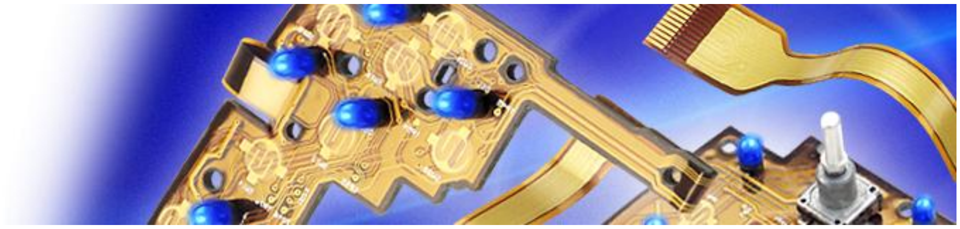
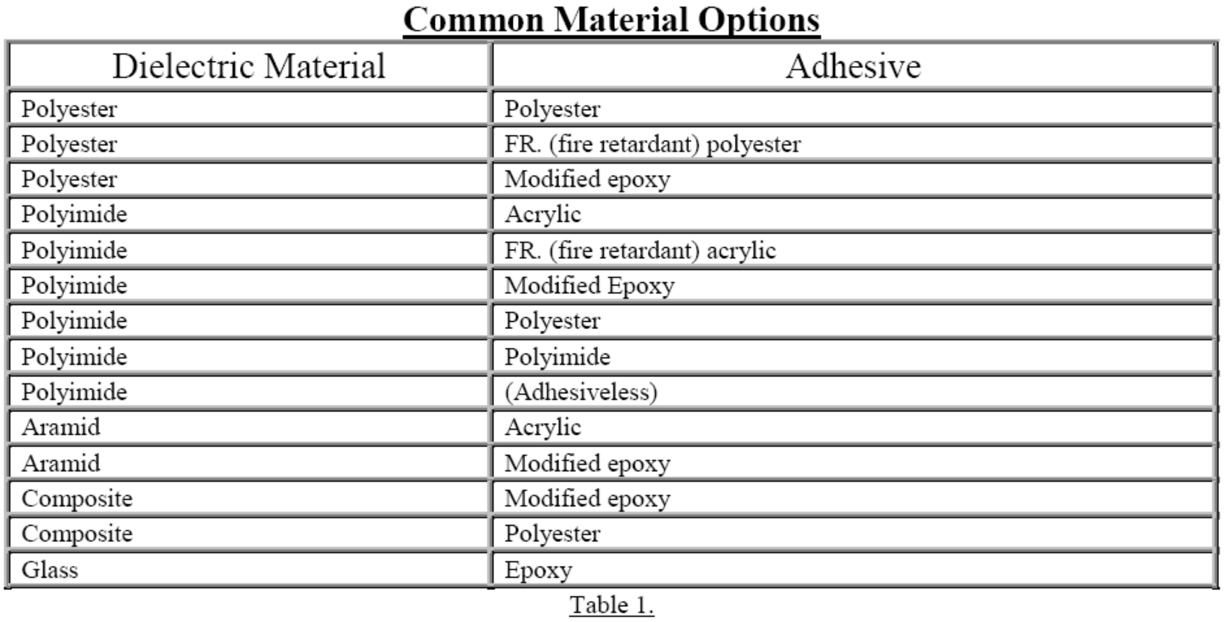


FLEXIBLE CIRCUIT DIELECTRIC BASE MATERIAL OPTIONS

Flexible circuits are used in a multitude of applications, ranging from the lowest end consumer products to the highest end military and commercial systems. It is no coincidence that the ranges of materials used to fabricate these circuits are as diverse in performance as the range of products in which they are used.

Materials such as polyester (Mylar), and polyimide (Kapton) have been industry standards for many years. Epoxy based laminates, both glass reinforced and non-reinforced, are also being used where cost advantages can be realized. Other materials are used for specific applications where certain performance characteristics are desired. This paper discusses the material options available for today's flexible circuit manufacturer and compares their performance and cost characteristics. Additionally it will look at the evolution of some laminate systems and comment on the introduction of new and improved polymer formulations.

