Reliability Issues Related to the Fatigue Strength of

Gold Wire Used in Electronic Assemblies

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Introduction:

Electronic designers have been moving towards higher part density in multi-chip modules (MCMs) for aerospace applications. This density can be achieved by combining multiple functions on a single die, including more dice in one package (single substrate) and by extending the substrate (die-to-die interconnect) into the z-direction. As density increases, the number of inputs and outputs increases, creating a wire bond configuration that is driven by minimum distances between the bond pads on the die and those on the package. This creates long wire bonds in the x-y plane. Stacked dice will have long bond wires in the z-direction.

The fracture strength of aluminum wire is well understood because the material is a standard construction material throughout the industry. Gold alloy wire is manufacturer unique, and the exact composition and quantity of the additives is considered proprietary by most (if not all) of the manufacturers. These additives are in the 10 ppm range and are used to enhance elongation, heat affected zone (HAZ) characteristics, and tensile, fatigue and fracture strength. The presence of the additives makes it very difficult to predict the fatigue strength of the gold wire used to make long bond wires, and this limits one's ability to predict the electronic part's reliability. Knowing the susceptibility of long bond wires to fatigue fracture and their resonant frequency will enable reliability predictions of electronic system that may be exposed to shock and vibrations.

Background

Component failure rate apportionment studies show that wire bond failure rates have been the cause of up to 30% of electronic packaging failures [3]. A significant amount of research has been done on wire bond processes and reliability. Absent from this research has been a thorough investigation of the strength not of the bond, but of the wire itself. This was identified during the resolution of a failure of NASA hardware that was detected during vibration testing.

Recent failures of wire bonds in NASA solid state recorders (SSR) highlighted the fact that bond wires can experience bending stress induced by self-resonance if the wires are long enough and the vibration frequency spectrum includes corresponding frequencies [4,6]. The bond wires used in the failed memory modules (which used stacks of memory dice) were between approximately 161 mils and 240 mils. Bond wires applied in packages with a single die are generally around 40 to 60 mils long. During final box-level random vibration testing with frequencies up to 850Hz and total spectral power of 6 Grms, four of the memory modules used in the SSR failed due to failed wires and bonds.

The memory used for the SSR is an array of 72 memory modules. Each memory module consists of two stacks of DRAM dice stacked 12 high. This yields 384 Mbits of memory per module. Due to the height of the die stack and placement of the bond pads on the die, this application requires unusually long bond wires, 161 to 240 mils in length (Figure 1, 2). The usual rule for bond wire length states that the ratio of length to diameter of the wire should not exceed 100[6]. In this application, the ratio is approximately 200.

During the failure investigation the wire bonds were inspected. Seven of the 100 wire bonds inspected were torn, lifted from the bond pad, or both for up to 33% of the width of the bond. As a result of the bond damage and long bond wire, the resonant frequency of the wire was dropped into the bandwidth of the box-level random vibration testing. During testing the wire was excited into resonance and the resulting stresses seen at the bond were sufficient to rupture the bond.

The cracks in the wire bond were found to be a result of a number of conditions including alignment of the bond, wire loop radius, wire length and the bond pad surface condition. Due to the number of variables contributing to this defect and the difficulty associated with analyzing them, Finite Element Analysis (FEA) was used to predict the resonant frequencies of the wires.

