New Developments in Testing for Microelectronics

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Abstract

This white paper summarizes topics discussed during a three day conference, held at Instron® in November 2003 between software developers and a consultant expert, on the physics of metals testing and recent improvements to the calculation algorithms used in Instron Merlin™ software. Items of interest include test control, changeover criteria, determination of the end of the discontinuous yielding region, and the effect of speed changes on both data and calculations.

Introduction

Mechanical evaluation in the microelectronics industry has seen a major revolution. Historically, much of mechanical evaluation done has focussed on simple techniques in testing with simple pass/ fail criteria. Designers of microelectronics has had little need to concern themselves with structural failures and the need for mechanical evaluation has been driven by manufacturing quality control requirements. For example, in the past, the chief concern during die attach was to ensure no voids were created during the process. The driving force of die shear or tensile bond testing therefore was to ensure bond strengths reached a minimum level to indicate that a 'good' bond was obtained. The interest was therefore less structural and more functional. Thermal cycling called burn-in test were the more important tests as it established the overall integrity of the package. As recently as 1995, the strategy of BGA package development was described as 'burn-in will be used to quantify the improvement and provide feedback to the package designer, as material and design changes reimplemented'. Mechanical testing was hardly referred to in the entire text. While the need for iterative design is fundamental, the simplistic view of using burn-in as the basis for technology development is no longer acceptable and this has become true for a number of important reasons.

The first is that the analytical tools developed for package design are now able to predict required material properties. These are highly specific in nature since stress levels can now be determined under different conditions. If material properties are specifically known, it is relatively, an easier task to explore alternative designs to ensure stresses remain within acceptable levels. Without the ability to measure such material properties, the potential of analytical tools becomes greatly curtailed. Materials development must also now be more focused. With the exception of silicon die itself, most other materials in a package can be modified based on functional and structural needs. The ability to tailor material properties imply the need to know what to look for. Knowing the characteristics desired, it must be confirmed and this means mechanical testing. Traditionally, materials were tested using conventional tests typical for bulk materials. That the materials are used in micro size scales has lead to disagreements on the efficacy of these traditional test methods. Testing of small specimens has therefore become necessary creating a new class of test methods. There are also material properties, such as interfacial properties that traditionally are of secondary importance. This has also led to development of new test methods. It is because of this a new catch phrase now rings in the industry. Heard previously only in major engineering circles such as the aerospace industry, the need for a materials database has become critical to the future of the industry.

Another important change is that even as package designs become more sophisticated, manufacturing techniques likewise has become more demanding. A new approach is now needed to address in-process problems. It is unacceptable to allow production development to proceed to the final product, followed by burn-in before iterating to resolve problems - which is then argued as design or process related. Testing at different stages of the process is needed. There is also a need to establish better in process quality assessments to optimize process equipment and improve production yields. Again, mechanical evaluation is the key.

New Developments in Testing for Microelectronics Continued

Finally, while the final qualification of a product may still be by burn-in, mechanical testing of finished components and its final form on a PCB is much faster and cost effective. The way to go remains to do burn-in testing only when all other tests have established that the product will not fail. To repeat a burn-in test is to delay a product's time-to-market by months. In today's business climate this could destroy a product's chance of success.

The evolution of the industry has therefore necessitated a shift in focus from thermal testing to mechanical testing. This shift is the reason for the revolution in mechanical evaluation to take place. However, while test method development has been active for nearly a decade, development has been hampered by the lack of suitable test equipment.

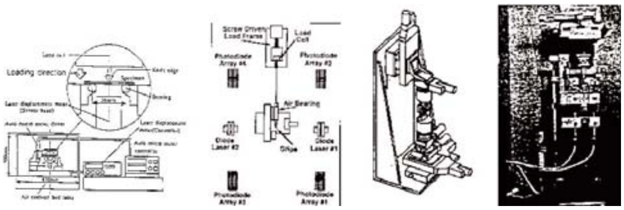

Figure 1.
Example of systems developed by researchers

Review of Testers for Microelectronic Materials

A survey of the literature has revealed a number of different uniquely designed testing machines. These were developed at universities and research institutions with specific research goals. Some of these have even seen commercialization.
A review of these has highlighted a number of key important features demanded of these test machines.

