Moisture effect on fracture strength of molding compounds (MCs) for electronic packaging in a wide temperature range

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Plastic encapsulated packages and other packages made with moisture permeable materials all encounter a reliability challenge during solder reflow after the packages are exposed to moisture before mounting. The background is that the vapor pressure of moisture inside a plastic package increases rapidly when the package experiences the high temperature of solder reflow. Under certain conditions, this pressure can cause internal delamination of the plastic from the die and/or leadframe, internal cracks that do not extend to the outside of the package, bond damage, wire necking, bond lifting, die lifting, thin film cracking, or cratering beneath the bonds. In the worst cases, the stress can result in external package cracks. This is usually referred to as popcorning. With packages moving to environmentally friendly (i.e. so called green or lead-free version), plastic packages are more susceptible to this problem as they must be exposed to higher reflow temperature up to 260 °C. Therefore plastic packages are classified according to their sensitivity to moisture level, and moisture sensitivity level reliability test has been one of the major reliability tests of packages.

To extensively understand and further evaluate the survivability of the packages at different moisture conditions, analysis and finite element simulations are commonly used in which moisture effect on the material property must be taken into account to firstly, verify how it influences the stresses in the packages and secondly, identify its importance for material strength. Therefore it is very important to characterize material properties and fracture parameters of the key packaging components under dry and wet conditions. Some of works have been done in the moisture related material properties [1, 2] and reliability analysis [3–9].

On the other hand, material data at different temperatures provided by the material vendors are incomplete in most cases and so far no material data consider the moisture effect systematically. Because of this reason, numerical simulations' lack of complete material input, and consequently analysis of package reliability based on the incomplete material data is not confident enough and sometimes simulation results are very hard to apply. In this circumstance, using material properties taking into account moisture content to analyze the thermo-mechanical behavior of the packages not only justifies the effect of moisture effect on material property but also improves the reliability assessment greatly. To this point, material testing at different moisture conditions and in a wide temperature range is very critical.

In last years, some work has been done to characterize the mechanical properties of MCs in electronic packaging, e.g. Ref. [10, 11]. Few papers have investigated the properties of MCs and their variation with moisture content and temperature [1, 2, 10, 12]. However, conflicting results of moisture effect on fracture properties of materials were reported. For example, obvious dependence of fracture toughness on moisture was observed in Ref. [2] but very limited variation of fracture property of MCs was concluded in Ref. [12]. This becomes a driving force to conduct more systematic experiments to clarify the moisture effect on the MC properties. In this work, fracture toughness and flexural properties like flexural modulus, fracture stress/strain of two green molding compounds GMC-1 and GMC-2 were investigated following international standards: ISO 13586 [13] and ISO178 [14] in a temperature range from −60 °C to 260 °C and under wet and dry conditions. Three-point-bending method was applied. It was found that moisture reduced modulus, rupture stress as well as fracture toughness of the selected materials.

For the schematics of the experimental setup, one can refer to Refs. [1] and [13] or [14], respectively, for flexural properties and fracture toughness determination. The material tester INSTRON 8848 Microtester installed in our AIT (Assembly and Interconnect Technology) laboratory, Infineon Asia Pacific Private Limited, was employed to conduct all the tests. This facility was such designed that it was able to adjust and control the moisture content and temperature in the testing chamber, therefore, the moisture in the specimens can be well maintained during the testing period. Fig. 1 is a picture of the tester together with its temperature and moisture controller.

The tests were conducted on wet and dry specimens obtained by molding. Specimens were called wet after they were soaked in the chamber under 85 °C/85% RH (relative humidity) condition for 168 hr following the soaking requirements stated in JEDEC standard IPC/JEDEC J-STD-020B, while dry specimens were baked at 125 °C for at least 24 hr just before the tests (no storage). For more details of specimen preparation, one can refer to Ref. [1].

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Figure 1 The photo of the INSTRON 8848 Microtester.

