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Characterization of Interfacial Adhesion in Semiconductor Packages

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CHARACTERIZATION OF INTERFACIAL ADHESION IN SEMICONDUCTOR PACKAGES

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Introduction

Delamination of the interfaces between the die, lead frame and the ambient materials is one of the major issues of IC reliability. There are several methods described in the literature how to characterize the adhesion of the die at these interfaces. Some of them are standardized. This publication gives guidance which method to choose for material selection, qualification or monitoring.

CHARACTERIZATION OF INTERFACIAL ADHESION IN SEMICONDUCTOR PACKAGES

(From JEDEC Board Ballot JCB-20-33 and JCB-20-33A, formulated under the cognizance of the JC-14.1 Subcommittee on Reliability Test Methods for Packaged Devices.)

1 Scope

This document identifies methods used for the characterization of die adhesion. It gives guidance which method to apply in which phase of the product or technology life cycle.

NOTE Inclusion in this directory of methods does not imply applicability to all die-package configurations.

2 Terms and definitions

die adhesion: Steady or firm attachment between die and an adhesive material e.g. mold compound

adhesion strength: the force needed to separate two materials by an defined method like shear or pull.

creep: the tendency of a solid material to slowly and permanently deform under stress.

Mode I (crack failure mode): An opening or tensile crack caused by loading normal to the crack

Mode II (crack failure mode): A sliding or in-plane shear crack caused by loading parallel to the crack surface sliding direction.

NOTE The crack surfaces slide over one another in direction perpendicular to the leading edge of the crack.

Mode III (crack failure mode): A tearing or out-of-plane shear crack caused by loading coplanar to the crack surface and perpendicular to the crack propagation direction.

wear: The erosion of material from a solid surface caused by interaction with another material.

3 References

ASTM D3165, Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies

ASTM D3433, Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints

ASTM D3762, Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)

ASTM D903, Standard Test Method for Peel or Stripping Strength of Adhesive Bonds

ASTM F459, Standard Test Methods for Measuring Pull Strength of Microelectronic Wire Bonds

JESD22-B109, Flip Chip Tensile Pull

JESD22-B115, Solder Ball Pull

MIL-STD-883 Meth 2012.7, Radiography

MIL-STD-883 Meth 2019, Die Shear Strength

MIL-STD-883 Meth 2027, Substrate Attach Strength

MIL-STD-883 Meth 2030, Ultrasonic Inspection of Die Attach

MIL STD 883 Meth 2031.1, Flip Chip Pull off test

SEMI G63-95, Test Method for Measurement of Die Shear Strength

SEMI G69-0996, Test Method for Measurement of Adhesive Strength between Leadframes and Molding Compounds

4 Die adhesion

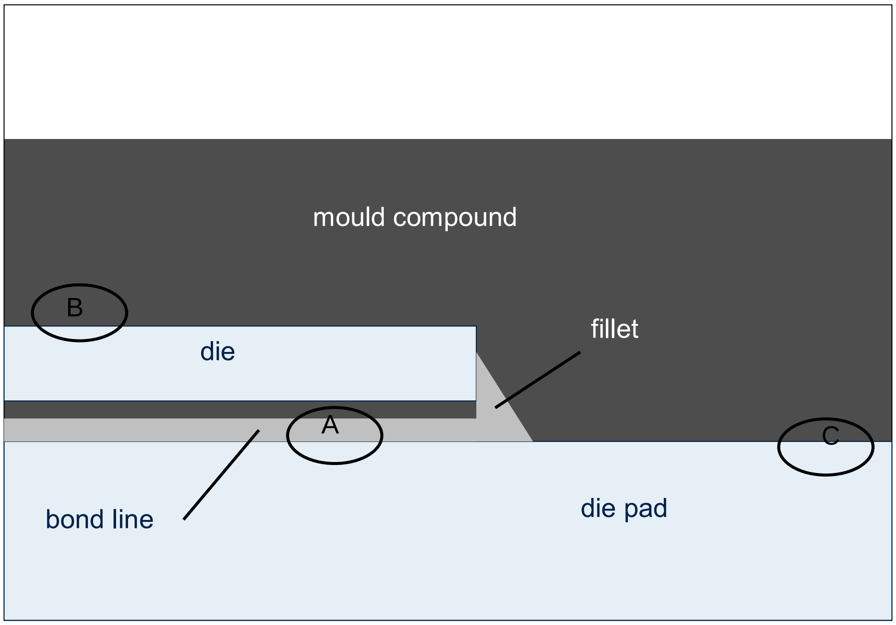
Failure mechanisms directly or indirectly affecting die adhesion are

- fatigue mechanisms,
- creep,
- wear,
- Interfacial fracture, and
- nonwetting due to contamination or residues.

The effect on time to failure depends very much on design and construction of the package.

4.1 Molded wire bond package

There are two major techniques for attaching a die to a die pad, adhesive or solder. For adhesives polyimide, epoxy or silver filled glass is used. A sketch of the three critical interfaces of this type of package is shown in Figure 1.



A) die – adhesive – pad, B) die – mold compound,
C) mold compound – die pad/leadframe

Figure 1 — Die adhesion interface

Delamination at C does not directly affect a die-related interface, but it should be taken into account because of its influence on delamination and related failure modes at die-related interfaces.

The attach process with adhesives has two potential failure causes:

- excessive die attach fillet resulting in die attach contamination and problems when performing die shear tests;
- too little die attach fillet resulting in die delamination or die cracking.

