concern by receiving inspection, it should be fully discussed with the manufacturer beforehand.

SPECIAL ELECTRICAL TESTING REQUIREMENTS

Should they be required, any special electrical tests should be defined in the documentation. This includes such tests as TDR or special “high pot” testing. Conditions of test, and test point locations, should also be thoroughly defined in advance.

SUMMARY

The list of items just provided provides a solid base in terms of understanding the general nature of need for flex circuit design documentation. However the list does not detail all the potential documentation requirements or needs of all possible flexible circuit designs. It is a never-ending list that is constantly evolving. Designers will, inevitably, have special needs for their particular circuit design. What is being stressed here is the need to provide as complete an information package as possible. The documentation sent to the vendor is the fundamental means of communication and, as such, must be as complete as possible to prevent potential confusion and loss of precious time.
Flexible Circuit Technology
Flexible Circuit Technology

INTRODUCTION

Specifications are developed to provide a common ground of understanding of what a product should look like and how it should perform. They are the framework that provides a measure of cohesiveness to an industry, a sort of industrial “glue” that helps hold the industry together and establish requirements for its products and services. Without good standards and specifications, there might never be any certainty as to how a product might look, be constructed or fulfill its obligation to the end user.

Most standards are either developed directly by the industry that produces the product specified (as is the case with IPC specifications) or by an end-user with significant industry input (such as with military specifications). While standards and specifications do provide a common reference point that serves all of the general industry, it is important to remember that the ultimate specification for any product is always the one contractually agreed to between the customer and the vendor. Were it not for this simple convention, progress in new materials development would be severely hampered, because changing specifications to include new materials or processes tends to be a long, drawn-out process.

Following is a listing of key standards and specifications relevant to the manufacture and use of flexible printed wiring and the raw materials used in their construction. The documents are briefly summarized here for quick referral purposes and reference to content only. These documents should be kept at hand for reference when designing, inspecting or testing flexible PCBs. There are many documents other than those listed here, which are commonly referred to in the manufacture of flex circuits but have a general interest level and are much broader in scope. These resources are normally referenced in the documents about to be referenced here, and, for the sake of brevity, they will not all be listed here.
**Relevant Flex Circuit Specifications**

As indicated earlier, the specifications of relevance to flex circuit manufacture come from two different sources: the industry itself and the military. They are here segregated for clarity.

**Primary Industry Specifications**

The IPC has been the primary progenitor of standards and specifications for the electronic interconnection industry. Recently, the IPC has been restructuring its specifications and documents in an effort to make them more compatible with other industry standards. As a result, new standards are being generated that will be replacing some of the older standards. However, since the older standards are likely to remain on blueprints and in other relevant documentation for some time to come, it is worth knowing both the new and the old document numbers. The various flex circuit-related documents are described here.

**General Documents**

**IPC-T-50G**

**Terms and Definitions**

While not specific to flex circuits alone, this document provides definitions for the most commonly used terms in the modern electronic manufacturing lexicon. As such, it is a valuable reference document to have for quick clarification of industrial terms.

**IPC-2615**

**Printed Board Dimensions and Tolerances**

This standard provides information on the dimensioning and tolerancing requirements for rigid and flexible, single-, double- and multilayered printed boards based on industry capabilities.

**IPC-D-325A**

**Documentation Requirements for Printed Boards**

This is a document of documentation. It encompasses the total documentation package necessary to define an end-product printed board, regardless of raw material, special fabrication requirements, layer-count, or end-product usage. It includes: Master drawing requirements, Board definition, Artwork/photo tooling, Solder mask requirements, Legend requirements, Specifications, Automated techniques, etc. The standard also covers documentation of basic board fabrication, heat sink bonding, and installation of terminals, eyelets and other hardware.
IPC-A-31  
**FLEXIBLE RAW MATERIAL TEST PATTERN**

This test film contains test patterns for: dimensional stability; chemical resistance; flammability; flexural endurance; flexural strength; tensile strength and elongation; dielectric constant and dissipation factor; volume and surface resistivity; moisture absorption; insulation resistance; and low-temperature flexibility.

IPC-ET-652  
**GUIDELINES AND REQUIREMENTS FOR ELECTRICAL TESTING OF UNPOPULATED PRINTED BOARDS**

Electrical test is becoming increasingly important, and this document provides information to assist in selecting the test analyzer, test parameters, test data and fixturing required to perform electrical test(s) on unpopulated boards and innerlayers.