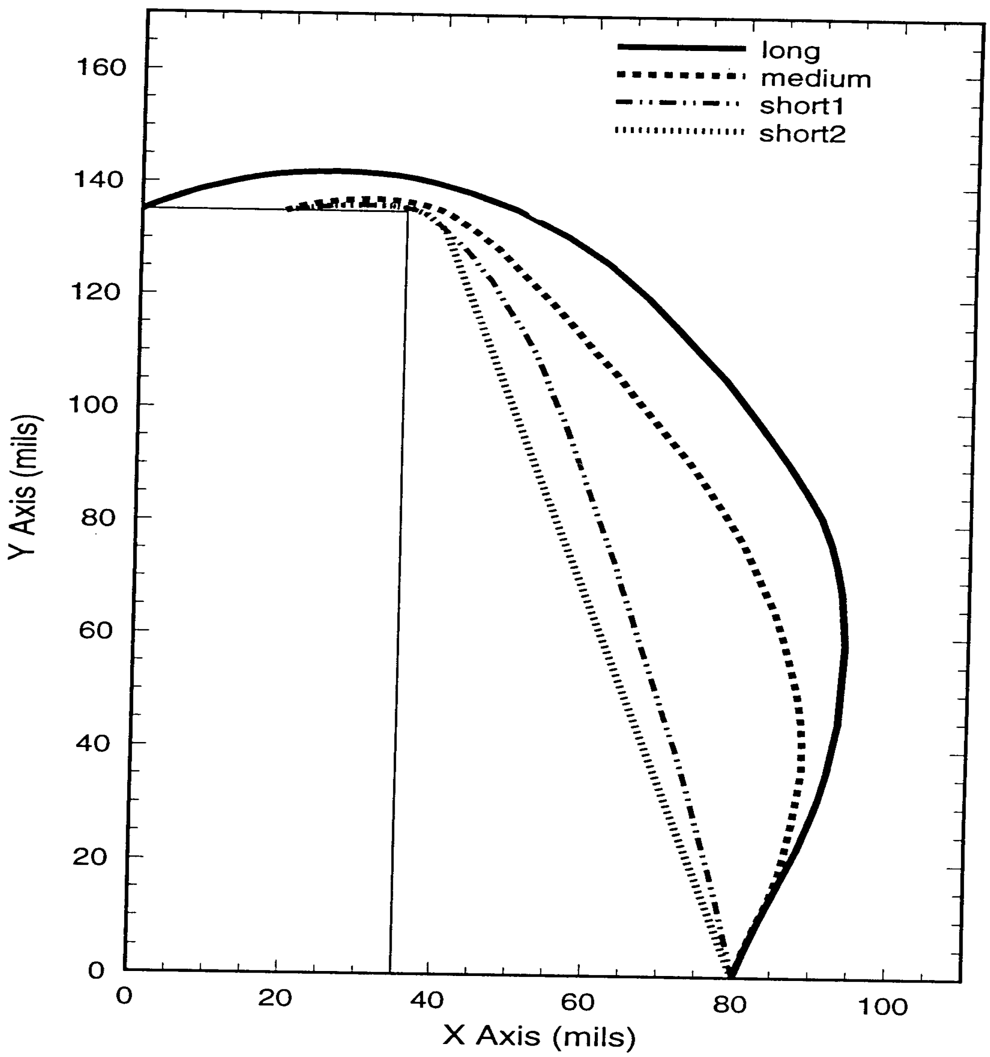

Figure 1. Variation in the shape of bond wires observed in stacked memory modules.

Using the predicted values as a starting point, testing was performed which showed that the measured resonant frequency values were within 15% of those calculated using FEA. Thus it was verified that FEA could play a significant role in bond wire failure/reliability predictions. With known fatigue and fracture strength data for a given wire, FEA can be used to identify the resonant frequency for a given wire length and shape allowing users to design for reliability and avoid overstressing the wires during acceptance testing.