The need to test at sub-newton level to around 10 N is the most common capacity of research machines built. In a typical microtensile test of a 200 μ by 200 μ specimen, break loads are typically up to 10 N. For materials such as copper or gold, the loads may be of the Figure 2 Miniature Thermomechanical test system. Reobuck et. all order of 0.5 N. This low force requirement has been the first driver for many institutions to develop a special test system. There has even been symposium's on testing of small specimens. Figure 1 and Figure 2 show the schematics of a number of these types of machines.

Among these systems, NPL's Electrothermal Mechanical Test system (Roebuck et. all. 1996), have unique features and capabilities for which a specialized system is clearly necessary. The ETMT has a unique ability of testing small specimens at temperatures of up to +1000 °C at very fast heating rates of +200 °C/ sec and cooling the specimen at controlled rates at +100 °C/ sec. Its capability is therefore focussed narrowly at measurement of physical properties and thermo-mechanical behavior of materials. The system is currently being marketed by Instron®.

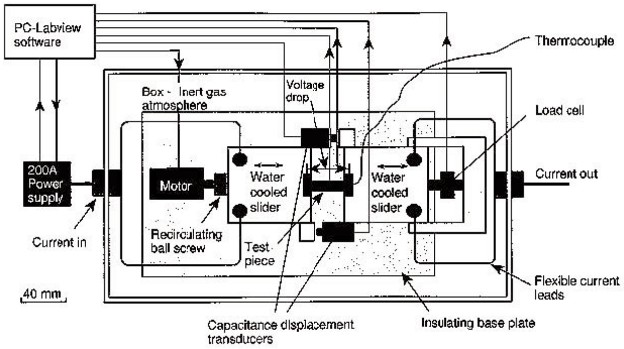

Figure 2.
Miniature thermomechanical test system

New Developments in Testing for Microelectronics Continued

For microelectronics applications though, the ability to perform low force testing while is a prerequisite is very limiting. A general purpose instrument must be able to perform static and cyclic testing for a wide range of tests. A review of tests of interest to the community shows some tests require static test loads as high as 2 kN. For example, many interfacial fracture test methods based loaded in bending involve loads between 20 N to 200 N. For methods such as the constrained short specimen and mixed mode tests such as the brazil nut tests where direct compression or tensile loads are applied, loads in excess of 1 kN may be reached. More conventional solder ball testing has loads of a < 10 N while die shear testing loads will easily exceed 500 N. Therefore, despite the ingenuity of many research machines, their potential is highly limited. A true instrument of the microelectronics industry must not only have the ability for low force testing but also be able to handle loads around 1 kN or more. For capacities in the region of 1 kN and below, conventional testing machines exists but a second key differentiator of many of these special machines is the accuracy of the displacement or strain measurement. For example, Hashimoto et. all 1994, designed a special 3-point bend test machine using a laser displacement measurement device to give resolutions of 50 nm. Others would use laser interferometry systems, dual camera video systems, capacitance devices all for the singular objective of having sub-micron resolutions.

Cyclic capability is also an important capability desired. The interest is fatigue properties of materials led to the introduction of direct drive test systems. The traditional servohydraulic systems are clearly unsuitable for microelectronics applications due to their physical size and problems of noise and hydraulic leaks affecting the clean environments found in microelectronics research facilities. Servo-electric linear drives therefore seemed to provide an alternative. These drives can offer high forces and acceleration and are used in high performance milling machines and x-y translation stages.