**DESIGN SPECIFICATIONS**

IPC-2221A  
**GENERIC STANDARD ON PRINTED BOARD DESIGN**

IPC-2221A is the foundational design standard for all documents in the IPC-2220 series. It establishes the generic requirements for the design of printed boards and other forms of component-mounting or interconnecting structures, whether single-sided, double-sided or multilayer. Among the many updates to Revision A are new criteria for surface plating, internal and external foil thickness, component placement and hole tolerances. Expanded coverage is provided for material properties, dimensioning and tolerancing rules, and via structures as well as updated coupon designs for quality assurance. At 112 pages in length, it was released in May 2003.

IPC-2223A  
**SECTIONAL DESIGN STANDARD FOR FLEXIBLE PRINTED BOARDS**

This document is designed to be used in conjunction with IPC-2221A. IPC-2223 establishes the requirements for the design of single-sided, double-sided, multilayer or rigid flex flexible circuits. Now in Revision A, it includes updated design rules for panel sizes, hole spacing, bend radii, shielding, palletization, nonfunctional lands, coverlayer access/spacing and conductor edge spacing. At 24 pages in length, it was released in June 2004.
MATERIAL SPECIFICATIONS

IPC-FC-234
PRESSURE-SENSITIVE ADHESIVES ASSEMBLY GUIDELINES FOR SINGLE-SIDED AND DOUBLE-SIDED FLEXIBLE PRINTED CIRCUITS

This document provides information on adhesive types available. It also provides processes suggested for their proper use and highlights strengths, weaknesses, or limitations, and it provides information on how to start implementation. It suggests guidelines for the use of PSAs in single- or double-sided flexible printed circuits, membrane switches and component attachments. It also describes the types of materials and processes that may be used to accomplish proper attachment of flex circuits to a housing or other assembly.

IPC-4562
METAL FOIL FOR PRINTED WIRING APPLICATIONS

This document, formerly known as IPC-MF-150, specifies the properties and performance requirements, as well as the tests required for, each of the eight classes of copper foil (four different types of electroplated foils and four different types of wrought foils) that are used in printed wiring applications, both rigid and flexible.

IPC-4101
LAMINATE PREPREG MATERIALS STANDARD FOR PRINTED BOARDS

This document, which replaces IPC-L-108, IPC-L-109B, IPC-L-112A and IPC-L-115B, covers the requirements for base materials (laminate or prepreg) to be used primarily for rigid or multilayer printed boards for electrical and electronic circuits but also for rigid flex and for stiffener material for flex circuits.

IPC-4202
FLEXIBLE BASE DIELECTRICS FOR USE IN FLEXIBLE PRINTED CIRCUITRY

This ANSI-approved document establishes the requirements for flexible base dielectric materials that are used in the fabrication of flexible printed circuitry and flexible flat cables. It provides comprehensive data, designed to help users more easily determine both material capability and compatibility. IPC-4202 includes flexible base dielectric material specification sheets that are identified by material type. IPC-4202 is closely aligned with IPC-4203 and IPC-4204. The document supersedes IPC-FC-231C with Amendment 1 included and, in turn, IPC-FC-231C, IPC-FC-231B, IPC-FC-231A and IPC-FC-231. At 32 pages in length, it was released in May 2002.
Flexible Circuit Technology

IPC-4203  
**Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Circuitry and Flexible Adhesive Bonding Films**

This ANSI-approved standard establishes the requirements for adhesive-coated dielectric film materials used in the cover sheets, and flexible adhesive bonding films used in the fabrication, of flexible printed circuitry and flexible flat cables. The document provides comprehensive data that will help users more easily determine both material capability and compatibility. IPC-4203 includes adhesive-coated flexible dielectric film material specification sheets that are identified by material type. It is closely aligned with IPC-4202 and IPC-4204. The document supersedes IPC-FC-232C with Amendment 1 included and, in turn, IPC-FC-232C, IPC-FC-232B, IPC-FC-232A, IPC-FC-232 and IPC-FC-233. At 45 pages in length, it was released in May 2002.