The eutectic process typically uses alloys Sn-Ag, Sn-Ag-Cu, Au-Si, Au-Sn, Pb-Sn or Au. Here voiding especially large voids are the main risk. These voids change the stress situation and therefore are the cause of die cracking.

Table 1 gives an overview of the cause-failure correlation at die interfaces. Delamination failures are covered by the column “die lifting”.

4.1 Molded wire bond package (cont'd)

Table 1 — Cause failure correlation, examples

Failure Cause	Die to mold separation	Die Lifting from LF	Die Cracking	Adhesive Shorting	Bond Lifting
contamination	X	X			
excessive die attach voids		X	X		
incomplete die attach coverage		X	X		
inadequate die attach curing	X	X			
die overhang			X		
insufficient bond line thickness			X		
excessive die ejection force			X		
absence of voids			X		
incorrect die attach material viscosity				X	
incorrect adhesive dispensation				X	
Out gassing from D/A cure	X				X
resin bleeding of the die attach material into the bond pads					X

4.2 Flip chip package

Flip chip packages have many interfaces which could delaminate or break (see Figure 2. Cohesive failure modes are not covered in this publication. Stress related failures due to thermal load have been studied for the interfaces

bump – underfill [6]
die – mold compound [7]
die – underfill [7].

Interface underfill-solder mask is not discussed here.

Especially the adhesion of the underfill is the most important factor affecting reliability of flip chip assemblies. An example of a detailed reliability analysis of a flip-chip-package can be found at reference [8].

4.2 Flip chip package (cont'd)

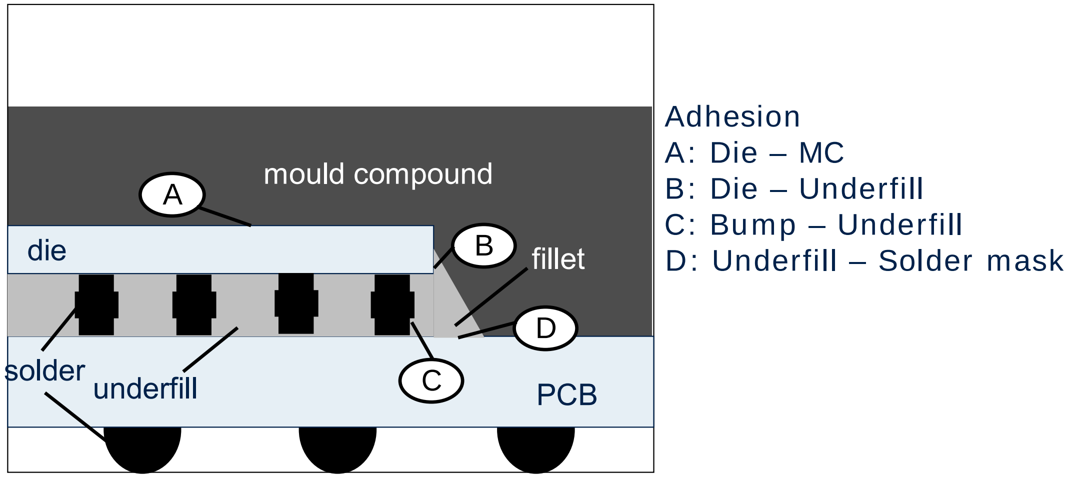


Figure 2 — Interfaces of flip-chip-packages (example)

Depending on the design different geometrical or material properties have influence on the strength of degradation:

- PCB thickness, CTE and Young's Modulus;
- underfill / adhesive CTE and Young's Modulus;
- die size;
- surface treatment;
- wetting angle;
- fillet width and height;
- flux residues.

Design specific sensitivity analysis should be done for stress intensity effect, energy release rate G and phase angle Ψ.

5 Characterization methods

This section gives an overview on existing methods used for characterizing the interfaces of the die to its surrounding materials. Standard references are given.

5.1 Die shear test

Die shear testing as described in MIL-STD-883, Method 2019 and SEMI G63-95 is the process of determining the strength of adhesion of a semiconductor die to the package's die attach substrate (such as the die pad of a lead frame or the cavity of a hermetic package), by subjecting the die to a stress that's parallel to the plane of die attach substrate, resulting in a shearing stress between:

1) The die-die attach material interface; and
2) The die attach material-substrate interface.

A typical die shear tester (Figure 3) consists of

1) A mechanism that applies the correct load to the die with an accuracy of ± 5% of full scale or 50 g, whichever tolerance is greater.
2) A die contact tool that makes the actual contact with the full length of the die edge to apply the force uniformly from one end of the edge to the other.
3) Provisions to ensure that the die contact tool is perpendicular to the die attach plane.
4) Provisions to ensure that the fixture holding the die may be rotated with respect to the contact tool so that the die edge and contact tool may always be aligned in parallel to each other.
5) A binocular microscope (10 times minimum magnification) and lighting system to facilitate the observation of the die and contact tool while the test is being performed.

