High Volume Applications of Commercial Rigid-Flex

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Abstract

Rigid-Flex printed circuits have enjoyed a prominent role in military and aerospace electronics applications for over twenty-five years. Their inherent ability to provide reliable interconnection within constrained form factors have earned them an excellent reputation as a versatile platform for the packaging and integration of military electronics. In recent years, this technology has been steadily migrating into commercial applications, where high volume and low cost are primary drivers. More often than not, however, commercial electronics designers choose rigid-flex circuitry for the same reasons as the military - high performance.

This paper examines the evolution of rigid-flex technology, from its military heritage through present-day, high volume commercial uses, highlighting the inherent advantages of the technology which have driven this migration. Performance characteristics of several products from military, high-rel commercial and high volume commercial applications are presented, including an illustration of the steps necessary to transition a typical rigid-flex circuit into a high-volume, cost sensitive product.

Introduction

As printed circuit technology has evolved, rigid-flex manufacturers have made various innovations to address issues ranging from thermomechanical reliability (initially raised by the military) to producibility and cost reduction, the latter two being important factors in high volume applications. As a result, rigid-flex circuitry has been increasingly designed into a wide variety of commercial products, not only for the usual benefits of packaging density, ease of assembly, and lower weight/unit volume, but also for superior electrical, mechanical and reliability characteristics. The broad range of materials available today allows the producer more latitude in optimizing those attributes through various constructions of rigid-flex, so as to make them particularly attractive to high volume, high performance commercial electronics. Interconnect MTBF, survivability in thermal environment extremes and flex endurance are examples of key attributes and will be discussed using actual product examples in the automotive, computer peripherals and portable electronics markets.

The increased levels of complexity and integration which often distinguish rigid-flex circuits from rigid boards can also create the perception that they are “custom crafted”. However, there are many excellent examples of high yielding rigid-flex products which have benefited from the aforementioned attributes at only a modest cost premium over conventional rigid boards. In most cases, the rigid-flex products have a lower final assembly cost than a design using multiple rigid boards/cards. The keys to cost effective utilization of rigid-flex circuitry in commercial products are better up-front design at the assembly level, proper selection of materials and process optimization. Further innovations in electronics packaging and circuit materials, combined with greater need for integration will continue to drive the migration of rigid-flex circuits into commercial products.

High-Rel and Military Heritage of Rigid-Flex

From an historical perspective, Rigid-Flex applications were developed primarily as an interconnect method for Military systems. System designs that used Rigid-Flex were found to be lower in weight and volume due to the elimination of connectors and other interconnect hardware. The flat configuration of the etched conductors provides 50% more surface area when compared to discrete wiring, which allowed for greater heat dissipation. By providing a three dimensional aspect to the printed wiring board designers were able to design unique solutions to the packaging of electronics in tight spaces. Applications utilizing Rigid-Flex as the interconnect have been subjected to harsh environmental conditions such as thermal shock, thermal cycling, humidity, and salt spray and been found to maintain electrical and mechanical integrity. The overall reliability of Rigid-Flex has been proven out many times through rigorous qualification testing on these Military programs. Rigid-Flex has been used on every major military aircraft platform including the newly designed F-22 fighter.

It was this high reliability, coupled with the ability to reduce weight and volume, that prompted other applications for Rigid-Flex. Many commercial avionics packaging applications have been designed that utilize this technology, including the 777 aircraft from Boeing.

Figure 1. 777 Analog/Digital Control Board

This aircraft was designed with strict weight requirements and designers used Rigid-Flex in several control boxes to achieve weight savings not possible with more traditional interconnect methods such as discrete wiring or multiple rigid boards linked via traditional connectors. Other commercial avionics applications that have used Rigid-Flex include flight control boxes and in-flight entertainment modules for passenger use.

Applications for high reliability interconnects encompass more than military and avionics applications. The medical market has taken advantage of the weight and volume reductions, coupled together with the reliability record. A manufacturer of implantable devices has used Rigid-Flex as the core interconnect for an implantable device. This application not only needed to pass customer qualification testing, but also had to gain FDA approval based on several aggressive reliability tests.