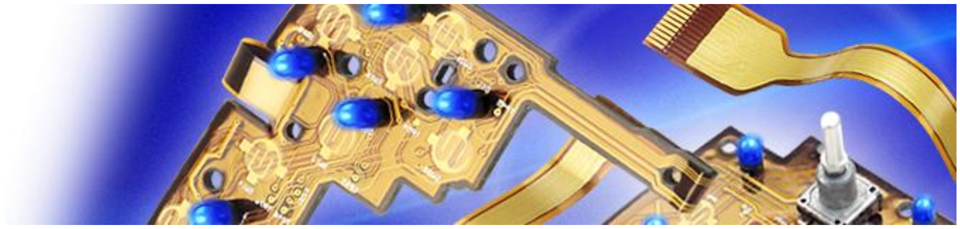


Common Material Options

Dielectric Material	Adhesive
Polyester	Polyester
Polyester	FR. (fire retardant) polyester
Polyester	Modified epoxy
Polyimide	Acrylic
Polyimide	FR. (fire retardant) acrylic
Polyimide	Modified Epoxy
Polyimide	Polyester
Polyimide	Polyimide
Polyimide	(Adhesiveless)
Aramid	Acrylic
Aramid	Modified epoxy
Composite	Modified epoxy
Composite	Polyester
Glass	Epoxy

Table 1.

In order to determine the best material for a given application one must first understand the major performance characteristics of each material. A good reference knowledge of the mechanical, electrical, thermal and chemical properties will allow an effective material choice to be made for each Flexible Printed Circuit (FPC) application. Such mechanical properties as flexibility, tensile strength, tear propagation strength and dimensional stability (Dim Stab); electrical parameters such as dielectric strength, dielectric constant and volume resistivity; thermal properties for glass transition temp (T_G), thermal coefficient of expansion (TCE) and service temperature range; and chemical considerations such as moisture absorption and resistance to acids or alkalines and automotive fluids (oils or grease) must be balanced to match the required design characteristics.



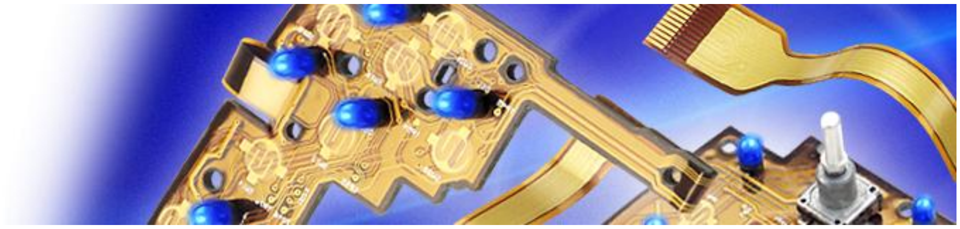
Properties of the common dielectric materials are summarized in Table 2.

From Table 1 it can be seen that FPC laminates commonly use adhesives to laminate the conductive material to the dielectric material. If adhesives are used, their properties must be compatible with the environment and operating parameters of the chosen dielectric material. Typical adhesive properties are shown in Table 3.

Adhesiveless materials that offer many performance improvements are now widely available but these improvements come at a cost. Table 4 shows the relative cost implications of some of the materials. The least expensive option is baseline as a factor 1.0 and each subsequent material is shown as a comparative factor.

A combination of the data in tables 1 thru 4 should drive the material choice for most FPC applications. For example, consider the flexible circuit often found in a telecom pager. This is an inexpensive consumer product where the most cost-effective material that will meet the design requirements should be chosen. In this case it would be reasonable to assume that the service temperature range would fall between -40 and +55 °C, that the electrical voltage and amperage requirements could be met by any of the materials listed, that the circuit would fit the non-demanding ‘flex-to-install’ criteria, and that the risk of exposure to anything apart from humidity moisture would be low. Polyester is probably the best material for the application, however great care must be taken when soldering polyester with conventional 63/37 Tin/Lead.