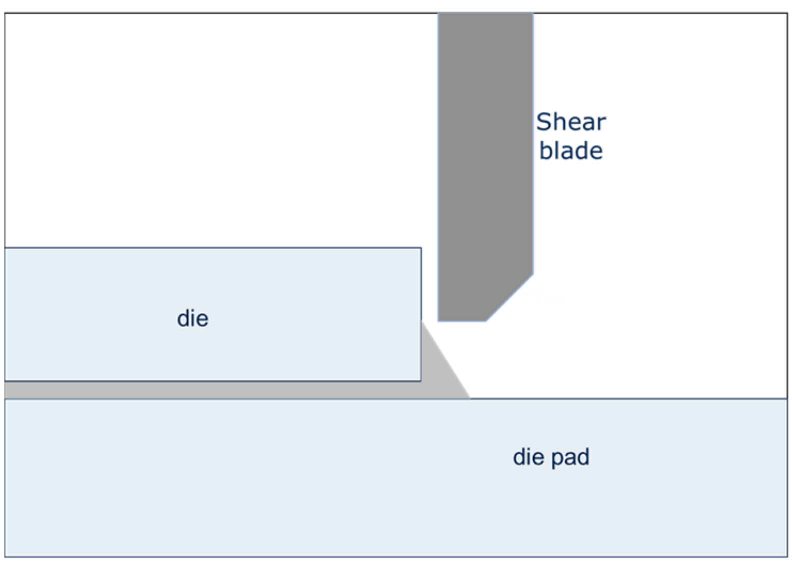


Figure 3 — Die shear test

5.1 Die shear test (cont'd)

For the die shear test done before molding, there is only preparation effort needed in cases where there is not enough space available for the contact tool. In these cases, the result can be affected by the preparation technique used.

The force applied to the die during die shear testing must be sufficient to shear the die from its mounting or twice the lower specification limit for the die shear strength, whichever occurs first. The direction of the applied force must be perpendicular to the die edge and parallel to the die attach or substrate plane. After the initial contact has been made and the application of force starts, the relative position of the tool must not change vertically, i.e., it must be prevented from contacting either the die attach material or the substrate.

A failure criterion for die shear strength is given as a function of area.

The mode of separation must also be classified into the following:

1) Shearing of the die itself with silicon remaining.
2) Separation of the die from the die attach material.
3) Separation of both the die and die attach material from the package substrate.

This method is most efficient if used for monitoring as long as data from a specific package are compared. Due to the influence of the fillet height, it is hard to compare adhesion data for different materials. For qualification it is an indicator test selecting parts with worse adhesion. There is no model available to correlate failure curves to operational field conditions

Solder reflow temperatures induce high stress at the die and leadframe interface and at the same time the adhesion strength of most organic adhesive materials drop drastically at high temperature. Because of this combination, a large number of delamination failures occur during solder reflow. Thus it is useful to check die shear strength at high temperature. High-temperature die shear testing is also useful to test larger die whose die attach strength could easily exceed the tool capability.

A high-temperature die shear test may be performed using the same tool as described above together with a heated stage; the setup and test method is similar as for room temperature except for the stage temperature. Temperatures can be defined by the user. (Typical temperature is 240 °C). The type of failure mode offers further insight into selection of materials.

5.2 Button shear test

The button shear test (Figure 4) is used to quantify the interfacial strength of two layers within a device that is assumed to contain some inherent cracks [5,8]. It also covers the influence of environmental effects of moisture and temperature and is typically used for the interfaces between mold compound and leadframe or flip chip packages.

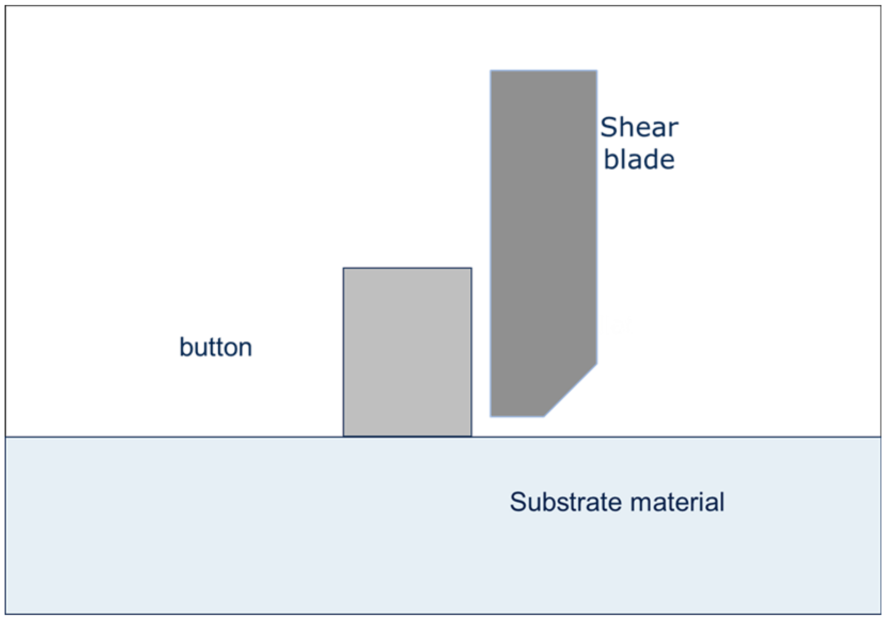


Figure 4 — Button shear test

The test method is described as one out of three alternative ones in SEMI G69-0996. Several applications are described in the literature [8]. Standard shear test equipment, which has to be calibrated, can be used.

Specific structures have to be prepared, which makes it independent from costly production processes. Pull or bending method can be used as an alternative test procedure.

The measured adhesive strength is calculated in N/mm^2 from the peak load.

Finite element modeling is used to obtain interfacial stresses and to calculate interfacial strain energy density, G and Ψ. Depending on the shearing height a theoretical failure criterion can be defined in the G-Ψ-plot. There is no absolute gating criterion for qualification purpose. Therefore the method is typically used for material selection.