What has become clear however, is that linear drive systems are not suitable for materials testing. This is because linear drives work on the principle of current is proportional to force. In positioning applications, the force (or current) is therefore proportional to the mass x acceleration. Therefore the control loop will only need to adjust for a constant mass. Even if mass changes, the acceleration only is affected which an outer velocity and position loop will compensate for. However, in materials testing, force (or current) is proportional to displacement with proportionality dependent on the stiffness of the specimen. This would be acceptable for control except for two complicating factors: the mass of the actuator and load string and the changing stiffness of the specimen. The mass of the actuator and load string tied to the elastic specimen creates a mass on a spring with resonance. If during the test any signal noise present in the control loop that is of the same order of magnitude as the resonant frequency, the system will go out of control. With low force specimens, the resonant frequencies are often within 100 Hz range, which limits the controllable range of the machine. The second complicating factor is the changing specimen stiffness. When specimens are changed, the system requires a complex and time consuming retuning of the machine. This is true even if the specimen stiffness changes by a small amount. However, specimen stiffnesses will change during a test and unless advanced realtime adaptive tuning algorithms are developed, the resultant loss of control cannot be resolved.

To date, therefore there are no machines for which the full range of testing for microelectronics applications including fatigue testing can be performed. Systems both commercially offered of specially developed are either unsuitable or only for a narrow range of applications. This paper introduces a new machine that covers all the above requirements in a convenient easy to use package developed by Instron®. Based on this new machine, an evaluation of the suitability of the end-notch fracture specimen was conducted for Mode II fatigue crack growth studies. A series of other applications are also presented demonstrating its full range of capability.

New Developments in Testing for Microelectronics Continued

Instron®'s New Microtester

Figure 3 shows Instron's new Microtest system designed specifically with the needs of the microelectronic's testing community in mind. It provides a comprehensive, versatile solution to the challenges associated with testing microelectronics, MEMs and other sub-miniature test specimens. Two versions are available. With Instron's series 5500 controller and Merlin™ application software the system is ideal for static, creep or simple cyclic testing. With Instron's FastTrack™ 8800 controller with its complete suite of FastTrack II application software suite, the MicroTest system performs the full range of static applications, creep, stress relaxation plus advanced fatigue tests such high and low cycle fatigue, complex fatigue and other dynamic applications.

Figure 3.
New Microtest Systems

The design is based on a precision aligned two column frame with a stiffness exceeding 18 kN/ mm to ensure negligible frame deflections during tests. The ergonomics of the frame is designed so that the test area is in front of the two main columns ensuring easy access to the load line for specimen setup or viewing during test using optional accessories such as a stereo microscope or CCD camera.

Central to the design is the MicroTest system's resolution and accuracy. Based on a unique encoder system which is mounted directly on the actuator shaft, the motion of the actuator is accurately measured and controlled. The system's position accuracy is guaranteed at one micron over its entire stroke although typical accuracy as Figure 4 shows is much higher. It should also be noted that since few high precision tests require displacements exceeding 1 mm, the accuracy is at least one order of magnitude better. The theoretical accuracy has been calculated at better than 40 nm which is similar to the system's guaranteed resolution. As shown in Figure 5 the 5500 version of the MicroTest system is able to achieve nano-level resolution.

Figure 4.
Actuator displacement accuracy over entire stroke

The design is based on a precision aligned two column frame with a stiffness exceeding 18 kN/mm to ensure negligible frame deflections during tests. The ergonomics of the frame is designed so that the test area is in front of the two main columns ensuring easy access to the load line for specimen setup or viewing during test using optional accessories such as a stereo microscope or CCD camera.