High reliability is not the only reason to utilize Rigid-Flex as a packaging alternative, however. The computer industry has implemented Rigid-Flex in several high volume applications. The ability of the flexible section to conform to a small form factor container results in decreased circuit volume. This aspect, coupled with the reduction of connectors at board interface regions, allow for lower weight portable electronics. Rigid-Flex was the primary element of one of the first notebook design that used a 386 20 MHz processor - developed in 1990. This packaging method facilitated the removal of seven connectors from the system which increased the reliability. Successful implementation through design and pre-production allowed the manufacturer to take advantage of the window of opportunity to secure their position in the marketplace for portable notebook computers. The success of this program led to other high volume computer applications. One application in particular will be discussed in greater detail in this paper.

YEAR	APPLICATION
1960's	Flex circuits used in space applications for NASA
early 1970's	Flex circuits used on Fighter Aircraft and Missiles for reduced weight
early 1980's	Rigid-Flex circuits first used in High Reliability Military electronics.
1987	REGAL®Flex developed by Teledyne to answer dimensional and thermal stability issues with Rigid-Flex.
1988	Military Version of VAX computer
1989	24 Layer backpanel for Military Avionics utilizing REGAL®Flex
1990	Notebook Computer
1991	Commercial Avionics Flight Box
1992	Computer Disk Drive
1993	Automotive Engine Control Automotive Navigation System
1994	Boeing 777 Instrumentation
1995	Implantable Medical Device

Table 1

Chronology Of Rigid Flex Applications
(Teledyne Electronic Technologies)

Constructions Available

There are many construction options that are offered by manufacturers of Rigid-Flex. The most prevalent, and the most mature, is a construction based on polyimide film with acrylic adhesives as shown in Figure 2. The polyimide film/acrylic adhesive is laminated to a sheet of rolled annealed (RA) copper. This flexible base copper substrate material is then imaged and etched to form the conductive pattern using conventional printed wiring board procedures and equipment. A coverlayer of polyimide film/acrylic adhesive is then laminated to the etched sheet to provide environmental protection and dielectric insulation to the innerlayer. Several of these innerlayers are then selectively bonded together to form rigidized sections allowing for the placement of drilled and plated holes.

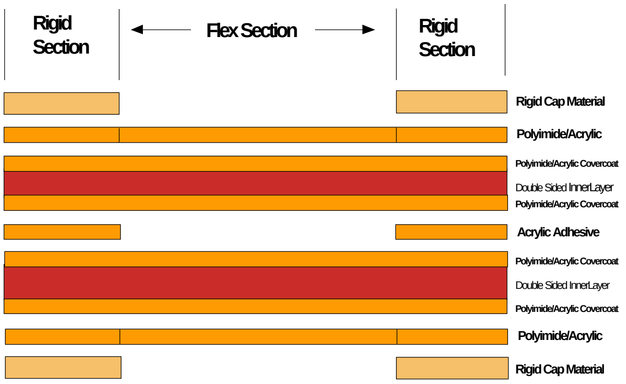

Figure 2. Conventional Rigid-Flex Construction

An improvement to this type of construction is based on adhesiveless core materials which remove a percentage of the acrylic adhesive. This is important when considering subsequent exposures to thermal extremes, such as soldering, since the acrylic is not a thermally stable material. The adhesiveless copper clad polyimide film is processed as an innerlayer as discussed before. The layers are then bonded together using a pre-tooled epoxy glass pre-preg to form rigidized sections. The use of the pre-preg allows for the amount of acrylic adhesive and polyimide film used to be even further reduced. The use of adhesiveless laminates in Rigid-Flex has continued to rise since their development and introduction to the marketplace.