5.3 (Leadframe) pull test

This test method addresses adhesion to of mold compound to a leadframe. Leadframe material is pulled out of molding compound using a tensile tester, which has to be calibrated and specific test samples. The test method is described as one out of three alternative ones in SEMI G69-0996. Adhesive strength is calculated in N/mm².

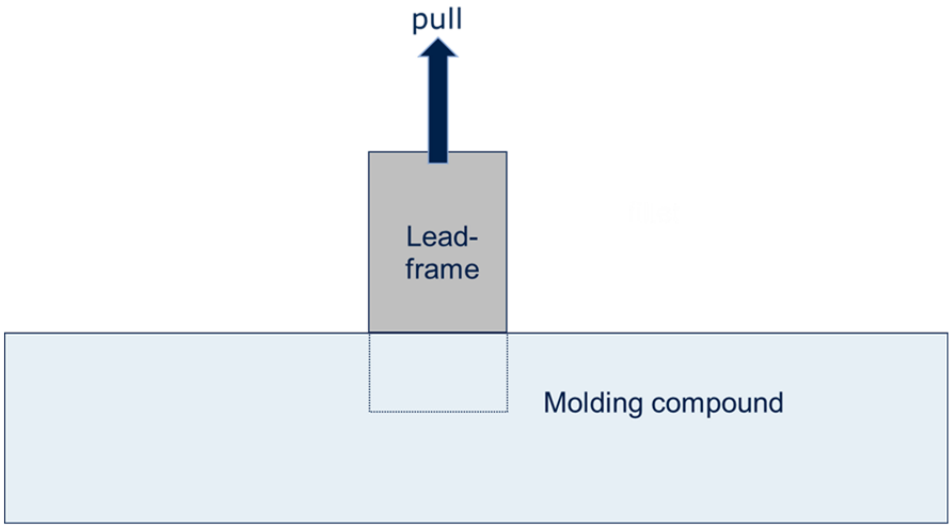


Figure 5 — Leadframe pull test

5.4 Stud pull test

For stud pull a contact tool has to be attached to the die in a way such that a force perpendicular to the die surface can be applied across the complete surface (Figure 6).

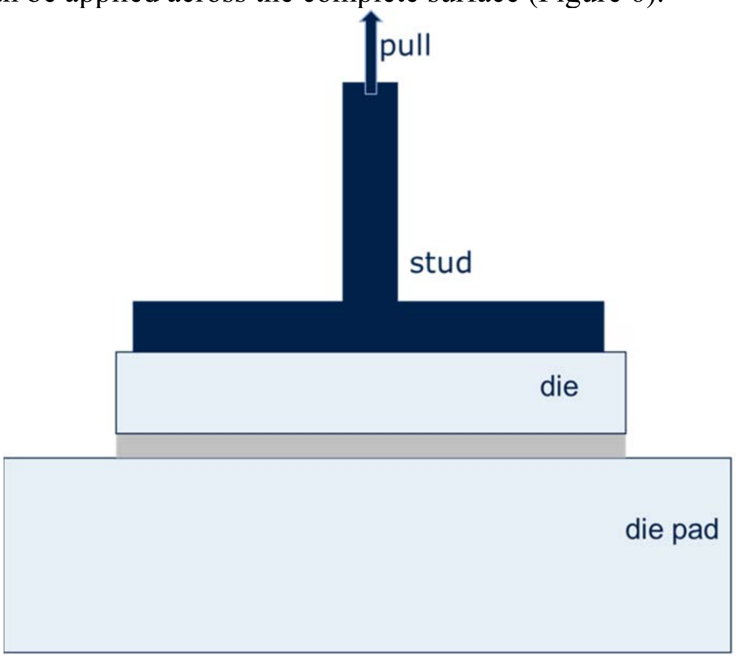


Figure 6 — Stud pull test

5.4 Stud pull test (cont'd)

Stud pull testing as described in MIL-STD-883, Method 2027 has the purpose to determine the strength of the die adhesion when subjected to force perpendicular within ±10° to the die surface. The test equipment shall consist of a tensile strength tester capable of applying a force equal to 6895 kPa times the area of the largest die to be tested with an accuracy of ±5 percent or 50 gm force.

A force shall be applied sufficient to lift the die from its mounting or equal to twice the minimum tensile strength specified in a table.

A failure criterion can be defined.

5.5 Laser spallation technique

The laser spallation technique [1,2], which has high reproducibility as long as the DUT is thin enough, consists of converting a laser pulse impinging on the back side of a sample into a mechanical stress pulse, which can then cause delamination of a layer or layers on the front side of a sample if the pulse is of sufficient strength. The magnitude of the stress pulse is determined through displacement interferometry focused on the front side of the sample. Failure is determined through optical or acoustical inspection of the front side of the sample. Typically, an experiment consists of testing different locations on a sample with incrementally increasing laser energy until delamination is first seen. The laser shot that caused this threshold damage is paired with the interferometric data from the shot, which is used to calculate the critical stress required to delaminate the sample.

Samples are prepared by coating the backside of the sample with two films–a sputter-coated metallic film and then a coating of sodium silicate (waterglass). The metallic film should be >100 nm and the sodium silicate layer should be on the order of micrometers thick. During the test, the impinging laser pulse ablates the metallic layer and the sodium silicate confines the resulting ablation, setting up the stress pulse within the sample. Since the metallic layer is ablated in the process, the same location cannot be tested more than once. Neighboring test sites should be >2 shot diameters away since collateral damage to the sodium silicate layer can occur with each shot. Typical shot diameter is in the range of 2 mm - 3mm.