IPC-4204  
**Flexible Metal-Clad Dielectrics for Use in Fabrication of Flexible Printed Circuitry**

This document establishes the requirements for metal-clad dielectric film materials used in flexible printed circuitry fabrication and flexible flat cable. The standard provides comprehensive data that will help users determine both material capability and compatibility. IPC-4204 includes metal-clad dielectric film material specification sheets that are identified by material type. Closely aligned with IPC-4202 and IPC-4203, IPC-4204 supersedes IPC-FC-241C and, in turn, IPC-FC-241B, IPC-FC-241A and IPC-FC-241. It is 57 pages in length and was released in May 2002.

Performance and Inspection Documents

IPC-A-600  
**Acceptance of Printed Wiring Boards**

One of the oldest of IPC documents, the IPC-A-600 provides visual standards for acceptance of printed wiring boards and includes a special section highlighting flexible circuits. Because many of the acceptance criteria for rigid boards and flex circuits are the same, the rigid board information can also prove of value. This four-color document provides photographs and illustrations of target, acceptable and nonconforming conditions that are either internally or externally observable on bare printed boards, based on current industry consensus information. The most recent document revision has more than 80 new or revised photographs and illustrations, providing coverage on topics such as smear removal, lifted lands and wire bond pads, along with updated and expanded coverage for measling and crazing of printed boards, annular ring requirements, etchback, foil cracks,
flexible circuits, and minimum foil thickness for conductive patterns. The document synchronizes to the acceptability requirements expressed in IPC-6012B and IPC-6013A. It is 140 pages in length and was released in July 2004.

**IPC-6011**

**Generic Performance Specification for Printed Boards**

As a generic standard, this document is designed to simplify the process of performance specification by bringing together all of the common points of concern. Other matters of specific concern are provided for in sectional documents.

**IPC-6013**

**Specification for Printed Wiring, Flexible and Rigid Flex**

This specification follows the format of IPC-6011 but is more specifically targeted at issues related to flexible and rigid flex circuits.

**IPC-6202**


The first joint standard developed by the Japan Printed Circuit Association (JPCA) and IPC, IPC/JPCA-6202 covers the requirements and considerations for single- and double-sided flexible printed boards. IPC/JPCA-6202 includes over 30 figures on accept/reject criteria for flexible printed boards and an appendix on the handling of polyimide-based flexible printed boards. Also included are all seven Japanese Industrial Standards (JIS) test methods. At 96 pages in length, it was released in February 1999.

**PAS-62123**


This is an IEC-approved Publicly Available Standard (PAS). It is identical to JPCA/IPC-6202. This standard covers the requirements and considerations for single- and double-sided flexible printed wiring boards. It is 96 pages long and was released in October 1999.

**IPC-TF-870**

**Qualification and Performance of Polymer Thick Film Printed Boards**

This IPC document covers the materials, qualification, certification, and performance requirements for polymer thick film (PTF), whether printed, extrusion-deposited, or otherwise applied for conductors, insulators, resistors and through-hole technology. (A good reference for the bookshelf that covers this subject in great detail is Polymer Thick Film:
Flexible Circuit Technology


FLEX ASSEMBLY AND MATERIALS STANDARDS

IPC-FA-251

ASSEMBLY GUIDELINES FOR SINGLE AND DOUBLE-SIDED FLEXIBLE PRINTED CIRCUITS

This document describes guidelines for populating and interconnecting components on flexible substrates, addressing the special needs of flex vs. rigid boards. Requirements for various classifications are provided. In addition, the guidelines describe the types of materials and processes that may be used to accomplish proper electronic assembly.

IPC-3406

GUIDELINES FOR ELECTRICALLY CONDUCTIVE SURFACE MOUNT ADHESIVES

This new document covers guidelines for selecting electrically-conductive adhesives for use in assembly of components to printed circuit boards or similar wiring interconnect systems. The focus is on the use of adhesives as solder alternatives. The process discussion attempts to stay within the bounds of the existing solder assembly infrastructure. Both major types of adhesives, isotropic (conducting equally in all directions) and anisotropic (unidirectional conductivity) are covered. The two major divisions of polymer adhesives, thermosetting and thermoplastics, are described.

IPC-3408

GENERAL REQUIREMENTS FOR ANISOTROPICALLY CONDUCTIVE ADHESIVE FILMS

This document covers requirements and test methods for anisotropically-conductive adhesive films used to bond and electrically connect components. Applications include the following: flexible PWB-to-glass, flexible PWB-to-rigid PWB, flip chip-to-glass, flip chip-to-flexible PWB, flip chip-to-rigid PWB, and fine-pitch SMD.