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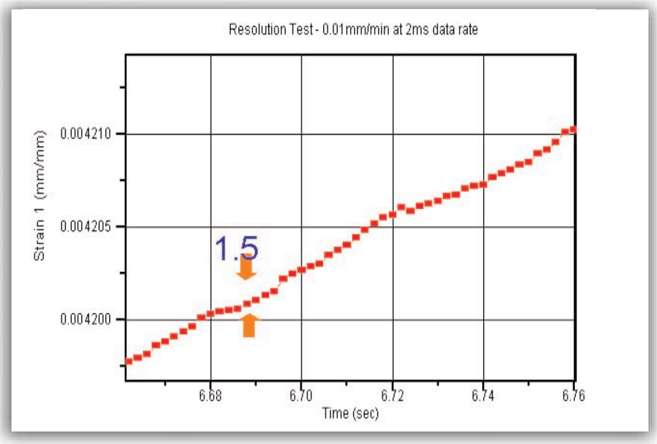


Figure 5.
Resolution plot of 5548

The combination of high resolution and accuracy together with advanced control systems, is important. Many microelectronics applications will involve extremely fine displacements. The ability to apply a load on a specimen without creating discrete steps and resolve the load-displacement curve accurately will enable all fracture events to be detected without false readings. Many types of high precision type tests have been published in the literature. While all the tests had previously required special dedicated instruments, they can now all be performed using this new universal but ultra high precision micro force system.

Another key feature of the system is its wide load range capability. Rated to maximum load of 1 kN for static or low frequency cyclic tests, the system with interchangeable load cells is perfectly suitable for testing at sub-newton load levels. It is also rated to 400 N for high cycle fatigue testing at 5 Hz. Dynamic capability is unique capability for the Microtest as it does not exhibit any control issues that direct drive systems currently face. The position control in static or dynamic tests is insensitive to specimen stiffness and magnitude of load applied. In load control, the control loop sensitivity to specimen stiffness is identical to standard servo-hydraulic machines allowing built in autotuning to simplify the set-up procedure.

Another issue often not recognized is that as dynamic test frequencies rise, Newton's law, F=ma, will interact with the test. This is a problem found in all fatigue test systems. A simple calculation will show the severity of the problem. Assuming a displacement amplitude of 1 mm and a load string mass of just 10% of the load cell capacity, Figure 6 shows that above a few Hz, the load output would be unacceptable. Both ISO and ASTM have committee's working on the problem of dynamic force calibration arising out of this fundamental problem. Note that with many low force applications, load string mass is often quite high relative to the load cell used, the problem is much more. Instron® has therefore introduced its range of dynamic load cells, which combines the use of a built-in accelerometer to allow automatic compensation of the inertia effects.

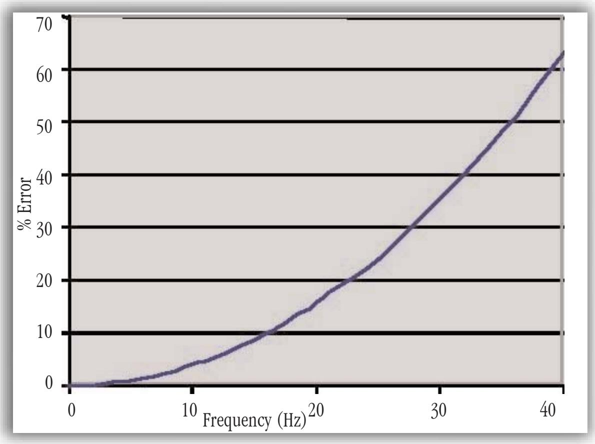


Figure 6.
Load cell error due to inertia Microtest effects

New Developments in Testing for Microelectronics Continued

Application in Fracture Studies

One of the challenging problems in microelectronics packaging design is the problem of interfacial cracking. As the failure is predominantly a Mode II fracture problem this problem has been studied in the past by Nishimura et. all, using the end notch specimen in 3-point bend loading. This method has advantages in its direct applicability in microelectronic systems such as for molding compound on lead frame. The test method has since been included in the SEMI G690996. However, one of the complexities of performing this test is the problem of measuring crack length. Nishimura and the standard both recommend the use of ultrasound to scan the specimen and determine the location of the crack. The added complication is that this should not be done by immersing the specimen in water but that the specimens be properly sealed first. The specimen must then be accurately positioned with respect to the 3-point bend anvil as the crack length is defined as from the crack front the bend anvil - not the edge of the specimen. A more effective way would be if the crack length was measured in-situ, as part of the test. The objective of this work was to evaluate the feasibility to using the MicroTest's superior resolution, accuracy and machine stiffness to determine the crack length of the specimen by monitoring the specimen stiffness with crack length. The success of this can then be used to perform not just static tests but even the more complex problem of fatigue crack growth under Mode II conditions.