For laser spallation, there is a high preparation effort and an additional analysis method, a normal displacement-interferometer is needed.

5.6 Flip chip tensil pull test for bumps

Flip chip pull-off testing, as described in JESD22-B109 and also MIL-STD-883, Method 2031.1, has the purpose to determine the strength of the die adhesion when subjected to force perpendicular within ±5° to the die surface. The test equipment shall consist of a tensile strength tester capable of applying the stress to the bonds with an accuracy of ±5 percent or ±0.25 grams force.

A force shall be applied sufficient to lift the die from its mounting or equal to twice the minimum tensile strength which constitutes a failure.

A failure criterion can be defined

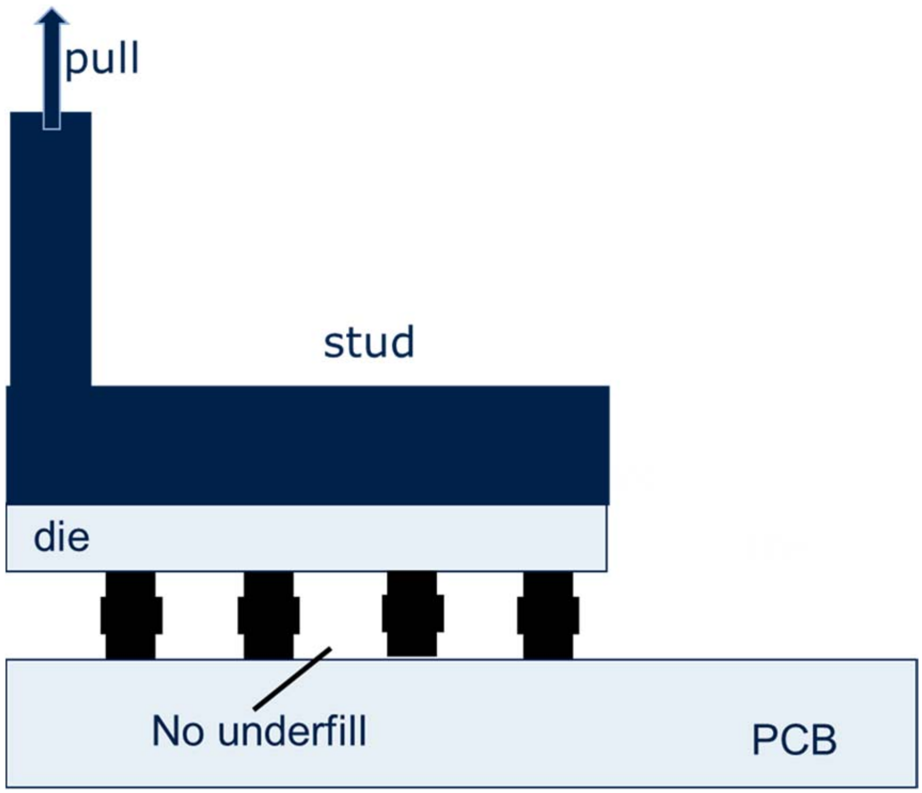


Figure 7 — Flip Chip Tensile Pull

5.7 Peel test

The peel test measures the strength required to pull apart a bonded surface in most cases, a thin layer bonded to a thick substrate. It is comparative in nature and useful in evaluating adhesives, adhesive tapes, or other attachment methods. The type of break has to be analyzed, whether it is cohesive, adhesive or mixed in nature or in the substrate. The measured result is the peel strength.

The test method is described in ASTM D903.

This is a tensile test of either flexible or rigid material, where specimens are 25 mm wide. Typical results include average load divided by specimen width.

Test frames can be single column or double column. Sample size should be high to reduce influence of non uniformities.

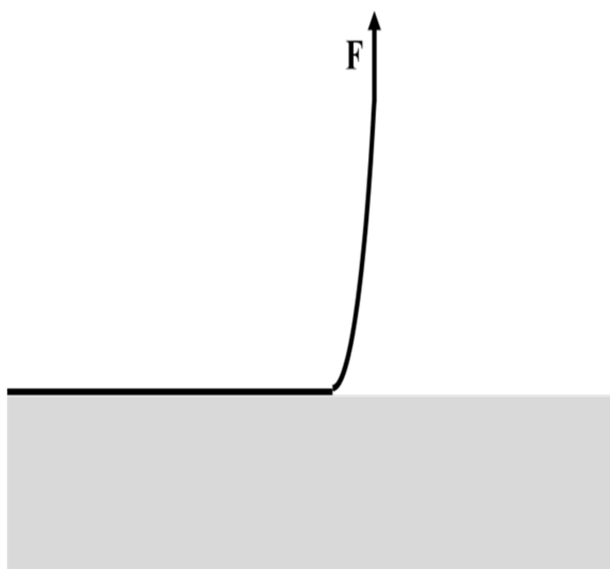


Figure 8 — Peel test

5.8 Wedge test

The Wedge Test [3] is used to measure the energy of fracture of an adhesive interface. A wedge is used to cleave adhesive joints. The sample can be exposed to elevated humidity and temperature. There are alternative applications in which only a static stress is induced see [4]. Typically this is a Mode I test, but if the thicknesses of the layers are different, some Mode II component should be taken into account.