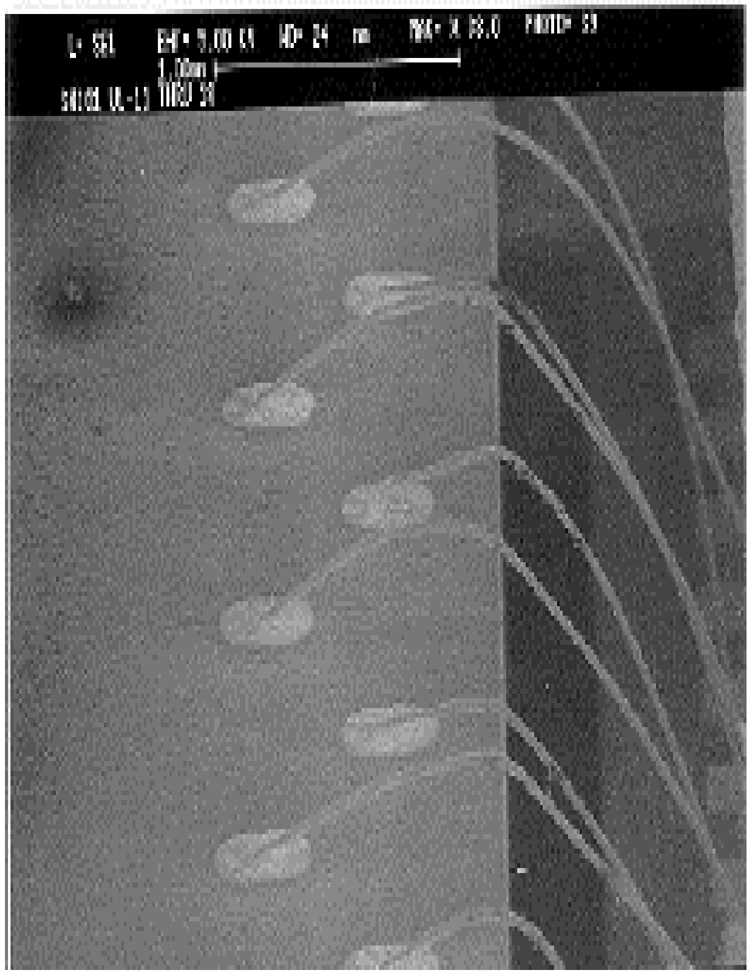

Figure 2. SEM photo of long bond wires in the stacked memory module

Test methods used to evaluate bond quality include destructive and non-destructive testing. The tests used by the military to qualify high reliability hardware are destructive and non-destructive bond pull and are documented in MIL-STD-883, Method 2011.7, and 2023 respectively. These methods have been adopted by industry as repeatable and reliable methods for evaluating bond quality. Destructive bond pull drives the cost of using the part through the destruction of samples and the cost of the labor involved. Non-destructive bond pull has been used to avoid wasting good parts but it is also labor intensive.

Research was performed to find other non-destructive methods for evaluating bond strength. Unisys has developed a test fixture for non-destructively evaluating the quality of bond wires based on excitation of the bond wire in a varying electromagnetic field (Figure 3). The sample is placed in the field of a permanent magnet which has a recessed area machined into it. The bond wires on the sample are perpendicular to the magnetic (B) field while in the fixture. A electrical alternating current is passed through the wires of interest which causes a motional displacement of the wire due to the interaction between the permanent and induced B fields. The advantage of this system is that the displacement can be varied by varying the current. In addition, this fixture has the ability to record the displacement (this value is calculated) by measuring the voltage drop on the wire caused by cutting the flux lines of the permanent magnet.

This test fixture is intended to be a non-destructive, "in-line", production level test to evaluate bond quality. It has potential for use as a fatigue strength tester since it uses self -resonance to exercise the wires. The draw back of this fixture is the cost and complexity if used for evaluation purposes only. The Unisys design would be more suited for a manufacturing environment where the cost could be justified by production volume.

