Application of Fracture Mechanics to Microscale Phenomena in Electronic Assemblies

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ABSTRACT

Avionics assemblies are complex hybrid structures formed out of many dissimilar materials which have been joined together to accomplish the desired electronic function. The structural integrity of these complex microscale structures is critical to the reliability of the electronic system. This paper discusses a research program to investigate the application of fracture mechanics techniques for life prediction to these small but highly loaded structures.

KEYWORDS

reliability; electronics; integrity.

INTRODUCTION

Avionics equipment has emerged as the most pervasive technology within a modern aircraft. The functions performed by modern avionics have grown from the radio in the 1940's to flight controls, weapons systems fire controls, electronic countermeasures, among others. Many of these functions are flight-critical and mission-critical. The failure of any one of these system could mean the loss of an aircraft or the inability to complete a mission. The emerging importance of avionics operational reliability has been recognized by the Air Force. The Air Force has formulated an initiative to address the avionics reliability issue - Avionics Integrity Program [AVIP] (Halpin, 1985).

The AVIP program is focused at impacting the reliability of an avionics systems early on in the acquisition process. A key component of this approach is to consider reliability as a failure free operating period (FFOP) rather than a mean time between failure (MTBF) (Burkhard, 1987). MTBF gives insight into logistics issues such as having sufficient spares to maintain the entire aircraft population as a group. The use of mean time between failure to express reliability is appropriate if equipment failures do not significantly impact safety of flight or the ability of an aircraft to accomplish its mission. This traditional approach to reliability prediction assumes that avionics failures occur randomly (Coppola, 1984) and can be represented by a constant failure rate model, while the FFOP approach assumes that failures are caused events and only appear to be random because of lack of detailed understanding of the failure processes.

The FFOP approach is concerned with each and every copy of the avionics equipment having sufficient life to not fail during its FFOP period. The length of the FFOP is dependent upon the stress history being experienced by the equipment. Therefore, FFOP values have to be expressed for a particular stress history, mission or mission mix (Burkhard, 1982). This approach is similar to that used in the Aircraft Structural Integrity program (Goranson, 1987). There is a defined period of time over which the structure will perform its function without failure. The FFOP approach to avionics reliability is consistent with the commonly used definitions for avionics reliability: "The probability that the required system will perform its intended functions for prescribed mission(s) and time period(s) in the specified operating environment" (Soistman et al., 1985). Therefore the attribute called avionics reliability is similar to what the discipline of structural analysis calls durability.

Avionics Assemblies are Complex Hybrid Structures

Electronic assemblies and components consist of many dissimilar materials, which have been bonded or joined together to obtain the desired electronic functions (Howard, 1982). Therefore an avionics assembly is a complex hybrid structure which is required to perform an electronic function. These assemblies are highly loaded structures - loaded thermally, mechanically and electrically. An electronic assembly experiences high mechanical loading from both thermally induced stresses resulting from the differences among the various material thermal coefficient of expansions and mechanical vibrations. Components of an avionics assembly are often more highly loaded from the vibration and/or thermal-mechanical loading than the main load bearing structure of many aircraft wings (Soovere et al., 1987).

Interconnections among the various electrical components that make up an electronic assembly must function in a dual role that is, as both the electrical signal path and the structural load path. In general the requirements for each function compete - from electrical considerations the interconnections need to be as short and contain as little material as possible to reduce signal delay times, while from a mechanical perspective the interconnections need to be as long and large as possible to reduce stress levels and provide compliance.

Each interface of an avionics assembly is a potential site for a latent defect to exist (Kallis et al., 1986). In addition to interfaces the bulk materials which make up an electronic assembly can contain latent defects. These defects are exacerbated by environmental stress until a failure is manifested. This is the basis for the emerging use of environmental stress screening (ESS) to weed out and thereby reduce the latent defect population of deployed avionics equipment (Anon, 1981).

Analysis of operationally failed avionic assemblies indicated that the loss of electronic function was caused by a physical change or failure in the avionics assembly which can be often related to the presence of latent defects in the assembly (Green, 1988). Therefore, An operational avionics failure is fundamentally not an electronic failure; rather it is a physical failure or change which resulted in the loss of the desired electronic function. This evidence suggests that the issues of operational reliability of avionics are materials/structural issues. Approaching avionics reliability from this perspective means that many of the powerful tools used to address durability in structural engineering could be used on avionics reliability.