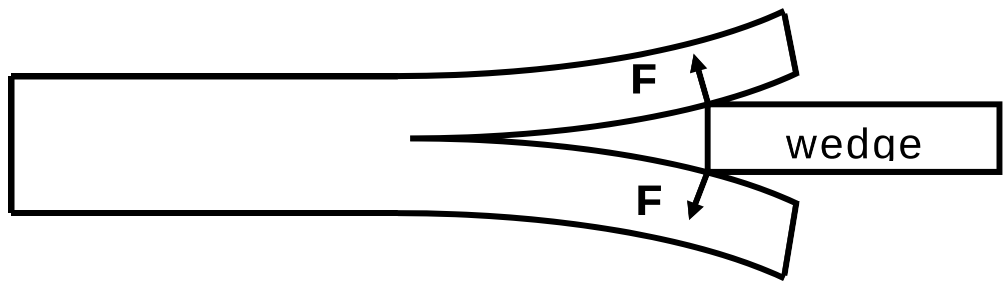


Figure 3 — Wedge test

The test method is described in ASTM D3762.

The test consists of creating an initial crack by inserting a wedge, and then following the propagation of the crack with time. The driving force for the propagation of the crack comes primarily from the stiffness of the beams separated by the wedge and this driving force decreases as the crack propagates.

An Energy Release Rate can be calculated from the crack length during stressing.

5.9 Cantilever beam test

This test (ASTM D3433) is used to obtain the mode I fracture energy of the adhesive bonds, which is a measure of the fracture toughness of the adhesive in the presence of flaws. Similar to a wedge test, a crack is initiated first by inserting a wedge. The specimen is then loaded by pulling apart two beams at a certain rate, this increasing load resulting in increased deflection of two beams.

From the results the energy release rate (ERR) G can be calculated [13]

$$G=(F^2/2w) / (dC/dl)$$

where

F: force
w: sample width
C: compliance of the beam
l: crack length

The strength of the interface is then characterized the G value at which the crack propagates.

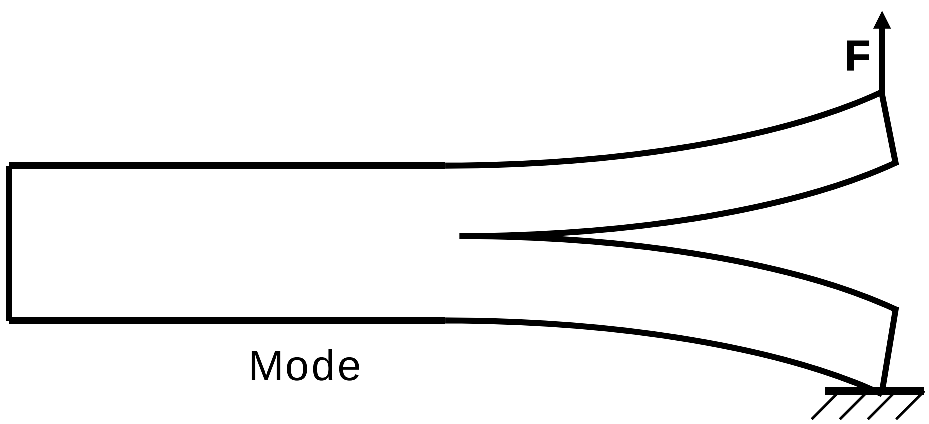


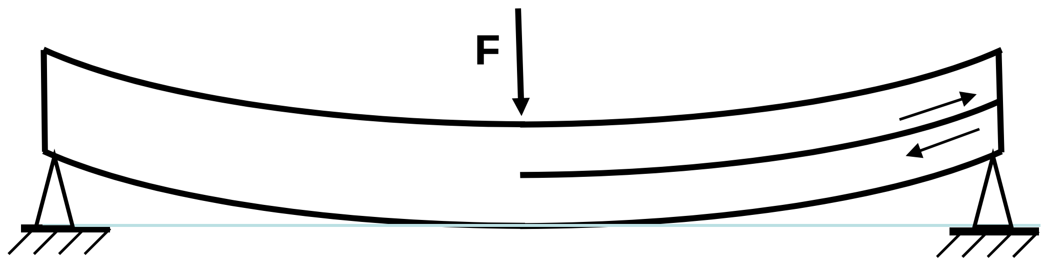
Figure 4 — Cantilever beam test

5.10 Three-point bend test

This test method as described in SEMI G69-0996 is used to calculate the adhesion strength between molding compounds and leadframes. To perform this test method, a special sample is required that has ‘pre-crack’. The leadframe has known dimension, as does the molding compound that is applied to one side of the leadframe. The “pre-crack” is generated by applying a controlled amount of a mold release agent on one of the leadframe and its length is verified using an ultrasonic inspection technique. This test method requires a minimum of two samples.

5.10 Three-point bend test (cont'd)

The sample is supported at two points near each edge on the bottom side and a force is applied at the center of the top side. A tensile tester is used to apply loading at a constant speed and record the peak load (prior to a sudden drop in load when fracture occurs. To calculate the "true adhesive strength" the test requires that one sample be tested with the mold compound up and then on a second sample with the leadframe up. The adhesion strength is then calculated for each stress condition.