PRIMARY MILITARY SPECIFICATIONS

The military announced more than a decade ago its intention and desire to use, whenever possible, industrial specifications for its products in an effort to simplify procurement and lower cost. Therefore, the documents referenced here are or will be mostly of archival interest only. Nevertheless, because of the numerous long-term military contracts in place, these standards may well have ongoing significance to certain situations or based on contractual agreements and are included.
MIL-STD-2118
Military Standard, Flexible and Rigid Flex Printed Wiring for Electronic Equipment

This document, one of the earliest standards on flex and rigid flex circuit design, contains much valuable information on standards and guidelines for designing flex and rigid flex circuits for military applications.

MIL-P-50884
Military Specification, Printed Wiring, Flexible and Rigid Flex

This specification provides performance requirements and defines testing for flexible and rigid flex circuits for military applications. The document also provides information on the artwork required for building qualification boards.

SUMMARY

These documents, at a minimum, should be kept nearby as ready references for the designer/user of flexible circuits. As stated earlier, there are other documents of value and importance referenced within these documents, which may be added to this list. For example, specifications for rigid board laminates and prepregs, which are used both as elemental parts of rigid flex constructions and as stiffeners for flex circuits, might also be included on this list. However, the most important concern is that the documents be used and not simply purchased and shelved. Thorough understanding of these documents will provide an important footing for successful implementation of flexible circuits.
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IPC-2615 Printed Board Dimensions and Tolerances
IPC-D-325A Documentation Requirements for Printed Boards
IPC-A-31 Flexible Raw Material Test Pattern
IPC-ET-652 Guidelines and Requirements for Electrical Testing of Unpopulated Printed Boards
IPC-2221A Generic Standard on Printed Board Design
IPC-2223A Sectional Design Standard for Flexible Printed Boards
IPC-FC-234 Pressure-Sensitive Adhesives Assembly Guidelines for Single-Sided and Double-Sided Flexible Printed Circuits
IPC-4562 Metal Foil for Printed Wiring Applications
IPC-4101 Laminate Prepreg Materials Standard for Printed Boards
IPC-4202 Flexible Base Dielectrics for Use in Flexible Printed Circuitry
IPC-4203 Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Circuitry and Flexible Adhesive Bonding Films
IPC-4204 Flexible Metal-Clad Dielectrics for Use in Fabrication of Flexible Printed Circuitry
IPC-A-600 Acceptance of Printed Wiring Boards
IPC-6011 Generic Performance Specification for Printed Boards
IPC-6013 Specification for Printed Wiring, Flexible and Rigid flex
IPC-TF-870 Qualification and Performance of Polymer Thick Film Printed Boards
IPC-FA-251 Assembly Guidelines for Single and Double-sided Flexible Printed Circuits
IPC-3406 Guidelines for Electrically Conductive Surface Mount Adhesives
IPC-3408 General Requirements for Anisotropically Conductive Adhesives Films
MIL-STD-2118 Military Standard, Flexible and Rigid flex Printed Wiring for Electronic Equipment
MIL-P-50884 Military Specification, Printed Wiring, Flexible and Rigid flex
Other References
Company Design Guides:
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Minco Design Guide for Flexible Circuits
Nitto Denko Design Guide for Flexible Circuits
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Rogers Selector Guide for Circuit Materials
Sheldahl (Multek) Design Guide for Flexible Circuits
TAB Design Guide, 3M Corporation
Tech-Etch Design Guide for Flexible Circuits

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Course handbook, IPC Flex and Rigid flex Workshop.
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Index

A
accordion flexing, 104
acrylic adhesives (see adhesive)
adhesive squeeze-out, 91, 174
adhesiveless laminates, 45, 47-48
aluminum, 17, 58, 59, 95, 151, 160 163
anchoring spurs (see hold down tabs)
anisotropic adhesive23, 103, 193
annular ring, 170
applications for flex , 13, 29, 115
aramid fiber, 41, 48, 93
artwork, 182
assembly 12, 157-1651
assembly fixtures, 159
assembly flow, 158
assembly materials, 157