Approaching Electronics Reliability From a Fracture Mechanics Perspective

Fracture mechanics has been used to estimate the fatigue life available in a structural system with very good success (Goranson, 1987). This approach is based upon the fact that every physical item contains latent defects which can propagate under stress fields until a failure is manifested. Extensive work has been done to understand and then model the behavior of different defect characteristic of structural systems. It was found that the failure free life could be estimated knowing the initial defect state, the environmental stress state, and how the defect grows and responds to the experienced environmental stress state.

A literature search has shown that application of fracture mechanics to avionics assemblies has been tried with some success by several investigators (Cozzolino et al., 1980; Yamada, 1987; Abdel-latif et al., 1981). Cozzolino and Ewell applied this approach to ceramic capacitors and found that the mechanical reliability (life) of these components can be estimated for different applications and that realistic limits can be determined for the allowable sizes and types of initial defects. Yamada studied the cracking of solder joints where the crack is contained in or adjacent to a thin brittle intermetallic layer with the solder containing massive yielding near to the crack tip. A J - integral approach was used and provided reasonable agreement with finite element analysis. Abdel-latif used J - integral approach to estimate the time for a crack to grow to a critical length that results in electrical shorting or arcing to occur in the high voltage section of a traveling wave tube assembly.

To further investigate and develop the application of fracture mechanics to electronics assemblies, a program entitled "Electronics Reliability - Fracture Mechanics" was initiated by the US Air Force with Hughes Aircraft Company. This effort is about one year into a five year effort. The rest of this paper will discuss this program and the technical approach being taken.

ELECTRONICS RELIABILITY FRACTURE MECHANICS PROGRAM

The objective of the Electronics Reliability Fracture Mechanics (ERFM) program is to develop and demonstrate a life prediction technique for electronic assemblies that are subjected to environmental stresses of vibration and thermal cycling. The prediction will be based upon the mechanical properties of the materials and packaging configurations which make up an electronic system.

For this program two shop replaceable units (SRUs) from the APG-63 radar used in the F-15 aircraft were selected. The front sides of the selected

SRUs are shown in Fig. 1 and 2. The module shown in Fig. 1 is a digital module consisting of two printed wiring boards (PWBs) bonded to a heat exchanger, through which coolant air flows. The dominant part type is an integrated circuit flatpack. The leads are formed in a "gull wing" shape and soldered to the surface of the PWB. A flow-under thermal transfer adhesive is applied under the parts. The module shown in Fig. 2 is an analog module consisting of a PWB bonded to a heat exchanger through which coolant air flows. The SRUs selected are still in production and contain several different types of electronic component technology.

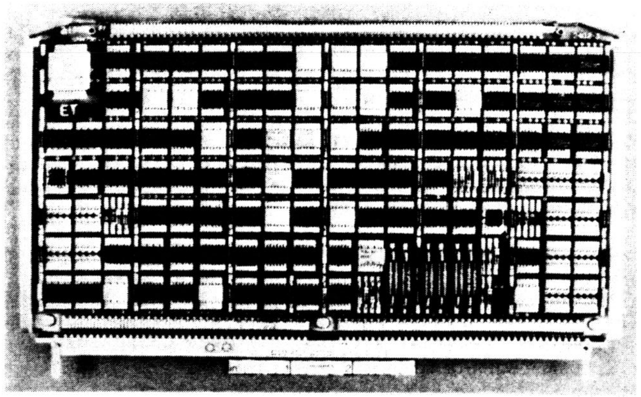

Fig. 1. Digital Module

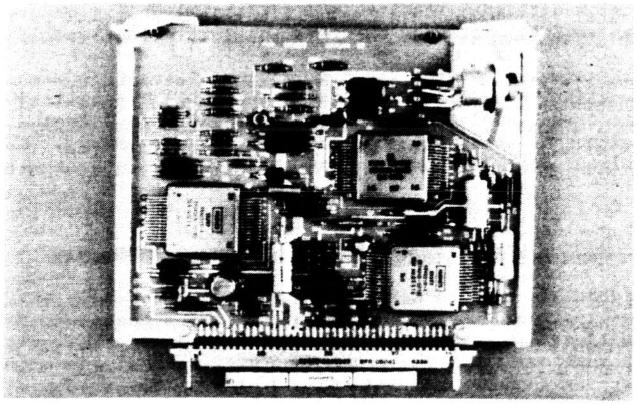

Fig. 2. Analog Module

To develop insight and a limited data base on which defect types are the most prone to manifest failures in these SRUs, failed (but not repaired) copies of these units are being obtained from the Air Force. These SRUs undergo the normal electronic checkout to confirm the electronic failure. After this is accomplished the units are inspected using nondestructive inspection techniques such as X-rays and infrared to determine the defect contribution to the failure which manifested. Destructive failure analysis is then accomplished to confirm or determine the defect contribution. The data from this analysis will not be conclusive since the initial latent defect population of these SRUs, the repair history and the environmental stresses experienced since fabrication will not be known. Even with these limitations this data will be used to help determine which defect types need to be modeled and important features which must be included in these models.