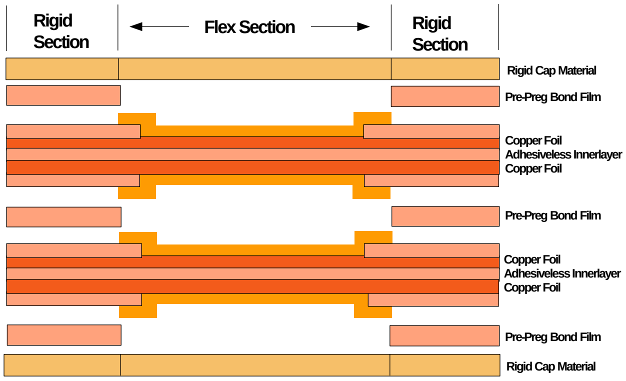

Figure 3. Adhesiveless Rigid-Flex Construction

Before adhesiveless laminates were developed several companies were working on other ways to manufacture Rigid-Flex circuits without the use of acrylic adhesives. Teledyne Electronic Technologies developed REGAL® Flex, a process based on the usage of epoxy glass pre-preg as the core dielectric. The pre-preg is bonded to copper sheets to form a very thin and flexible base substrate. The substrate is imaged and etched using conventional board manufacturing techniques to define the circuitry pattern. A flexible coverfilm dielectric is then laminated to the intended flex region to allow for increased flexibility. Several innerlayers are selectively laminated together to form rigidized sections to allow for through hole drilling and plating. It is in these rigidized sections that the through hole and surface mount devices will be placed.

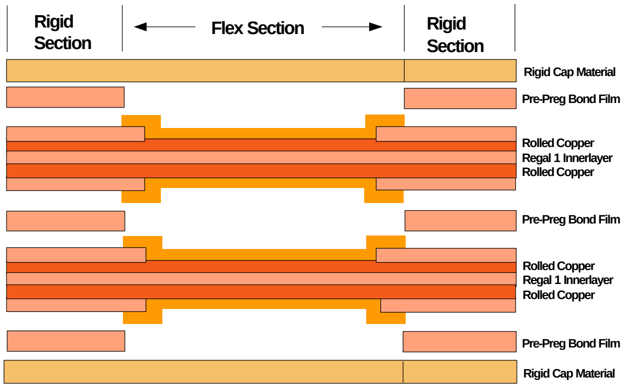

Figure 4. REGAL® 1 Rigid-Flex Construction

The use of this type of construction will yield a finished assembly that is capable of several hundred bend cycles without any mechanical or electrical failure. What is gained is the ability to subject the board to any one of several assembly operations such as reflow or wave soldering without concern for thermal failure of the plated through hole. REGAL®Flex has been successfully used in many military and commercial applications and found to be superior in performance when compared to other material constructions available today.

Performance Characteristics for Commercial Applications

When discussing reliability on any electronic module the need for testing criteria and data to support that testing are crucial. A tremendous amount of data has been collected on military programs for designs that included Rigid-Flex as the interconnect at a system qualification level. The testing requirements for Military applications are generally more specification oriented rather than application oriented. This then leads to certain testing requirements to be imposed by the designer that may not otherwise be required, thus adversely affecting cost. For those commercial applications where cost is a significant driver, testing requirements need to be generated around assembly and system requirements so that accurate data can be collected and analyzed. For many designs that use Rigid-Flex the Mil-Spec requirement for flexibility is that the unit must be capable of being formed during installation and subsequent servicing. This amount of flexibility, known as a "flex-to-install" application, requires a flexing test of 25 cycles. This test could be more aggressive than the system level requirement where a flexing cycle test of 10 cycles would meet the testing requirement. This does not mean that the flex section is any less reliable, but rather that the testing requirement and frequency matches the system requirement so that costly redundant testing can be eliminated. Teledyne is currently in large volume production for a commercial disk drive circuit that is a flex-to-install application. The qualification test requirement for this unit is that the circuit be capable of withstanding 25 cycles of bending around a 1/8 inch mandrel. Actual testing of the product after design revealed that the circuit was capable of over 350 flex cycles. The majority of Rigid-Flex circuits manufactured will only be flexed once during assembly.

Another critical test for printed wiring boards is thermal stability. Most boards are subjected to thermal extremes during assembly operations and many are used in thermal environments. Traditionally, Military boards would be tested to a pre-existing specification that would be imposed due to flow down contractual requirements as opposed to actual application requirements. The thermal stress requirement for a Rigid-Flex board manufactured to Mil-Spec requires a solder float for 10 seconds at 550°F. The sample coupon is allowed to be pre-conditioned by baking to remove moisture and to reduce the thermal gradient prior to stress. In a high volume commercial market many boards are double sided surface mount designs, including mixed technology, which requires several reflow operations. There is not enough cycle time to allow for extensive baking or pre-conditioning of boards prior to solder assembly and reflow. Therefore, to test to Mil-Spec requirements may yield product that is not capable of surviving real world assembly techniques and processes. The REGAL®Flex product currently being produced at Teledyne is capable of passing a double IR reflow exposure at high volume production quantities (> 10,000 units per week) without any special handling or operations. This demonstrates that assemblers can process the REGAL®Flex boards in the same manner as any other circuit board.