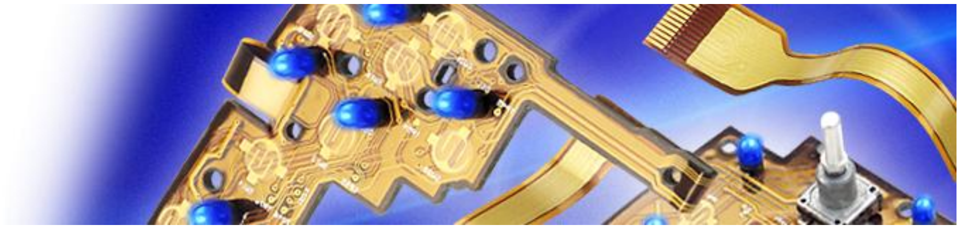
Alternate attachment techniques (lower temperature solder alloy or conductive adhesive) may be necessary to maintain acceptable process yields. If conventional solder processing is necessary but polyimide is cost prohibitive, hybrid materials have been developed to give properties somewhere between that of polyester and polyimide. These materials will be discussed later in this paper.



Common Material Properties

Property	Polyester	Polyimide	Aramid	Glass Epoxy
MECHANICAL				
Tensile Strength (PSI X 1000)	22 - 28	25 - 30	11	35 - 100
% Elongation at break	60 - 165	60 - 80	7 - 10	3 - 5
Tear Strength Initiation (lb./in X 1000)	1 - 1.5	1.0	N/A	N/A
Tear Strength Propagation (g/mil)	12 - 25	8 - 10	50 - 90	N/A
THERMAL				
Service Temp Range (°C)	-60/+105	-200/+300	-55/+200	-55/+150
CTE (PPM / °C)	27	20	22	10-12
T_G (°C)	90 - 110	220-260	-	90 - 165
CHEMICAL RESISTANCE				
Strong base	poor	poor	good	fair
Strong acid	good	good	good	good
Automotive Fluids (oil / grease)	good	good	good	good
Organics	good	good	fair	good
Moisture Absorption	0.3%	2.9%	8-9%	.05 - 3%
ELECTRICAL				
Dielectric Constant @ 1 KHz	3.1	3.0	2.0	4.2 - 5.3
Dielectric Constant @ 1 MHz	3.0	3.4	4.5 - 5.3	2.0 - 2.1
Dielectric Constant @ 1 GHz	2.8	3.0	4.5 - 5.3	2.0 - 2.05
Dielectric Strength (volt/mil)	3400	3600	500	240
Volume Resistivity (ohm-cm)	10^{18}	10^{18}	10^{16}	10^{15}

Table 2.



Adhesive Material Properties

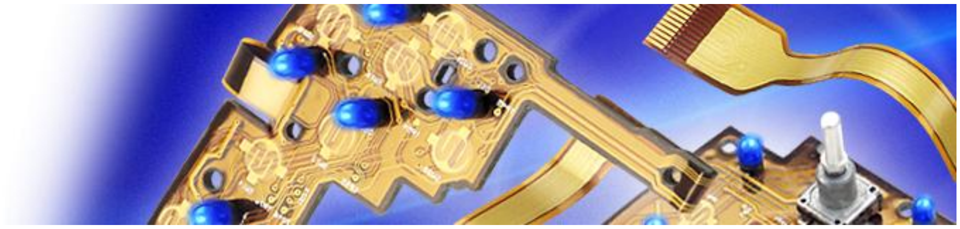
Property	Polyester	Acrylic	Modified Epoxy	Polyimide
MECHANICAL				
Peel Strength (Lb. / in)	3 - 5	8 - 12	5 - 7	2.0 - 5.5
Adhesive flow	10 mils	5 mils	5 mils	<1 mil
CHEMICAL				
Chemical Resistance	fair	good	fair	good
Moisture Absorption	1 - 2 %	4 - 6 %	4 - 5 %	1 - 2.5 %
THERMAL				
CTE (PPM)	100 - 200	400 - 600	100 - 200	5 - 40
T_G (°C)	90 - 110	30 - 40	90 - 165	220 - 260
ELECTRICAL				
Dielectric Constant @ 60 HZ	4.0	3.0 - 4.0	3.5 - 5.0	3.4
Dielectric Constant @ 1 KHz	3.1	2.5 - 3.5	3.5 - 4.5	3.4
Dielectric Constant @ 1 MHz	3.0	2.2 - 3.2	3.3 - 4.0	3.4
Dielectric Strength (volt/mil X 1000)	1.0 - 1.5	1.0 - 3.2	0.5 - 1.0	2.0 - 3.0

Table 3.