Mode II Fracture Mechanics

Nishimura et. all had shown based on simple beam bending that the compliance, C of the specimen, which is the inverse of stiffness, S, under 3-point bend is related to the crack length, a, by the equation given in table 1. B, in the table refers to the specimen width, L, the half span and t and E are the thickness and modulus, where the subscript 1 and 2 refer to the upper and lower layers. Table 1 also provides the equation for G where P is the applied load.

For stress intensity K, the eqution used was:

$$K = 4\cosh(\Sigma\pi)\sqrt{\frac{G}{\frac{\kappa_1+1}{\mu_1}+\frac{\kappa_2+1}{\mu_2}}}$$

where

$$\Sigma = \frac{1}{2}\left[\left(\frac{k_2}{\mu_2}+\frac{1}{\mu_1}\right)\Big/\left(\frac{k_1}{\mu_1}+\frac{1}{\mu_2}\right)\right]$$

Nishimura et. all had shown that the energy release rate K, calculated analytically is only five percent higher than that based on finite elements and therefore reasonably accurate. However, it has not been established how well the compliance follows experimental results. It should also be noted that as C is related to the third power of the crack length, while G is related to the second power, the method is therefore amenable to stable crack growth if the test is conducted in a constant displacement mode. Tests under constant load conditions would result in an accelerating crack growth rate with crack length. Ideally, an outer-loop control algorithm used in standard fracture testing software would allow K or G control. Note also that there is found to be sensitivity of the critical stress intensity with crack length. The analytical solutions do not provide a reason for this though the crack closure or opening effect is most likely the cause and that a more rigorous solution should ideally be used.

New Developments in Testing for Microelectronics Continued

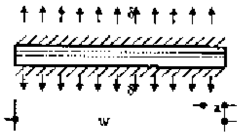
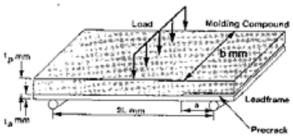
Test Method	Compliance and Energy Release Rate Equations
Constrained Short Specimen (Chen et. all) 	$C=\frac{1}{(W-a)k'}$ $\frac{1}{k}=\sum_{i=1}^{n}\frac{1}{k_i}$ $G=\frac{P^2C}{2B(W-a)}$
Single Cantilever Beam (Chen et. all) 	$C=\frac{a^3}{3E_cI_c}\left\{\left[1+\frac{3}{\beta^2a^2}\left(\frac{\mathit{sinh}^2\beta c+\sin^2\beta c}{\mathit{sinh}^2\beta c-\sin^2\beta c}\right)+\frac{3}{\beta a}\left(\frac{\mathit{Sinh}\,\beta c\,\mathit{Cosh}\,\beta c+\sin\beta c\cos\beta c}{\mathit{Sinh}^2\beta c-\sin^2\beta c}\right)+\frac{3}{\beta^3a^3}\left(\frac{\mathit{Sinh}\,\beta c\,\mathit{Cosh}\,\beta c+\sin\beta c\cos\beta c}{\mathit{Sinh}^2\beta c-\sin^2\beta c}\right)\right]+\left(\frac{a_c}{a}\right)^3\left(\frac{E'_cI_c}{E'1}-1\right)\right\}$ $\beta=\sqrt[4]{\frac{k}{4E_cI_c}}$, and $E_cI_c=E_1I_1+E_2I_2$ $G=\frac{P^2a^2}{2BE_cI_c}\left[\left(\frac{\mathit{sinh}^2\beta c+\sin^2\beta c}{\mathit{sinh}^2\beta c-\sin^2\beta c}\right)+\frac{1}{\beta a}\left(\frac{\mathit{Sinh}\,\beta c\,\mathit{Cosh}\,\beta c+\sin\beta c\cos\beta c}{\mathit{Sinh}^2\beta c-\sin^2\beta c}\right)\right]$
End Notch 3-Pt Bend (Nishimura et. all) 	$C=\frac{1}{B}\left[\frac{a^3}{(t_1^3E_1+t_2^3E_2)}+\frac{(t_1E_1+t_2E_2)(2L^3-a^3)}{4t_1E_1t_2E_2(t_1+t_2)^2+(t_1^2E_1+t_2^2E_2)}\right]$ $G=\frac{3P_2a_2}{2B^2}\left\{\frac{1}{(t_1^3E_1+t_2^3E_2)}+\frac{t_1E_1+t_2E_2}{4t_1E_1t_2E_2(t_1+t_2)^2+(t_1^2E_1+t_2^2E_2)}\right\}$
Blister Test (point loading) (Hutchinson et. all) 	$\frac{\delta}{P}=C=\frac{3(1-v^2)R^2}{4\pi E_1h^3}$ $G=\frac{2E_1h^3\delta^2}{3(1-v^2)R^4}$