Fracture mechanics models of the defect types selected will be formulated. To demonstrate the applicability of these models, duplicate copies of the SRUs which underwent extensive failure analysis will be fabricated. These will be specially inspected during the fabrication process using nondestructive inspection techniques to characterize the initial defect population. The specially inspected SRUs will undergo Combined Environments Reliability Testing (CERT) using the F-15 mission profiles (Burkhard, et al., 1982). The failure free operating period (FFOP) of these SRUs predicted by the fracture mechanics models will be compared to these test results.

Selected Failure Locations to be Modeled

Based upon previous studies, it is anticipated that the detailed failure analysis of the selected SRU's will identify one or all of the following four general failure locations for modeling. These four are common to most avionics assemblies regardless of the electronic component technology making up the assembly. These four are: wire bonds, plated-through-holes in printed wiring boards (PWBs), glass seals and solder joints. In the next few sections a short description of each one is given along with a discussion of the technical challenges associated with each from a fracture mechanics perspective.

Wire Bonds, Wire bonds, as shown in Fig. 3, are small diameter (0.001 in. to 0.010 in. dia.) wires that are used as interconnections within semiconductor devices. Failure can occur in the wire itself or in the bond between the wire and its mounting surface. Wire bond failures can be caused by high-cycle vibration or low-cycle fatigue thermal cycling. Thermal cycling failure is caused by mismatch of coefficients of thermal expansion of the wires and the materials to which they are bonded. Maximum flexure loading generally occurs at the heels of the bonds.

Plated-Through-Holes. The copper barrel, surface lands, and inner conductors of plated-through-holes (PTHs) are subject to low-cycle fatigue cracking due to thermal cycling as shown in Fig. 4. The cracking is due to the mismatch of coefficients of thermal expansion (CTEs) of the copper and the PWB materials, copper generally having a much smaller CTE than the PWB in the through-thickness direction.

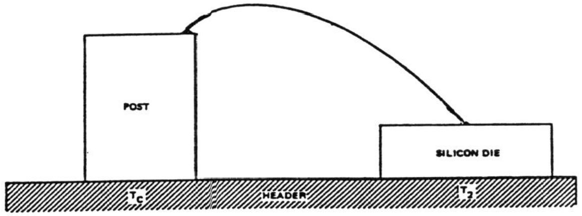

Fig. 3. Wire Bond Loop

When the temperature increases, the PWB forces the copper barrel to elongate beyond the point of its otherwise free thermal growth. This tensile-like pulling of the barrel gives rise to multi-axial states of stress and strain within the PTH. The copper is often strained beyond the elastic limit, especially when the CTE of the PWB matrix material increases at temperatures beyond the glass transition temperature. The PTH can be plastically strained during negative temperature excursions as well. The cyclic straining beyond the elastic limit can lead to cracking of the copper in a few thousand temperature cycles. This is considered to be low-cycle fatigue.

Solder Joints. A solder joint for a gull-wing leaded surface-mounted device of the type used in APG-63 is depicted in Fig. 5. It is well known that solder is subject to both low-cycle fatigue and creep. Life prediction methods must account for plasticity in addition to creep. These methods must also account for damage accumulation due to combined thermal and vibration environments.

Glass Seals. An annular glass-to-metal seal in a microelectronic device is depicted in Fig. 6. The glass provides a hermetic seal between the lead wire and the case. Loss of the hermetic seal causes failure of the internal components. A glass seal can be stressed due to the differences in coefficients of thermal expansion of the lead, the glass, and the device case. Vibration of the printed-wiring-board can also stress the glass seals since the lead wires deform to adjust to the displacements of the vibrating board.

A glass seal can have defects such as internal discontinuities, voids, or surface nicks and scratches. If the stress at a defect is high, rapid fracture can occur which destroys the seal. Under some conditions, a defect can grow to a sufficient size to cause leaks which exceed acceptable limits. In either case, the device has failed.