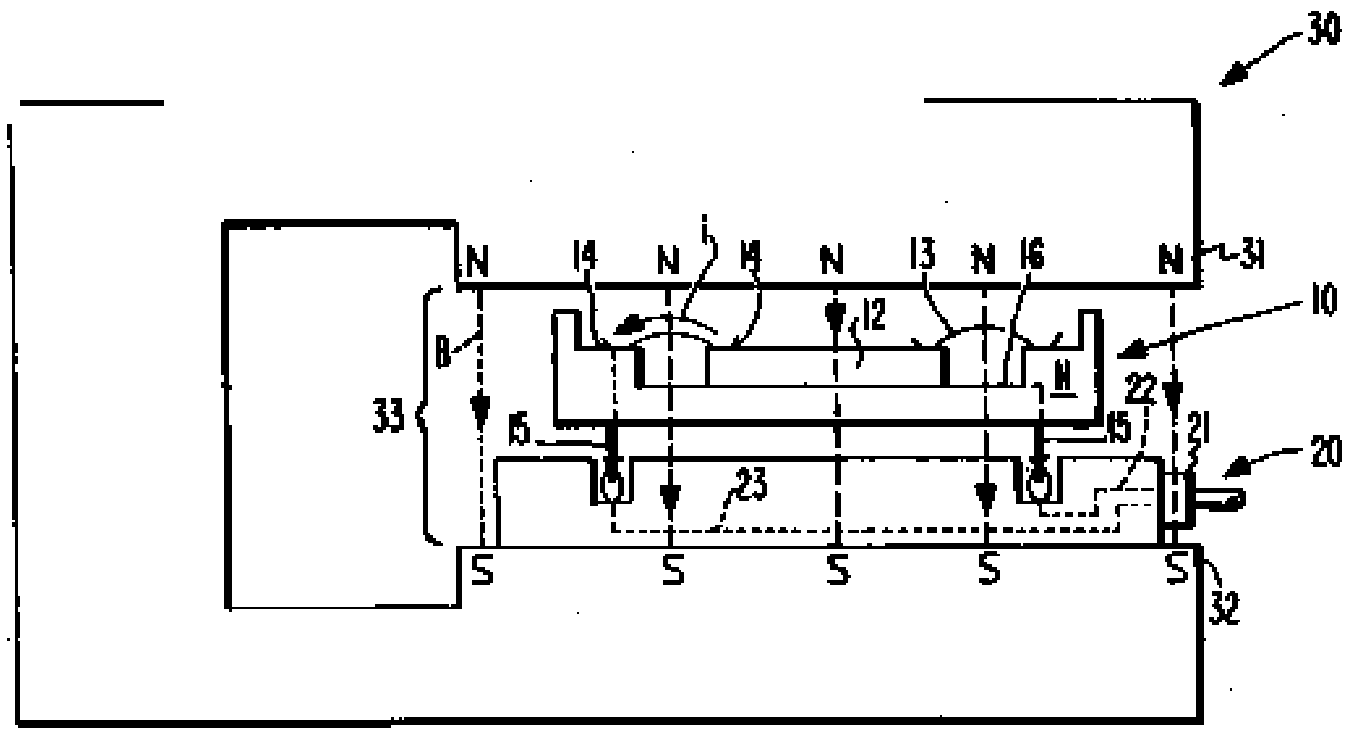

Figure 3. Non-Destructive Bond Wire Tester Based on wire excitation

The critical region determining the mechanical reliability of a wedge bond is the heel joint. This critical region is about 25 microns in length and is therefore very difficult and impractical to exercise [3]. Researchers at Cornell University designed a fixture to test wire fatigue strength in long sections of wire by inducing a tension/compression cycle [1]. This was achieved by passing a section of wire through a pair of mandrels from one pick-up reel to another (Figure 4, 5). The fixture was capable of sensing the take-up reel position so that after the length of wire had passed completely through the mandrel assembly in one direction the DC motor was switched to rotate in the opposite direction. Two gold and one aluminum wire samples were used. Three different strain amplitudes were applied; 0.7%, 5%, and 10%.

The strain on the wire was varied by varying the gear reducer and mandrel diameter.

The strain on the wire is given by:

$$\tilde{A} = E * r / R$$

Where: $\tilde{A}$ = Strain

E = Young's Modulus

r = Wire Diameter

R= Mandrel Diameter

In addition to varying the strain on the wire, testing was performed over temperature. Testing was done at 20°C, 75°C, and 125°C. Results of the testing showed that cycle-to-failure time increased with decreasing strain, and decreased with increasing temperature.

This approach to the analysis of wire fatigue failure is good but in itself is not enough. The disadvantage of this technique is that the central area of the wire is neutral. Examining the equation given for strain indicates that the strain decreases with decreasing wire diameter, that is, as the center of the wire is approached, the strain approaches zero. This testing needs to be complemented with one that exerts force over the entire cross-section. The results of this analysis are useful to our evaluation as a starting point, but should be expanded to include cold temperature (-55°C to 25°C), and samples from numerous vendors. This would make the data more useful to aerospace and high reliability users.