Annular ring acceptance criteria vary with the class of product being fabricated. See page 170
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B
back-bared circuits, 5, 121
back side access (see back bared)
base materials, 114, 115, 151
beam lead construction, 18
bend radius, minimums, 107
bending and flexing 103
  techniques for, 104
  tests for, 167
benefits of flex, 10-12
beryllium copper, 59, 95
bonding adhesive, 44, 96
bonding of stiffeners, (see stiffeners)
bondplies, 46
bond strength, 167, 175
bookbinder construction, 80, 117, 148
breakeven point, 71-73
buckling, 80, 111, 148
built-in resistors, (see embedded resistors)
butyral-phenolic (see adhesives)

C
C4 (controlled collapse chip connection), 18
CAD (Computer Aided Design), 70, 115, 182
cast adhesive film, 47
catalytic toners, 61
chemical resistance, 43, 168
chip on flex, 17-20
chip scale packaging 20
class (of product), 66, 182
cleanliness, 170
coefficient of thermal expansion, 48, 52, 159
COF (see chip on flex)
cold weld interconnection, 135
collapsing radius test, 175
component preparation 158
component hole sizing, (see holes)
component holes, stiffener (see holes)
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conductive adhesives 161
conductors, 80
  current carrying capacity, 81, 85
connectors, 30, 1008
construction types,
  back-bared, 5, 121
  double-access, 5, 121
  double-sided, 133-136
  multilayer, 25, 138, 140-141
  rigid flex, 7
  rigidized flex, 7
  sculptured, 5
  single-sided, 9
  stiffened flex, 7
construction integrity, 176
contact design, 113
controlled impedance, 14, 82
co-planarity, 158
copper bias in design, 76
copper foil 54-57
  electro-deposited, 54, 55
  electroplated, 56
  heat treated, 55
  properties, 58
  rolled and annealed, 56
  sputtered, 56
  structures, 56
  types, 54-57
  wrought, 55
costing,
  flex circuits, 12, 43, 49, 71-73
  materials, relative 49 (graph)
covercoats, 46, 90-91, 127, 139, 183
coverlayers, 45-46, 93, 127, 183
creasing flex circuits, 107
crosshatching, 84
CTE (see coefficient of thermal expansion)
CU foil (see copper foil)
current carrying capacity, 81, 85
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D
datums, 77-78, 183
delamination, 170
die cut process, 120
dielectric constant, 16, 32, 42, 50-53, 168
dielectric loss (see dissipation factor)
dielectric strength, 51, 169
dimensional stability, 42, 76, 167
disk (disc) drive, 9, 13, 176
dissipation factor, 168
documentation checklist, 181
dome switch, 110, 113, 127
double-access flex circuits, 5
double-sided flex circuits, 133-138, 177
dynamic folding, 176

E
ED copper foil, (see electro-deposited copper foil)
edge card contact, 101-102
edge condition, 170
electrical properties, 42, 168
electrical test, 21, 69, 168, 185, 189,
electro-deposited copper (see copper)
electroplated copper (see copper)
elongation, 51, 54, 58, 107, 166, 189
embedded passives, 60
embossed circuits, 113
environmental conditions, 178
epoxy, (see adhesives)
etch factors, 82
etching polyimide, 122
etching process, 60, 82, 119, 122, 134-135
eyelets, 135
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For a free sample of this circuit, visit www.3M.com/FCT
fatigue ductility, 175-176
filleting,
  lands and pads, 87, 99
  stiffeners, 99
finite element modeling 110-111
finishes, 149-151, 184
fixtures,
  assembly, 96, 157, 159,
  plating160
  test, 69
  wave solder, 159
flammability, 168
flex circuit mockups, 70, 75
flexing, 6, 10, 13, 68, 80, 103-105
flexible laminates, 42, 44-45, 137, 139, 149
flexibility endurance, 176
flexibility, low temperature, 167
flex circuit types, (see constructions)
flip chip, 17-20
fluoropolymer films, 48, 129
flying lead construction, 18
folded phone, 11, 28-29
fold over IC packaging, 20
folding, 79, 83, 101, 107, 176
folding flexibility test, 176
foreign entrapments, 286
formable backplane, 148
formable composites, 48
fungus resistance, 169