Another reliability requirement for circuit boards is the ability to pass temperature cycling. Once again traditional Mil-Spec testing would require certain parameters that would be specification driven rather than application driven. The Mil-Spec temperature cycling requirements normally focus on temperature extremes of -25°C to +125°C for either 5, 25, 50, or 100 cycles. There are many commercial applications that will never see temperature extremes to this magnitude, therefore, to impose these testing parameters to a vendor would add unnecessary costs, which would adversely affect pricing.

There are commercial applications for printed wiring boards with even more aggressive thermal cycling requirements. The automotive industry requires thermal cycling qualification tests to be conducted at -50°C to +125°C for 1000 cycles for under the hood applications. Using a REGAL®Flex construction for an eight layer board Teledyne engineers were successful in passing this requirement.

TEST	RESULT	METHOD
THERMAL STRESS		
10 Sec Solder Float @ 550°F	**PASS**	Microsection
5 Sec. Solder Float @ 550°F (Repeat 5X)	**PASS**	Microsection
THERMAL CYCLING		
-50°C to +125°C		
25 Cycles	**PASS**	Microsection
50 Cycles	**PASS**	Microsection
125 Cycles	**PASS**	Microsection
1000 Cycles	**PASS**	Microsection
FLEX ENDURANCE (2)		
REGAL®Flex 1		
10 Cycles	**PASS**	Visual/Elect.
25 Cycles	**PASS**	Visual/Elect.
350 Cycles(3)	**PASS**	Visual/Elect.
TEAR STRENGTH		
Flex Sections		
500 gm. (1.1 lbs.)	**PASS**	Gauge/Visual
	Min. Value Achieved 1.8 lbs.	
	Max. Value Achieved 3.5 lbs.	

(1) Sample Product .0025" Core Epoxy Pre-Preg with Polyimide Film Coverlay
(2) Mandrel Size Equal To 12X Material Thickness or 1/8" Diameter
(3) Test Criteria 90° Bend, No Mandrel - Flex To Failure

Table 2

RELIABILITY TESTING ON REGAL®Flex

High Volume Disk Drive Application

Teledyne is currently processing an eight layer Rigid-Flex based upon the REGAL®Flex process for Seagate. This board is used in the Barracuda™line of high reliability disk drives. (See Figure 5.) Seagate design and reliability engineers worked with engineers from Teledyne to design an interconnect scheme based on Rigid-Flex that would fold into a tightly constrained form, that would eliminate the need for connectors and related interconnect hardware, and would increase reliability. All of this would need to be achieved while maintaining specific cost guidelines for the substrate. It was stated that the board would be subjected to a double IR reflow during the assembly process so thermal stability in the Z-axis for plated through hole reliability was needed. A further requirement was that the board needed to be capable of passing a flex-to-install test of 25 bending cycles around a 1/8 inch mandrel. First Article testing requirements included a thermal shock test criteria of solder float for 5 seconds at 550°F. The solder shock was to be repeated 5 times to the same sample, which was to be subsequently microsectioned. With these parameters in mind Teledyne engineers chose a REGAL 1 construction to fill the needs of this application. Following the design cycle prototype circuits were manufactured at Teledyne's Hudson NH facility. These circuits were used for qualification and First Article testing. The REGAL®Flex met or exceeded all the requirements imposed by Seagate Quality Engineering. The next delivery of boards were manufactured at an off-shore facility in Singapore. This facility, Teledyne Gul-Technologies (TGT), is a joint venture formed in 1991 between Teledyne Industries and Gul-Technologies Pte., Singapore. The transition to TGT allowed Teledyne to meet the aggressive cost reduction program imposed by the customer. The compatibility of the CAD systems at the two sites allowed for quick and accurate electronic transfer of the database files with minimum cycle time. This enabled Teledyne to ramp up to production quantities in a very short time so that the customer's delivery schedule was not affected by the transfer.