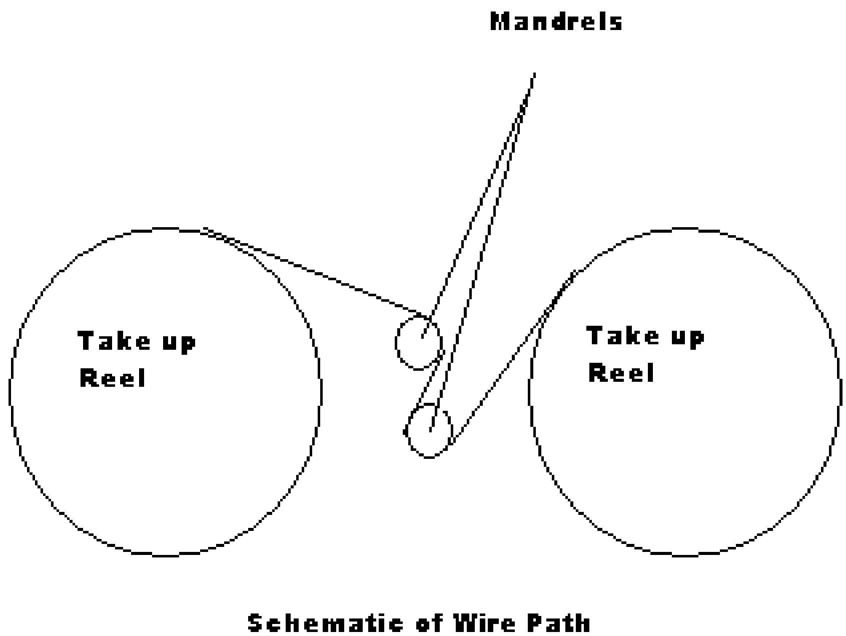

Figure 4. Wire path Schematic

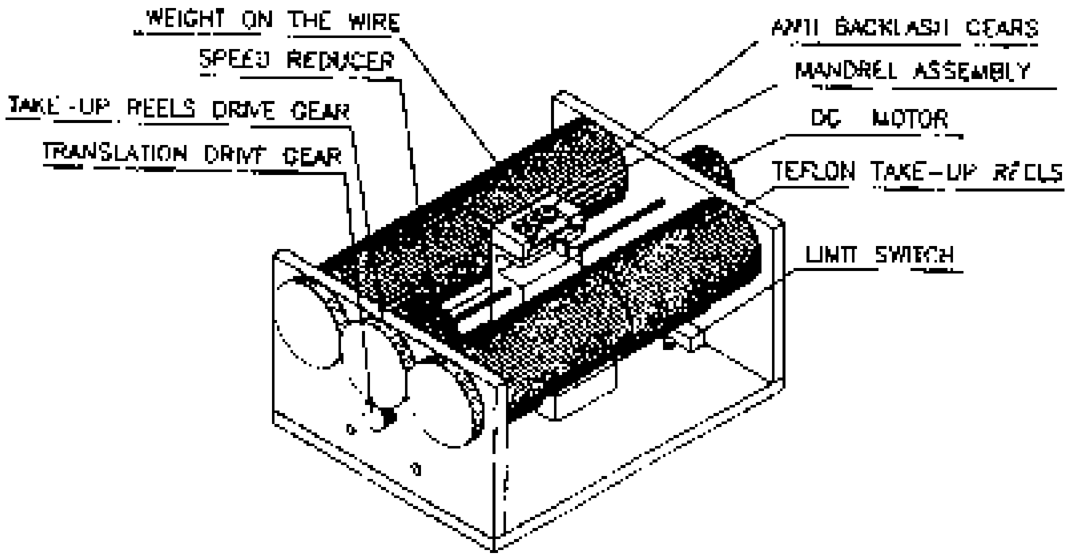

Fig. 2 Fatigue machine

Figure 5. Fatigue Machine

Project Objectives

Our evaluation will use a simplified version of test fixture as in Figure 6 and a second fixture that exerts force across the cross-section of the wire (figure 7).