Consider another application, an automotive engine controller. The operating range for these units is -60 to +155 °C. This immediately rules out polyester as an option (based on Table 2.). FPC's are preferred over conventional rigid board (FR4) technology due to superior thermal dissipation characteristics and long term high temperature reliability. Polyimide is therefore an excellent choice. It is also a good example of a material that has evolved from merely a flexible dielectric to one which offers performance far in excess of hardboard technology.

Evolution of Adhesiveless

In the above example FPC constructions were originally based around polyimide / acrylic adhesive technology. This was a relatively robust material system but acrylic adhesive has a low T_G, (35-45 °C), extremely high TCE (400-600 PPM/ °C) and is prone to moisture absorption (3% by weight). This coupled with the additional thickness taken up by the acrylic adhesive in the laminate system (typically 0.9 mils per ply) meant that there was room for thermal improvement.



Adhesiveless polyimide technology is the evolution.

By removing the acrylic layer the overall base laminate thickness reduces from around 3.8 mils thick down to 2.0 mils or even 1.6 mils thick (depending on the metalization technique chosen). The acrylic ‘weak link’ is removed and the thermal dissipation characteristics are enhanced by almost a factor of 2 (due to reduction in thickness).

Adhesiveless Material Relative Cost Factor

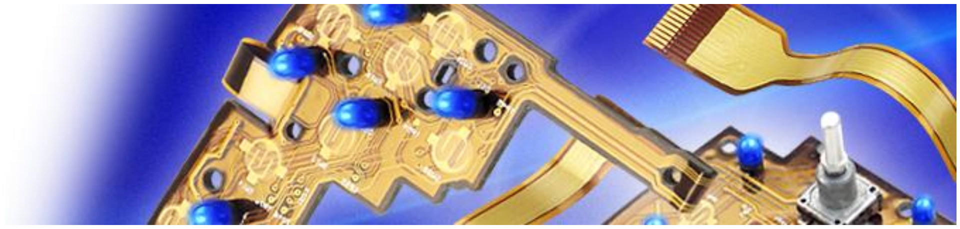
Double Sided Metal Clad Dielectric / Adhesive	Relative Cost Factor
Polyester / Polyester	1.3
Polyester / FR. (fire retardant) polyester	1.3
Polyester / Modified epoxy	1.1
Polyimide / Acrylic	2.7
Polyimide / FR. (fire retardant) acrylic	2.3
Polyimide / Modified Epoxy	2.0
Polyimide / Polyester	2.1
Polyimide / Polyimide	3.9
Aramid / Acrylic	-
Aramid / Modified epoxy	-
Composite / Modified epoxy	-
Composite / Polyester	-
Glass / Epoxy	1.0
Adhesiveless polyimide (Vacuum deposition)	3.5
Adhesiveless polyimide (Sputtered deposition)	3.5
Adhesiveless polyimide (Chemical deposition)	3.5
Adhesiveless polyimide (Solution Cast)	4.1

Table 4

Following is a brief summary of the current methods of manufacturing adhesiveless base laminate:

Vapor deposition - Copper is vaporized in a vacuum chamber and the metal vapor is deposited onto the polyimide film. A surface treatment on the film enhances the copper adhesion. Copper is deposited to a thickness of 0.2m m (typ); additional copper can be added by electrolytic plating.

Sputtered deposition - This involves placing the polyimide film in a vacuum chamber with a copper cathode. The cathode is bombarded with positive ions causing small particles of the copper to impinge on the film. Additional thickness can be achieved by electrolytically plating copper. A base metal of chrome or nickel is often required to enhance the materials performance.



Chemical deposition - Polyimide film is roll processed through electroless metal chemistries to produce a thin ‘seed’ layer. This material is then processed through electrolytic plating processes to achieve the desired thickness of copper.

Solution cast - A liquid solution of polyamic acid is cast onto the copper foil. It is subsequently heated to a point where the solvent is evaporated off leaving a polyimide (or amide) film. This is an efficient process for creating single sided laminates, but for double-sided laminates a thermal compression stage is required to laminate two single sided sheets together.