Table 1.
Proposed Fracture test geometries

New Developments in Testing for Microelectronics Continued

Experimental

The tests were set-up using a special bend fixture designed to provide repeatable alignment and incorporates a micrometer setup so that the extension of the specimen beyond the anvil can be accurately adjusted via a micrometer. Figure 7 shows the design of the fixture. Tests were conducted using a commercially available moulding compound and lead frame material. Specimens were then prepared according to the SEMI standard recommendations. Pre-cracks of specified lengths were carefully induced in the specimen. The pre-cracks were also ink marked so that following the test they could be peeled apart for direct measurement.

The compliance calibration was performed using three different pre-crack lengths. Then using the micrometer to adjust the position of the specimen with respect to the anvils, the compliance of the specimen could be repeatedly measured with crack lengths changing in steps of 1 mm.

Fatigue crack growth tests were similarly setup but at constant displacement amplitudes. Some tests were also carried out in load control but unstable crack growth quickly developed resulting in specimen failure. This was particularly a problem since crack growth rates of 0.05 mm/cycle and above was the objective. It is believed an outer-loop control algorithm would address this problem by adjusting the load levels real-time as the crack length increased to maintain a constant delta G range.

The tests were conducted at 2 Hz using a constant displacement amplitude of 200 μ.

Figure 7.
Three-point bend fixture with micrometer for specimen testing

Note that in this study, all mid-point loads were applied from the moulding compound side. No attempt was made to follow the procedure outline in the SEMI standard to load from both the moulding compound side as well as the lead frame side in order to remove the effect of residual stress present in the specimen. This experiment focussed purely on the feasibility of using compliance for crack length monitoring and extending that capability to crack growth. Loading from the lead frame side would have similar characteristics.

New Developments in Testing for Microelectronics Continued

Experimental Results and Discussion

In observing for stiffness change, it is important to observe if the changes in stiffness can be reliably detected in the actual test data. Figure 8 shows the load versus displacement plots. It can be seen that the changes in stiffness are very clear and easily resolved.