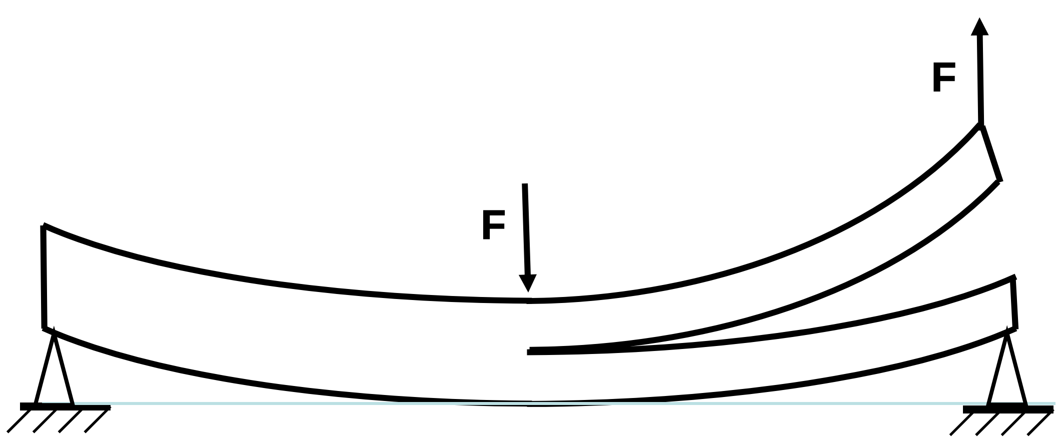


Mode II: in-plane shear

Figure 5 — Three-point bend test

5.11 Mixed-mode bend test

This method uses production samples avoiding residual stress calculation of test samples and crack tip singularity [9]. It can be applied if other methods, e.g., bend tests, failure due to brittleness or residual stress of the test samples. Preconditioning or pre-aging is possible to study the influence of temperature and humidity. A test apparatus, based on a mixed-mode chisel setup, is described in [9] together with a proposed test procedure. Using FEM fracture mechanics the energy release rate can be calculated.



Mixed Mode (I and II)

Figure 6 — Mixed-mode bend test

6 Comparison and assessment of methods

Several criteria have been used to assess the methods for their potential application range:

Handling effort: The effort needed to prepare the DUTs and to perform the test method. Is the test fast enough to be integrated into manufacturing process?

Reproducibility: Is gauge repeatability and reproducibility (Gr&R) possible and what are typical results. Is it possible to generate quantitative or qualitative data?

Addressed failure mechanism: Which failure mechanisms are covered by the test or method and what is the typical sensitivity? Is a differentiation between different failure mechanisms possible?

Destructiveness: Does the test affect the integrity of the device? Can the device be used for production after the test?

Suitability: For which decision or which phase of development or production are the data generated by the test suitable?

Target values: Values to separate pass from fail parts

References: Standards or publications describing the method.

6.1 Scope and application range of the method

The methods used to characterize the adhesion of the die with the surrounding materials can be divided into three categories:

- techniques characterizing the failures like delamination, cracks or interface weaknesses
- methods to measure the material specific adhesion at interfaces
- methods to measure product specific adhesion strength

6.1 Scope and application range of the method (cont'd)

An overview of the scope of the methods of clause 5 is given in Table 2.

Table 2 — Scope of characterization Methods of section 5

Method	Mode	Reference	Scope	
			Type	Interface
5.1 Die Shear Test	II	MIL-STD 883 Mtd 2019	flip chip	die - substrate
5.2 Button Shear Test	II	SEMI G69-0996	molded leadframe	MC - LF
5.3 (Leadframe) Pull Test		SEMI G69-0996	molded leadframe	MC - LF
5.4 Stud Pull Test		MIL-STD 883 Mtd 2027	several	die - substrate
5.5 Laser Spallation Technique		[1,2]	flip chip	substrate - solder balls Cu - dielectr
5.6 Flip Chip Tensil Pull test for bumps		JESD22-B109	flip chip	die - substrate
5.7 Peel Test	I	ASTM D903	several	die - film
5.8 Wedge Test	I	ASTM D3762	several	adhesive bonds
5.9 Cantilever Beam Test	I	ASTM D3433	several	adhesive bonds
5.10 Three Point Bend Test	II	SEMI G69-0996	molded leadframe	MC - LF
5.11 Mixed Mode Bend Test	I & II	[9]	several	adhesive bonds

For each interface of a flip-chip package a characterization method is recommended in Annex A. An example of how design parameters of a flip chip BGA package like the fillet height and corresponding material selection can be done based on energie release rate ERR and phase angle measurements is given in reference [7].

For molded wire bond packages the recommendations for characterizing the interfaces are given in Annex B.

6.1.1 Failure characterization techniques

The inspection methods,

- Ultrasonic inspection (described in MIL-STD-883, Method 2030),
- X-ray inspection (described in MIL-STD-883, Meth. 2012.7.),

are typically used to characterize interfaces before and after environmental stress tests for delamination cracks or voiding. Therefore they are applied within qualification and process control or monitoring of production. Especially for characterization of voiding, the sensitivity has to be evaluated before drawing quantitative conclusions.

6.1.2 Methods for interface characterization

The following techniques generate quantitative results in terms of a force needed to separate two layers of material, which can be used for adhesion measurement:

- Button shear test;
- Leadframe pull test;
- Peel test;
- Wedge test;
- Cantilever beam test;
- Three-point bend test;
- Mixed-mode bend test;
- Laser spallation;

They are typically used for material selection in the development phase and they all require the preparation of specific test samples, which make them easy to perform but a transfer to operational condition is needed. The mixed-mode bend test reduces this problem by using samples from production.