It should be noted at this point that you do not always have to use ‘true’ adhesiveless polyimide to benefit from many of the enhanced material properties. DuPont offers an all polyimide construction (AP) in which they attach foil to the laminate using what is essentially a polyimide adhesive layer. In this case the finished film thickness is 2.0 mils. This is achieved by starting with a thinner polyimide core layer and by casting thermoplastic polyimide onto each side to facilitate the attachment of copper foil or to create a dielectric bondfilm. DuPont claims to have developed this high temperature adhesive technology to a point where they can combine different polymer streams to give defined laminate properties (i.e. increased moisture and chemical resistance, better thermal conductivity, improved mechanical performance, higher tensile strength, less dimensional distortion etc.).

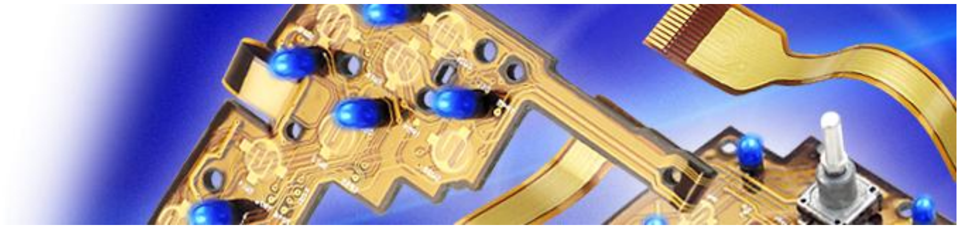
Innovations in adhesiveless and high temperature adhesive technology will continue due to the considerable level of R&D activity currently underway in North America and the Pacific Rim.

Electrical Advantages of Adhesiveless Materials

Adhesiveless technology offers certain electrical advantages that are not instantly obvious. These result from the range of thinner conductive coatings that are typically available. Thinner coatings are possible because adhesiveless materials are metalized using roll processing techniques. Time is the major controlling factor for metal thickness so creating a thinner foil can be as simple as increasing roll speed or reducing amperage to the plating rectifier.

From an electrical standpoint, thinner conductive coatings offer greater latitude to the electrical engineer who is designing an impedance controlled board. Consider a micro-strip or stripline design. With adhesiveless material, the dielectric spacing is reduced which usually necessitates a thinner conductor to achieve the desired impedance factor. This may make the design less manufacturable and subsequently cost prohibitive, but with the option of using ¼ oz copper (½ oz finished) the cross sectional area of the conductor can be reduced by 50% without impacting the line width. This coupled with a lower dielectric constant (typical of adhesiveless materials) allows for higher impedance values without seriously affecting image and etch production yields. In this instance there may be a yield reduction based on batch handling of the ultra-thin base material, therefore an FPC manufacturer who utilizes roll processing techniques has a distinct advantage.

A beneficial side effect of using adhesiveless materials for impedance controlled designs is a narrowing in the impedance range as noted on the TDR (Time Domain Reflectometer). Acrylic adhesive has the tendency to allow embossing (conductors settle into the adhesive). This can result in a variation in dielectric separation which is somewhat determined by the density of the conductor pattern. This is seen on the TDR curve as a greater delta (tolerance) between the min and max impedance values.



Mechanical Advantages of Adhesiveless Materials

A reduction in dielectric spacing typically half that of a traditional acrylic adhesive based material means that the metal foil layers are significantly closer to the neutral axis and therefore subject to less stress and strain during flexing. This is especially important in dynamic (continual) flexing applications where increased life performance and reliability can be achieved. Mean time between failures (MTBF) are seen to increase from 300 - 500 flexes (conventional adhesive based construction) to 10,000 to 20,000 flexes (adhesiveless construction).

Thermal Advantages of Adhesiveless Materials

In high layer count rigid flex applications the advantages of adhesiveless materials are well known. Acrylic adhesive with a Z axis CTE of 500 - 600 (PPM per °C) and a T_G of 30-40 °C is the known weak link from a reliability standpoint. The more acrylic in a construction the greater the chance of barrel cracking and outerlayer pad lifting during thermal cycling or soldering operations. By utilizing adhesiveless inner layers combined with polyimide prepreg bondfilms and polyimide cap layers a high reliability (all polyimide) rigid flex capable of 20+ layers can be produced without plated through hole reliability issues.