It is generally understood that glass is not susceptible to subcritical crack growth due to cyclical fatigue except at stress intensity levels very close to the (critical) fracture toughness. In contrast to the behavior of glass to cyclical fatigue, glass is subject to subcritical crack growth at relatively low stress levels when loaded in "static fatigue". Static fatigue (more properly known as environmentally-assisted crack growth) is failure due to a sustained load like that as experienced by pressure vessels or load-bearing structures. Long duration exposure to high or low temperatures may also lead to static fatigue of glass seals.

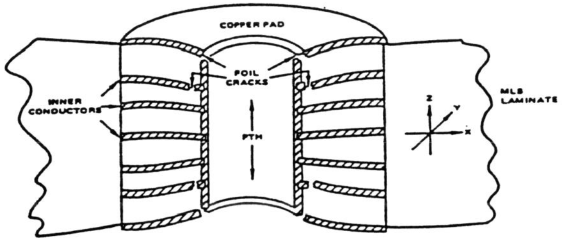

Fig. 4. Plated Through Hole

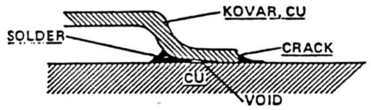

Fig. 5. Solder Joint

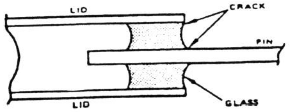

Fig. 6. Glass Seal

Test and Analysis Approach

The life modeling approach will be fracture mechanics based. However, because of the small size of electronic components, it must first be determined that such an approach is appropriate. A number of issues must be resolved before it is determined whether existing fracture mechanics modeling approaches are appropriate for the selected failures. Specifically, the following two issues must be resolved:

1. The fraction of the lifetime that is spent in crack initiation must be determined. If the fraction is small then fracture mechanics is applicable. If the fraction is large, then fracture mechanics will not be very useful. Instead a conventional fatigue analysis is applicable.

2. The second issue is whether macro fracture mechanics techniques, used in large structures such as bridges, are applicable to the tiny structures in electronic equipment.

Data have been generated on solder joints which suggest that the fatigue life of the components is crack growth dominated (Kallis et al., 1986). Insufficient data exist to determine the generality of this conclusion for wires, copper plated holes, and other element types of interest. Studies of the propagation of short cracks in materials suggest that the bulk material properties are different than the material properties of tiny wires and plated through holes. (Suresh et al., 1984).

There appear to be two general classes of problems for the application of fracture mechanics to electronic components. The first, typified by soldered wires, involves high frequency vibrations that could produce high cycle fatigue failures, In this case it is likely that the deformations are essentially in the linear elastic range. In the second class of applications, typified by copper plated holes, components are exposed to thermal cycling that, combined with large thermal expansion coefficient mismatches, produces deformation well into the plastic range. Such components can fail by a combination of creep and low cycle fatigue.

Summary of Planned Tests and Analyses

The analyses that will be performed to develop and verify the life models will begin with linear elastic fracture mechanics. Comparison of results and predictions to the test data will establish whether there is a need to move into the more complex inelastic formulations. In either case, existing handbook solutions for the appropriate fracture mechanics parameters will be used as a starting point. If these methods are shown to be inadequate due to differences in loading and/or geometry, refined solutions will be obtained by means of finite element analyses.

Aluminum Wire Bonds. In-situ Scanning Electron Microscope (SEM) tensile cycling tests of aluminum wires will be performed. Both notched and unnotched wires of several diameters ranging from 1 to 10 mils will be tested unless analysis of the early data indicates that an alternative approach should be adopted. Testing of the unnotched wires will establish whether crack initiation or crack propagation dominates the fatigue lifetime. The notched wire tests will facilitate the experiments by providing known crack locations. The material and wire diameters will be representative of wires used in the APG-63 modules.

Vibration tests of aluminum wires will also be performed. These tests will simulate the vibration environment that a wire experiences in an electronic assembly. However, it will not be practical to view an open crack in this case, since the crack cannot be inspected while a wire vibrates and the crack will close when the vibration is stopped. Instead, the wires will be inspected optically before being tested, and periodically thereafter. The surface evidence of a crack will be measured so that crack growth information can be inferred for future analysis. Similar numbers of specimens and wire diameters will be used in both the tensile and vibration tests. Both notched and unnotched wires will be included.

Thermal cycling tests of empty (i.e., without devices) hybrid packages will be performed. These thermal cycling tests will be designed to simulate the physical conditions that wire bonds experience in functioning packages. The wires are bonded to the leadframe at one end and the package substrate at the other. The wires will be inspected in a SEM before testing, and periodically during the test program, in order to monitor and track crack presence and growth.