G
graphite, 112, 114, 134
grain direction, 79, 106
  effect of, 106
ground plane design, 84
ground plane hatching (see crosshatching)
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hatching (see crosshatching)
heat dissipation, 95
high speed circuit, 26
hold down tabs, 87
hole pattern accuracy, 172
holes, 86
  component, 98
  mounting, 97-99
  plated through, 7, 90, 166, 171
  sizes, 86, 174
  stiffener, 97-98
  unsupported, 98, 175
horns, (see hold down tabs)

I-beaming, 83
IC packaging, 20
immersion plating, 151-152
  immersion gold, 152
  immersion silver, 151
  immersion tin, 151
indium-tin oxide (ITO), 60
inspection, visual, 170, 176
instrument cluster, 29, 121
insulation displacement connector, 100
insulation resistance, 42, 169, 179, 189
ionic contamination, 179
iron alloy foils, 59

K, L
Kapton® (see polyimide), 50
laminates, 41, 45-52
LCP, 49
lamination, 25, 46, 52-53, 57, 89, 121, 130, 142, 145-146
land hold down, (see hold downs)
laser machining, 123
layer to layer registration, 177
lead-free, 42, 49, 53, 69, 87, 97, 149, 151-152, 157, 161 , 163
lifted lands, 176-177
liquid crystal polymer (see LCP)
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Flexible Circuit Technology

M
marking
marking requirements, 184
material properties, 43, 48
mechanical skiving 122-123
membrane switches, 41, 59, 85, 113-115, 191
metal foils, 45, 54, 58, 111
metallic coatings, 54
microstrip circuits, 114
mockups, 70, 75
moisture absorption, 43, 169
moisture and insulation resistance, 169, 178
Moore's Law, 35
multichip modules (MCMs), 36-37, 142
multilayer flex circuit (see construction types)

N, O
nesting of circuits, 79
neutral axis, 91, 105, 128
nicks, edge, 170, 174
Nomex®, 48
organic contaminants, 179
OSP, 152
Organic solderable protective coating, 152

P, Q
paper doll mockups, (see mockups)
paraffin-coated paper, 41
patents, flex circuit 1, 37-38
peel strength, 52-58, 167
PE (see polyethylene)
PEI (see polyetherimide)
PEN (see polyethylene naphthalate)
PET (see polyester)
photoimagable coverlayer (see coverlayer)
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PI (see polyimide)
plasma etching of holes, 124
plateable toner technology, 127
plated post interconnect, 142
plated through holes, 7, 90
evaluation, 166
voids, 171
polyester (polyethylene terephalate) PET 49-51
polyester adhesive, 51, 53
polyetherimide (PEI), 48, 53
polyethylene (PE) 48
polyethylene naphthalate (PEN), 49
polyethylene terephalate (see polyester)
polyimide, 17, 44, 48-52, 106, 110, 122-123
polyimide adhesives, 44, 52
polymer thick film (PTF), 7, 40, 50, 59, 85, 112, 125, 137
design guidelines, 85
polymer thick film design, 85
pressure-sensitive adhesives, 47, 96, 189
printed electronics, 153
PSA, (see pressure-sensitive adhesive)
PTHs, (see Plated Through Holes)
propagation tear strength, 167
pseudo coaxial construction, 115

R
RA copper, (see copper)
rabbit ears, (see hold down tabs)
reel-to-reel (see roll-to-roll)
reinforcements, see stiffeners
reliability, 17, 44, 66, 86, 90, 149
resistors,
   embedded, 60
   resistor material, 61
   resistive ink, 59
   screen printed, 85
return to web punching, 96
RFID, 10, 34, 38, 162
rigid flex (see constructions)
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rise time, 16, 32
roll to roll processing, 138
rolled & annealed copper, (see copper foil)
routing of conductors, 83
  capability, 23
  Manhattan, 26
rout and retain stiffeners, 96