Though all of these methods generate a quantified result, it should be taken into account that they can be used for a relative assessment only. Therefore they are used for the selection of the best material out of several options by choosing the one with the highest adhesion force between die and surrounding material.

Some test methods like peel tests require a high number of samples to avoid unwanted effects from test execution. To find the optimum stress conditions, it is recommended to perform a sensitivity analysis on the test condition first, especially if the results are used as input for Finite-Element-Model (FEM) simulations.

The results can be used to calculate the energy release rate for specific interfaces.

It should be taken into account that the button sheer and the peel tests have limitations due to the plastic deformation and relaxation of residual stress [10,11].

Another weakness of shear tests is the fact that the shear mode is not quantified as the die material may fail cohesive [12].

For the methods in which specific test devices have to be build, high frequency monitoring to control production lines is not feasible. Therefore either mixed mode bend test with production samples or inline machine parameters have to be used to control the stability of die adhesion in the production process. With a certain frequency, samples can be taken after die attach process to control the adhesion by stud pull or die shear.

6.1.3 Methods for measurement of adhesion strength

These methods are used for assessment of adhesion strength using productive samples by measuring the force at point of fail:

- Die shear test ;
- Stud pull test.

It should be taken into account that these tests have limitations due to the plastic deformation and relaxation of residual stress [10,11].

Due to the missing correlation of the target curves, separating passing from failing parts, to the operating conditions in the field it is not possible to make an absolute judgment on the applicability of a certain device under given operating conditions.

For die shear and stud pull Gr&R data are generated by using standard weight. But this procedure covers the equipment dependant effects only. All handling, operator or preparation effects are not taken into account by this method. To get reproducible results with these two methods, all boundary conditions should be kept as stable as possible. Under these conditions, these indicator tests could uncover weaknesses if values are low compared to target values

6.2 Failure mechanisms

The characterization methods do address adhesion weakness due to voiding and delamination. The methods used for quantification of adhesion are using a preexisting crack and measuring its propagation. They are not used to measure whether a fail condition has been reached but they are used to generate input for calculation interface properties like the energy release rate.

Depending on the area of the interface indicator tests like stud pull and die shear generate quantitative results by measuring the force at the interface disruption point. The quantification is limited by the die size or the maximum force that could be applied respectively. Die lifting as the extreme form of delamination or die cracks can be detected and separated from delamination by careful analysis of the DUT after stress.

Failure criteria for gating tests can be voiding volume or delaminated area, but it should be considered that these parameters could not be measured very precisely. It is also not possible to correlate the fail conditions at the test to the failure distribution that could be measured under real application conditions. Adhesion related failure mechanisms should be characterized in relation to temperature and humidity. High humidity at the interface can weaken the adhesion by 20-40% [14].

Depending on the interface in question, one method may be better than another. For example, laser spallation can be a good way to measure adhesion between the die and underfill; whereas a simple button shear or 3-point bend test may be better for mold compound to die or mold compound to leadframe.

7 Summary and recommendations

Best practice recommendation for using test methods during development characterization and qualification of new process or material are:

- characterize (energy release rate) and select the most reliable materials in the first phase of development;
- simulate package and mitigate risks by design;
- perform indicator tests at qualification;
- monitor changes in adhesion strength during production.

Annex A (informative) Flip – chip package interfaces

Interface		Metrology
Package Interfaces		
Integrated heat sink	Sealant	Stud pull/button shear
	Thermal interface material	Stud pull/button shear
Silicon	Underfill	Button shear
	Thermal interface material	Stud pull/button shear
	Dielectric	Cantilever beam/3-pt. bend/4-pt. bend
	Die backside films	Peel/stud pull
	Die attach film	Peel
Underfill	Dielectric	3 pt. bend/4-pt. bend
	Solder resist	Cantilever beam /3-pt. bend/4-pt. bend
	Copper	Button shear
Substrate Interfaces		
Cu	ABF*	Peel/ stud pull
	Solder resist	Button shear/ stud pull
Die interfaces		
Silicon	Inter level dielectric	3-pt. bend/4-pt. bend/laser spallation
	Copper	3-pt. bend/4-pt. bend /laser spallation

*Ajinotomo Buildup Film

Annex B (informative) Molded leadframe-package interfaces

Interface		Metrology
Silicon die	Mold compound	Button shear
	Bond line	Shear (ASTM D3165)
	Alu wedge	Pull (ASTM F459)
	Bond ball	Solder ball pull (JESD22-B115)
Die pad/Leadframe	Bond line	Shear (ASTM D3165)
	Mold compound	Button shear

Annex C (informative) Bibliography

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4) "*Effects of mechanical stress and moisture on packaging interfaces*", Buchwalter, S. L., et al., *IBM J. Res. & Dev*. Vol. 49 Nos. 4/5 July/September 2005

5) "An energy-based failure criterion for delamination initiation in electronic packaging", Fan, H.B,. *J. Adhesion Sci. Technol*., 2005.

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Annex D (informative) Differences between JEP167 and JEP167A

This annex briefly describes the changes made to entries that appear in this publication, JEP167A, compared to its predecessor, JEP167 (April 2013).

Clause	Description of change
3	Added description to MIL STD 883 Meth 2031.1 Flip Chip Pull off test
5	Fixed minor punctuation and grammatical errors

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   The referenced clause number has proven to be:
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