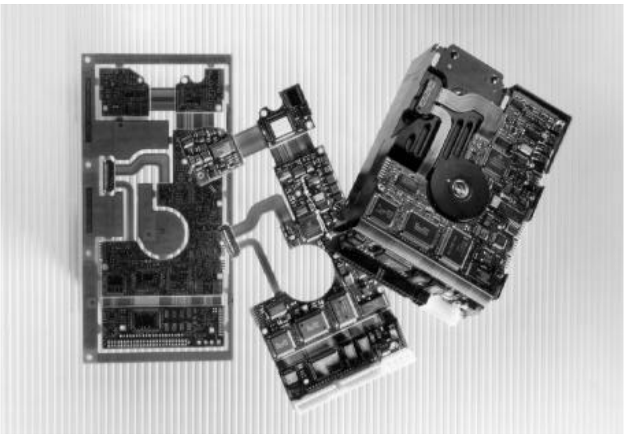

Figure 5. Computer Disk Drive Application

Following first run production, the process engineers in Singapore teamed together with Teledyne engineers in Hudson to form a cost reduction and process improvement team. The objective of this team was to identify each process and how it contributed to either the quality or the cost of the product. Processes and materials that were targeted for improvement were analyzed with the clear cut objective of reducing cost and decreasing cycle time. One of the first areas targeted for improvement was the lamination area where it was revealed that certain indirect materials were causing this process element to be outside the projected budget. The lamination release material that was used in Hudson was switched from a press conformal material that was used once and discarded to a lower cost material that could be used hundreds of times. This reduced indirect material costs and the amount of waste material generated. A further analysis of the lamination process revealed that the layers could be laminated in a 7 high stack vs. a 4 high stack which further reduced the cycle time. To allow for greater product throughput the panel size was changed from a 12” X 18” size to 16” X 21” panel size. This change doubled the number of circuits up per panel which allowed for greater utilization of equipment and resources. Further improvements were realized in the lamination area when the focus turned to the final lamination process. Once again expensive indirect press pad materials were replaced with multi-use lower cost materials. The stack height at final lamination was changed from 3 high to 5 high thus improving throughput and helping to reduce the bottleneck at lamination. Process improvements were continuously tested and verified for their impact to the quality of the product prior to implementation

In 1993, after approximately one year of production experience, the team of engineers met in Singapore to focus on specific areas for further process improvement and cost reduction. One such area included an operation which required an operator to cut and manually remove a section of rigid material from three sections of every board. A method was developed to replace the rigid material with sheeted copper would could be etched away during final etch to expose the flexible portions and remove the need for any hand cutting. This process improvement not only reduced the cost and increased throughput, but also increased yields by avoiding damage normally associated with the hand cutting operation.

A chronological account of the process improvements and cost reductions realized over the life of the disk drive product is presented in Table 3.

PROCESS	IMPROVEMENT	TIME	REMARKS
Covercoat lam w/ sheet conform matl	Laminate using rubber conformal	Q2 ‘92	↓ indirect material costs
Final laminate using TMR3 mat’l	Change to TGC	Q2 ‘92	↓ indirect material costs
Double treat RA Cu in Flex Core	Single treat RA Copper	Q3 ‘92	↓ direct material costs
Covercoat lam 4 High stack	Covercoat lam. 7 high stack	Q3 ‘92	↑ throughput; ↓ costs
Process panel size 12” X 18”, 3-up	Process panel size 16” X 21”, 6-up	Q1 ‘93	↑ throughput; ↓ costs
Final lamination 3 high stack	Final lamination 5 high stack	Q1 ‘93	↑ throughput; ↓ costs
Covercoat Lam 7 High Stack	Covercoat Lam. 10 High Stack	Q2 ‘93	↑ throughput ↓ cost
Drill1 High Stack	Drill2 High	Q2 ‘93	↑ throughput
Final Lamination 5 High Stack	Final Lamination 6 High Stack	Q2 ‘93	↑ throughput ↓ cost
Cap Method Lam With Slit/Scour	Foil Method minus Slitting/Scouring	Q3 ‘93	↓ cost ↑ yields
Flex Layer RA Cu	Approved to use Super HTE Cu	Q1 ‘94	↓ direct material costs
Drill 2 High Stack	Drilling 3 High	Q2 ‘95	↑ throughput
5 & 6-mil core layer	Standardize to all 6-mil cores	Q2 ‘95	↓ direct material costs