S
scoring, 96
screen-printed resistors (see resistors)
Sculptured flex circuits, 5
semi-additive processing, 119, 125
sequential lamination, 140, 142
service loops, 79
shielding flex circuits, 111
signal integrity, 16, 115
single-sided flex circuits (see construction types)
skiving, mechanical, (see mechanical skiving)
smart cards, 10, 20, 34
soda-strawing, 174
solar array, 33
soldering, 69, 86, 89, 157-59, 163, 177
solder wicking, 171
solderability, 151-152, 170, 172, 179
solvent extract resistivity, 179
specifications, 187-194
sputtered copper, 56-57
squeeze-out, adhesive, 91, 173-174
SSP (see stair stepped package)
staggered conductors, 84
staggered conductors, 138
staggered length circuits, 80
stair stepped package, 21
standards, 187-194
steel rule dies, 131
stiffeners 7, 95-99, 131, 171, 184, 195
  attachment of, 96, 170
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filleting of, 99
folding contact area around, 101
holes for, 96, 98
location, 185
materials for, 47
pressure-sensitive, 96
scoring of, 96
special techniques, 95
strain relief, 97-99, 107, 159
stripline circuits, 115
surface mount (SMT), 16, 610, 88-89
surface mounting lands, 88

T
TAB (Tape Automated Bonding), 18
tactile feedback, 113
Tape Automated Bonding, 18
TDR, 178, 195
Time Domain Reflectometry (see TDR)
tear drop land terminations (see filleting)
tear resistance, 42, 50, 93
tear initiation, 167, 170
tear propagation strength, 170
tensile strength and elongation, 166
terminations
electrical components, 6
I/O, 21
location of, 183
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testing,
chemical resistance, 43, 168
electrical, 69, 168, 185, 189
dielectric constant, 168
dissipation factor, 168
dielectric strength, 169
surface and volume resistivity, 169
environmental 169, 178
moisture absorption, 169
moisture and insulation resistance 169
tensile strength, 166
elongation, 166
tear initiation, 167, 170
tear propagation, 170
peel strength, 167
physical testing, 175-176
flexibility testing, 167
plating adhesion, 175
thermal relief, 160
thermal resistance, 42
thermal cycling. 66, 87, 148, 158, 178
thermal shock, 178
thermal stress, 148-149, 170, 176-177
thermoplastic films, 45, 48, 97
360° shielded stripline, 115
tie-down tabs (see hold down tabs)
tolerances, 77-78, 82, 85, 183-184, 188
traces, (see conductors)

U, V
Underwriters Laboratories, 168
unsupported hole bond strength, 175
unsupported mounting holes, 98
via hole sizing, 86
VSMI, 36-37
voids,
plated through hole, 171
lamine, 165
volatile content, 168
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<table>
<thead>
<tr>
<th>FLEXIBLE</th>
<th>RELIABLE</th>
<th>QUALIFIED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Quick-turn</td>
<td>ISO9001:2000</td>
</tr>
<tr>
<td>Fabrication</td>
<td>On time</td>
<td>Mil-P-50884</td>
</tr>
<tr>
<td>Assembly</td>
<td>Responsive</td>
<td>RoHS, UL</td>
</tr>
</tbody>
</table>

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W, X, Y, Z

wave soldering, 159
wave solder fixturing, 159
wire harness 2, 12-13, 15, 26, 72-73
wire bonding, 17, 163
workmanship, 171
wrought copper (see rolled and annealed copper)
z wire interconnection, 135
Z-axis adhesives (see adhesive, anisotropic)
Z-axis interconnection, 23, 143
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About this book

This is the third edition of *Flexible Circuit Technology*. It has become one of the most popular texts available on the subject as a result of its simple approach to tackling this important and highly enabling electronic interconnection technology. The book was written to provide a bridge of understanding by offering a clearly defined set of steps which take the reader from basic concepts to a more detailed review of the various technology and materials that must be brought together to create these modern wonders of electronic interconnection wizardry. The book opens with an overview and brief history and then proceeds to describe the basic structures and some of the myriad applications and steps that the prospective user can take to engage in flexible circuit design and use. Materials used for flex circuits are reviewed next, followed by a comprehensive review of established flex circuit design practices and an overview of manufacturing process. The final chapters of the book are devoted to issues related to test, inspection and a review of the important industry specifications used to help communicate needs between vendor and user.

About the Author

Joseph Fjelstad is a 34-year veteran of the electronics interconnection industry and international authority, author, columnist, lecturer and innovator with more than 150 issued and pending US patents in the field. He is co-founder and CEO of SiliconPipe, a leader in high speed interconnection architecture design, much of it, not surprisingly, based on flexible circuit technology. Prior to founding SiliconPipe, he was with IC package technology developer Tessera Technologies, where he was appointed the company’s first fellow.

Fjelstad and his innovations have been recipients of many industry awards and accolades, but he is most proud of the accomplishments of his children and grandchildren.