To address the need for information about the strength of gold wires being used in electronic devices the following are the objectives of research that has been started through NASA's Advanced Interconnect Program.

- Build test fixtures and develop test procedures for producing data on the number of bending and tensile stress cycles required to produce fatigue-fracture in gold alloy wire and providing repeatable results. The test procedure should be designed such that it can be performed by individuals with varying technical abilities with a minimum of special training. The test procedure should reference ASTM or other industry recognized standards for identifying the compositions and dimensions of the samples tested. Wherever possible, other test parameters, such as mandrel diameters, should be identified by reference to industry standard definitions and terms. Electrical and mechanical conditions, such as mechanical pre-loads must be calibrated.
- Determine the first order statistics (average, mean, median) for the number of bending and tensile stress cycles required to produce fatigue-fracture in gold alloy wire. Determine the second order statistics for this value (number of cycles to fatigue-fracture) where meaningful. Determine the difference in the cycles to fatigue-fracture statistics for samples with different heat treatments and cold working processes. Determine the cycles to fatigue-fracture for samples with different alloy compositions and diameters.

FY98 Accomplishments

Research has been done regarding the best strategy for accomplishing the objectives and the best test fixture that can be implemented reasonably in terms of cost and schedule. Two fixtures were designed and are in the process of construction (Figures 6,7). Both of these fixtures are based on the test apparatus used by Deyhim, Yost, Lii and Li. These fixtures were developed to facilitate the cycles to fatigue fracture analysis in ambient conditions and over temperature.

The two fixtures designed share the same base and equipment. Figure 6 consists of a DC vibrator motor, strain gauge (in the gram range), and adjustable plate for setting the pre-load. The wire is epoxied to a flange mounted in the chuck of the motor and threaded through the mandrels. The free end of the wire is then epoxied to a piece of RTV. The RTV will allow the wire to follow the motion of the vibrator motor without allowing slack that will result in backlash. The wire will be preloaded with approximately 1 gram for testing. The pre-load will be measured with the strain gauge. The pre-load measurement will be accomplished by tacking the wire to the strain gauge with epoxy.

Figure 7 is essentially the same as 6 except that the wire is not passed through a pair of mandrels. This will allow the strain or force exerted by the motor to be exerted across the entire cross-sectional area of the wire.

Both of these fixtures will be modified to allow automated cycle count and wire failure monitoring.