Table 3

Process Evolution For High Volume REGAL®Flex

Seagate has provided Teledyne with actual reliability data on the Printed Circuit Board Assembly (PCBA) used in the Barracuda™ product line of disk drives. The long term reliability goal at design was 250,000 hours MTBF. According to Seagate, the PCBA accounted for 15.9 percent of the early life failure returns. Of that percentage only two failures were traced to the printed circuit board. This translates to only 1.2 percent of the 15.9 percent or 1.5 Defects per Million (DPM) for the printed circuit board. System level testing by Seagate has yielded the following reliability data on the Barracuda product line:

PRODUCT	MTBF In Hours
Barracuda™ Disk Drive	800,000
Barracuda™ 2LP Disk Drive	800,000
Barracuda™ 4LP Disk Drive	1,000,000

Emerging Applications

The performance and cost improvements in the rigid-flex technology, as discussed in this paper, have led to more challenging applications in commercial product packaging such as medical implantable, optoelectronics and RF/microwave systems. Figure 6 shows a rigid-flex circuit for an implantable medical device currently under development. This circuit features double-sided SMT and serves as an integrated packaging platform for the control and power electronics. It is rigid-flex’s past performance in military applications which has given designers the confidence to utilize it in this product.

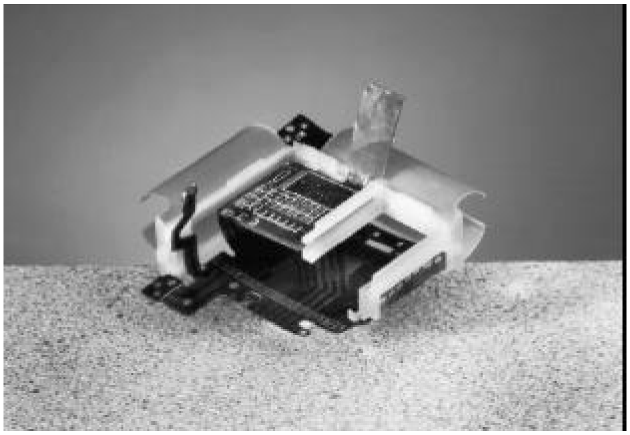

Figure 6. Implantable Medical Device Application

Similar circuits are being developed for telemetry devices in orthopedic transplant applications. In the area of optoelectronics, Teledyne is developing a rigid-flex MCM-L for a FOTR module. This product will be an example of rigid-flex’s role in converting a costly military communications module to an affordable commercial version. Finally, for potential RF and microwave applications which are cost sensitive, testing underway at Teledyne (up to 10 GHz) has demonstrated excellent impedance matching characteristics between the rigid and flex sections.

Materials Trends

The printed circuit industry is supported by a strong materials infrastructure, and there are a wide variety of materials choices just within the so-called traditional rigid and flex circuit domains. Flexible soldermask, unreinforced dielectrics, adhesiveless flex, and high ductility ED copper are just a few examples of materials innovations which beneficially impact the manufacture and use of rigid-flex circuits. Specifically, improvements in and availability of these materials will help to overcome what have been barriers to substantially decreasing the cost of rigid-flex circuitry. Newer materials systems like Teflon/ceramic composites and liquid crystal polymers promise improved electrical performance but, interestingly, could blur the classical definition of “rigid-flex”, since their mechanical properties lie somewhere between the standard epoxy-glass used in the rigid section and the polyimide film used in the flex section. Both of these materials systems are currently being evaluated in rigid-flex applications.

Summary

Over twenty-five years of military and high-reliability commercial applications of rigid-flex have resulted in a wealth of data illustrating the inherent and evolved reliability and performance attributes, many of which are also desired in higher volume commercial products. A strong printed circuit market and infrastructure has helped to drive the recent emergence of new materials technologies which will enable rigid-flex producers to address the concerns of cost and manufacturability. Together, these factors provide commercial electronics designers with a more integrated approach to packaging and interconnection in their products. Rigid-flex circuits can play a significant role not only in high-reliability performance-driven applications, but also in lower-cost, high volume commercial applications.

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