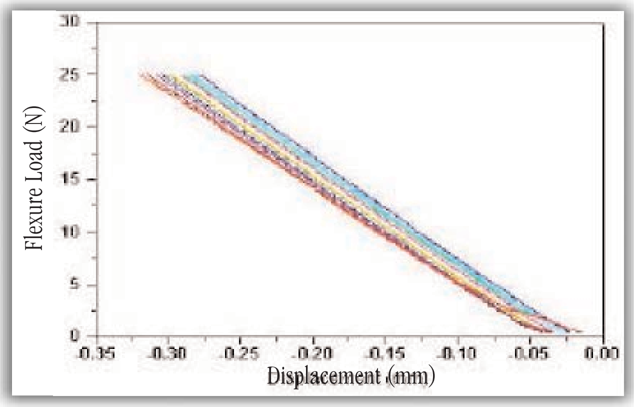


Figure 8.
Load displacement plots for length

Figure 9 shows the plot of stiffness change versus crack length with the theoretical curve based on the compliance equation. The change in compliance at different crack length was found to be well defined and consistent with the theoretical calculations. It should be noted that the modulus of the materials should be accurately determined or that the specimen with zero crack length be used to calibrate the equation as the crack length. A normalized stiffness plot can also be used to the same effect. It is noted that the equation is not extremely sensitive to relative thickness of the adherends but more to the overall thickness and the moduli of the materials. The resolution of the compliance technique is dependent on the length of the crack where crack lengths exceeding 5 mm shows the strongest sensitivity where crack length of less than 0.1 mm changes can be easily resolved.

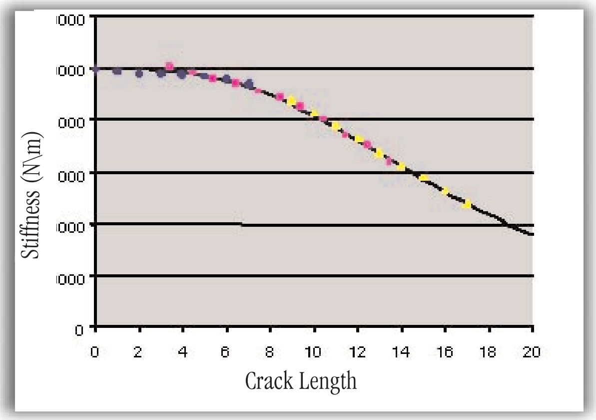


Figure 9.
Stiffness change with crack different crack lengths. Line refers to analytical result

In fatigue crack growth, the chief concern is the ability to propagate the crack in a controlled stable fashion. The displacement amplitude of 200 microns applied resulted in a peak load 35.7 N which as the crack propagated fell to about 15 N. Figure 10 shows the compliance change as seen in the load - displacement plots for a different test cycles. The results show some noise present in the load not seen in static tests which can be attributed to the friction between the mould compound and lead frame. Note that this would be present for load on the mould compound due to the closed crack but should be absent for the inverted case which experiences Mode I stresses at the crack tip.

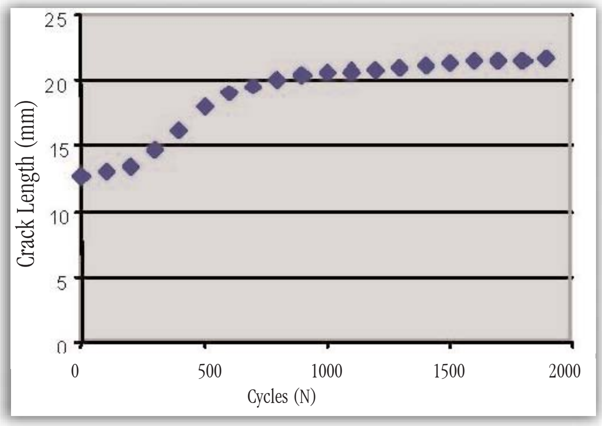


Figure 10.
Crack growth versus cycle

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The stability of the crack growth is seen in Figure 11. There is an initial bedding in period where the crack growth seemed retarded. Data points for the initial few cycles were therefore discarded. The crack grew after that in the expected fashion slowing down as crack length grew. Converting the results to the standard Paris law plot in Figure 12, it shows the expected trend of increasing crack growth rate with higher stress intensity range.