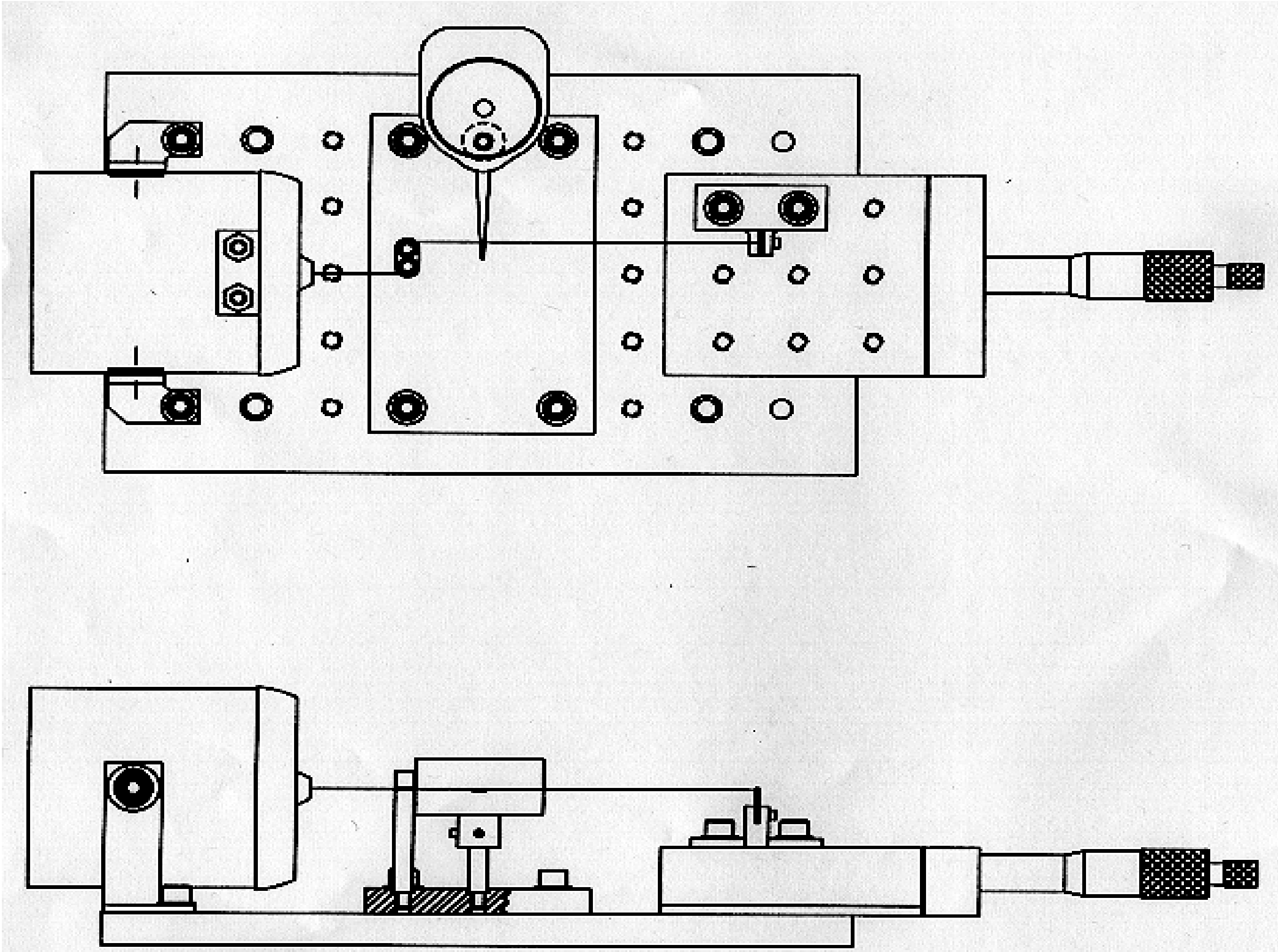

Figure 6. Fatigue Fixture Incorporating the use of Mandrels.