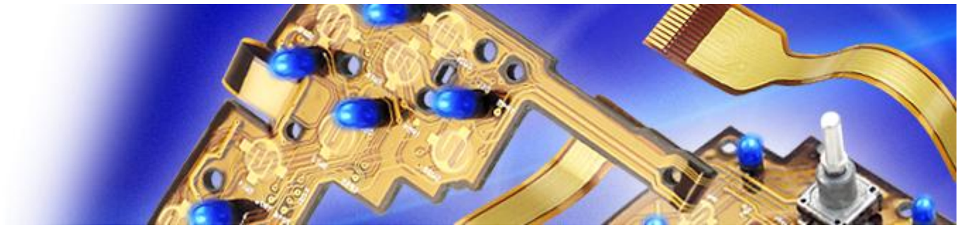
These constructions are excellent for military/aerospace and other high reliability applications but the materials used can be cost prohibitive for commercial applications. In such instances other innovative material solutions are being successfully utilized to build rigid flex boards in the 3 - 10 layer range. A number of manufacturers are using ultra thin epoxy glass as the flexible inner layers and modified epoxy clad foils (non reinforced) as flexible cap layers; others are using thin aramid fiber inner layers to yield high reliability boards at an assembled cost that is competitive with rigid multi-layer boards.

Advantages of Roll Processing

As noted in Table 4, the cost of buying clad adhesive material can be expensive. The real cost savings are available to manufacturers who metalize their own material. In this case the film is guided through the various processes using sophisticated unwind / wind equipment. Because the web is held under constant tension traditional batch handling issues are eliminated.

In contrast conventional adhesive based laminates are made by thermally bonding copper foil to adhesive coated dielectric material. This is done by laying up sheets of foil and dielectric between steel caul plates and laminating under temperature and pressure conditions or by continuous roll lamination techniques. These processing technique make it extremely difficult to handle foils of less than 1 oz thickness without affecting process yield.

One of the major cost savings realized by the roll processors is that the circuit holes can be punched, etched, or laser drilled prior to metalizing the film. Until recently it was normal to buy copper clad material only to drill it and have to plate additional copper onto both surfaces in order to get the through-hole connections. If you consider that technique as the baseline the roll process manufacturers get their throughholes free.



Future Material Options

A modified material system has been developed that exhibits performance characteristics somewhere between polyester and polyimide. The material, Polyethylene naphalate (PEN) is not new, it has been considered a possible replacement for a high percentage of polyimide applications for many years but it has never exhibited enough performance enhancements to warrant serious attention.

Finally modified formulations capable of withstanding conventional soldering operations and exhibiting properties approaching those of polyimide have become reality. At a cost factor of 1.5 - 1.8 (based on table 4.) this material could have a real impact on the price of flexible interconnects.

Another recent innovation is a material which is ‘loaded’ to enhance thermal conductivity. Based on DuPont’s Kapton MT as the core material and utilizing 0.2 mils of thermoplastic polyimide on each side (to facilitate foil lamination), the material achieves conductivity numbers equivalent to FR4 (0.30 - 0.35 W/m • K) at a total thickness of only 2 mils (1/10th that of thin double sided FR4 technology). This development is particularly exciting as it provides the packaging densities of 4 layers (flex multilayer) with better heat dissipation than double sided hardboards.

Future Technologies

Newer generation packaging technologies such as Ball Grid Array (BGA) and Flip Chip will rely heavily on FPC substrates. With the emphasis on higher density interconnects the need for effective heat dissipation is increased. As mentioned above adhesiveless polyimide offers the thermal conductivity parameters capable of meeting these requirements. It also lends itself to the preferred methods of small hole via generation; plasma reactive ion etching; wet chemical etching; or wide area laser ablation. These techniques can only be effective with single layer film based materials. Add to these factors the compliant nature of a film based laminate and you have an ideal carrier for solder bumping and reach through via technologies.

With the rapid evolution of new packaging requirements, the demand for a new generation of flexible circuit materials will accelerate. More integration with the electronic and mechanical package, increased thermal demands, higher signal speeds and the ever-present pressure to reduce price will prove to be the ‘mother of invention’. It is incumbent upon the fabricator that he remains keenly aware of material advances and that he supports the developers of these products with a coordinated R&D effort.