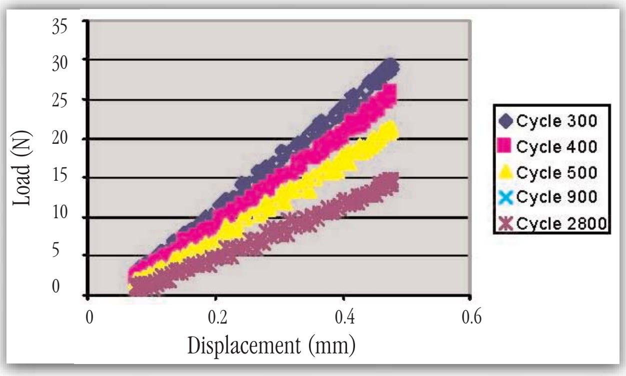

Figure 11.
Stiffness change with crack growth

Note that the result should be interpreted with caution due to the uncertainty over the influence of crack length to the actual stress intensity applied on the specimen. The stress intensities calculated being based on the simple beam theory is therefore only an approximation whose error increases with crack length. A more rigorous study into this specimen to understand the bounds of applicability is therefore required.

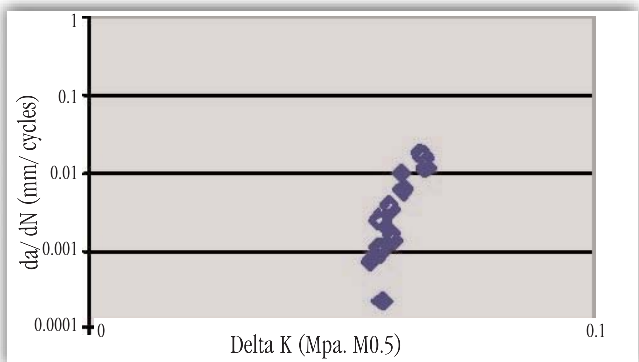

Figure 12.
Crack growth rate versus stress intensity range

The results demonstrates the potential of using a high precision test instrument to perform challenging experiments necessary for future development and understanding in materials for packaging design. The Mode II results shown demonstrate clearly that the idea of using compliance to simplify the experimental protocol is a viable. As a consequence it is pertinent to explore the implications of this in the context of other fracture specimen models proposed by various researchers. In conjunction also, other applications where accurate compliance is important is also discussed.

Amongst the fracture mechanics based test, four other test methods have been receiving attention in the literature. These are the Constrained Short Tension (CST), Single or Double Cantilever Beam (SCB or DCB), Center Cracked Beam Bend (CCBB) and Blister Test using a point loading probe. Other methods do exist such as the Brazil Nut test but has not found supporters due to the difficulty in manufacturing meaningful specimens required by the microelectronics community.

Table 1 summarized the key equations found in these test methods. In all cases, there is a strong analytical relationship between crack length and compliance. The CST specimen has the highest stiffness of all since specimens of interest refers to where the thickness of the layers are small with respect to width.

However, the usual arrangement of bonding the specimen to a metal pull rod results in stiffness masking and energy storage within the pull rod. The rigidity of the specimen also requires that the lateral stiffness of the actuator be high coupled with very high alignment. Lateral rigidity is important as the presence of the crack results in offset loads. Any lateral deflection will therefore affect the test. These complications make this test less attractive.

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Of the other tests, like the Mode II test, there is good dependence of compliance on crack length. Although deflections in all cases are small, the accuracy of the Microtest will have little difficulty discriminating. Note that for the SCB proposed, there is desensitization of the compliance due to the length of the extension arm. It is therefore important that the arm should not be excessively long < 3 times the actual test specimen is suggested.

Conclusion

The use of a new ultra high precision, low force test system was presented compared with the systems previously published. The versatility of the system and significance of its capability was demonstrated using the End Notch 3-point bend specimen of SEMI 69-0996. It was shown that it is possible to perform in-situ crack length measurement using the measured specimen compliance. This ability was then used to demonstrate measurement of Mode II crack growth rates.

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