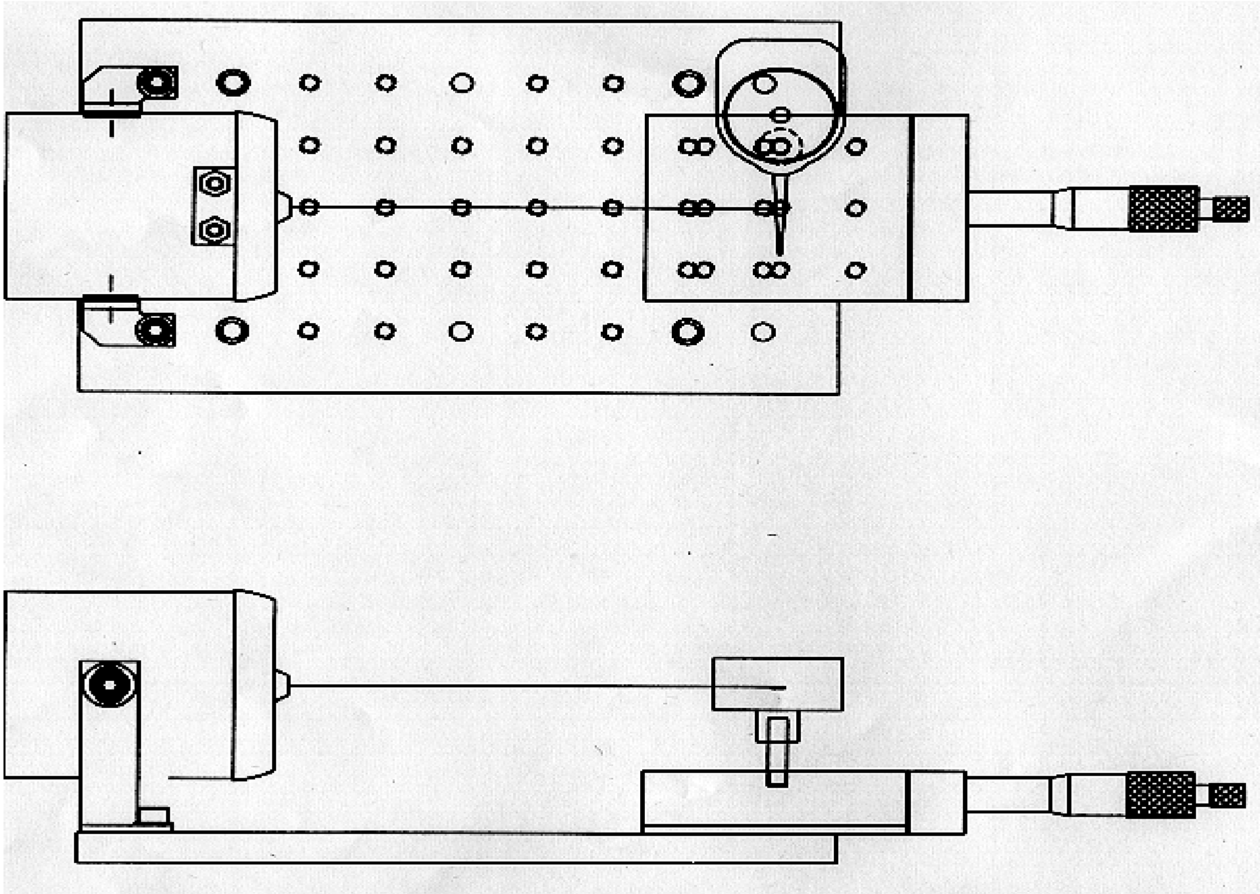

Figure 7. Fatigue Fixture, applying force across the cross section of the wire.

FY99 Objectives

The following are the tasks planned for FY99:

- Obtain the gold wire samples. To reduce cost, gold wire already on hand will be used. It is 1 mil and 2 mil in diameter and 99.99% pure gold. A material analysis will be done to try to identify the trace materials.
- Build the test fixtures.
- Produce a test plan and procedures.
- Baseline the repeatability of the procedure and test fixtures using 0.001"gold alloy (99.99% pure) wire.
- Complete the testing and publish the results.

FY00 Plans

The following are the tasks being proposed for FY00:

- Adapt the fixture designs to operate in simulated space environments (i.e. thermal vacuum and thermal cycling chamber with mechanical excitation applied).
- Obtain additional wire samples from a variety of manufacturers and repeat testing and reporting.
- Duplicate experiments documented in the scientific literature to validate existing conclusions.
- Complete testing and publish the results

References

[1] A. Deyhim, B. Yost, Mirng-Ji Lii, and Chc-Yu Li "Characterization of the Fatigue Properties of Bonding Wires" 1996 IEEE Electronic Components and Technology Conference.

[2] J.I. Tustaniwskyj, R.J. Usell, Jr., and S. A. Smiley of Unisys Corporation. " Progress Towards a Cost- Effective 100% Wire Bond Quality Screen", IEEE

[3] Jun Ming Hu, M. Pecht, A. Dasguta. " A Probabilistic Approach for Predicting Thermal Fatigue Life of Wire Bonding in Microelectronics'. J. Electronic Packaging v. 113 (September 1991) p. 275.

[4] H. Leidecker, S. Hull, J. Plante, "Analysis of Wire Bond Failure in Stacked Memory Modules"

[5] Tustaniwskyj et al., U.S. Patent number 4,667,370, Method of testing wire bonds for defects using a magnetic field.

[6] H. Leidecker, S. Hull, Vibration Induced Fatigue Failure in Bonding Wires Used in Stacked Chip Modules, 1998.

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