It is expected that the wires will exhibit creep and that the wire strains will be in the inelastic range. Accordingly, the subsequent life model development will probably be more complex than can be accounted for accurately by linear elastic fracture mechanics (LEFM). However, as noted above, an LEFM analysis will nonetheless be useful for scoping the problem.

Plated-Through Holes. Tensile cycling of copper foil specimens will be performed in a SEM with lodaing high enough to stress the test articles into the inelastic range. This will simulate conditions experienced by copper barrels in printed-wire-boards (PWBs) that undergo thermal cycling. Both notched and unnotched samples will be tested. Cracks in the test specimen will be monitored to obtain crack growth data in the plastic range.

The foil samples will be fabricated so that they are metallurgically similar to real barrels. An important feature to include is the electrolytic copper layer which is deposited on the surface of the hole in the board prior to the electrodeposited barrel. The electrolytic layer is less ductile than the electrodeposited layer and, as such, may serve as a crack initiation site.

Thermal cycling tests of flat copper foil/PWB laminates will also be performed. The test specimens will be fabricated to match the difference between the coefficients of thermal expansion (CTE) in the copper and the PWB in the thickness direction. This test is useful because it captures the interaction of the copper and the PWB laminate (to a degree) which may be important relative to crack initiation and propagation. The flat specimen will not simulate the biaxial stress condition that a barrel in a board would experience. However, it may be possible to capture this effort if the specimens are wide enough and center cracks can be tested.

Thermal cycling tests of PWBs of the types used in the selected APG-63 modules will be performed. The test specimens will consist of F-15 type PWBs with a large number of plated-through-holes. Strings of holes will be electrically wired together in order to enable monitoring a large sample of holes with a reasonably sized data acquisition setup.

These tests will be important because they are a direct simulation of the conditions that the barrels will experience. Due to the small barrel diameters, it will not be practical to attempt to see into the barrels to monitor cracks. Instead, electrical continuity of holes in series will be monitored during the thermal cycling tests. When continuity is lost in a string of barrels, each hole will be probed to find the failure. Since a circumferential barrel crack would close at ambient temperature, the holes will be heated locally, while they are probed for continuity. Failed barrels, and barrels in various stages of thermal fatigue, will be microsectioned so that visible evidence of cracks in various stages of development are obtained.

Solder Joints. There has been a large amount of effort invested in solder joint testing throughout the industry. Much of this data has been published and is available from numerous sources (Lau et al., 1985). Although these data are valuable, they may not be adequate for the development of fracture mechanics models. Therefore, it is anticipated that additional fracture mechanics oriented testing must be performed to fill in the inevitable data gaps. The planned test is described below.

Failure of a solder joint occurs by failure of the solder bond between the soldered parts that are not subject to creep as is the solder itself. Accordingly, failure of the soldered joint might be amenable to analysis by consideration of the strain energy release rate that occurs during crack propagation (Yamada, 1987). Analysis of the energy release rate considers the material on each side of the solder joint. Since these materials don't creep, creep considerations do not enter directly into the analysis.

A double-cantilever beam/crack propagation test is proposed to investigate this idea. The solder joint fatigue crack propagation specimens will consist of machined copper "adherents" soldered together at the interface. The solder joint thickness will be consistent with typical electronic hardware.

Glass Seal Tests. Glass seals in microelectronic packages are stressed when the package leads are loaded due to vibration or thermal cycling. The movement of the microelectronic package relative to the PWB must be accommodated by distortion of the package leads. The distortion and loading of the leads is reacted through the glass seals resulting in stress and possible cracking in the seals.

For the purposes of life model development, the approach for simulating the above glass seal loading will be to apply loads and/or displacements directly to the leads of empty F-15 hybrid packages. Since the test specimens will not be attached to, for instance, a PWB, inspection of the seals will be greatly facilitated. Furthermore, by applying known loads or displacements directly to the leads, prediction of the resultant glass seal stresses will be much easier. This approach eliminates the uncertainties regarding interaction with a PWB and the analytical model for determining glass seal stress can be more detailed in the important region of the glass seal. The glass seals will be inspected optically and also by means of fluorescent penetrant inspection.

SUMMARY

This development and demonstration program will show the productivity and usefulness of approaching avionics reliability from a fracture mechanics perspective. This approach to avionics reliability provides linkage among the design, assessment and manufacturing. The fracture mechanics approach to avionics reliability translates reliability requirements into material, design and defect population parameters in a trackable manner. Significant technical challenges exist to fully implement such an approach, but this effort will be a major first step.

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