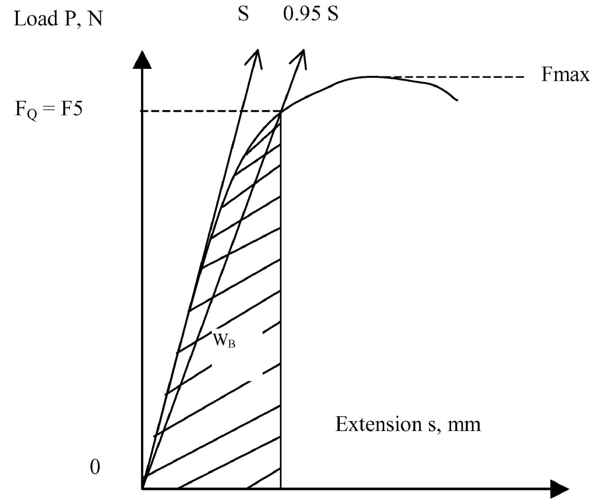

Figure 2 Load-extension curve for a notched test.

For the specimens for fracture tests, all the notches in specimens were made at constant notching speed to ensure process consistency. After notching, the specimens were baked at 125 °C for at least 24 hr before they were put into soaking chamber or tested under dry conditions. The specimens were soaked batch by batch according to the schedule of tests so that the soaking time for all specimens was the same. In the temperature range from −60 °C to 260 °C, we chose 10 separate points as testing points, namely −60 °C, −20 °C, 25 °C, 60 °C, 90 °C, 100/110 °C, 130 °C, 175 °C, 220 °C, and 260 °C. However, for fracture tests, only a few tests had been done at low temperature between −60 °C and 25 °C since little temperature effect on the fracture toughness of the molding compounds (MCs) was observed. Totally more than 400 tests have been completed in this work. Listed in Table I are the specimen dimensions for fracture and flexural tests. Any specimen whose thickness within the central third of the length deviates by more than 2% from its mean value shall be rejected. The corresponding maximum deviation for width is 3%. The cross section of the test specimen shall be rectangular for flexural properties tests, with no rounded edges. The cross section of test specimen for fracture toughness tests follows ISO 13586 [13].

For fracture property tests, the specimens were V-notched after post-mold-cure and then a natural crack at the tip of the notch of each specimen was generated using the crack-notching rig designed specially for production of cracks. Test pieces for flexural tests were kept in dry cabinet and baked at 125 °C for at least 24 hr before tests to ensure them dry enough. 4–6 test specimens were tested for every testing condition. More tests could be performed if any abnormal deviation was observed or greater precision of the mean value was required.

TABLE I Specimen dimensions

Test	Flexural	Fracture
Length, l	80 ± 0.1 mm	80 ± 0.1 mm
Width, w	10 ± 0.02 mm	10 ± 0.02 mm
Thickness, h	4 ± 0.02 mm	4 ± 0.02 mm
Span length, L	60 ± 0.2 mm	40 ± 0.2 mm
Crack length, a	—	$0.45 < a/w < 0.55$

Following the assumptions for linear elastic fracture mechanics (LEFM), data validation was selectively performed at a few test conditions. If all the size criteria for specimen dimensions as in Ref. [13] are satisfied, then the established method of material testing is effective for fracture tests, and equations for facture toughness calculation in Ref. [13] are valid. Cross check was also conducted to ensure the accuracy of the recording results by comparing stiffness modulus with the modulus value obtained from fracture toughness data. It was confirmed that deviation was less than 15% in all cases. Thus, fracture toughness, i.e. critical energy release rate G_Q, of the MCs can be determined from the recorded force-extension curves by the following equation:

$$G_Q = \frac{W_B}{w \times h \times \Phi(a/w)} \quad (1)$$

where W_B couldbe obtained by F_Q and its corresponding strain, as shown in Fig. 2, $\Phi(a/w)$ is the energy calibration factor [13] depending on the crack length. F_Q, the load at crack initiation, was determined differently for different load-deflection features. w and h are width and thickness of the specimen. If the load-extension curve is a non-linear one, a zero-point tangent is drawn to the curve in Fig. 3 to determine the initial stiffness, S. This stiffness is then reduced by 5%

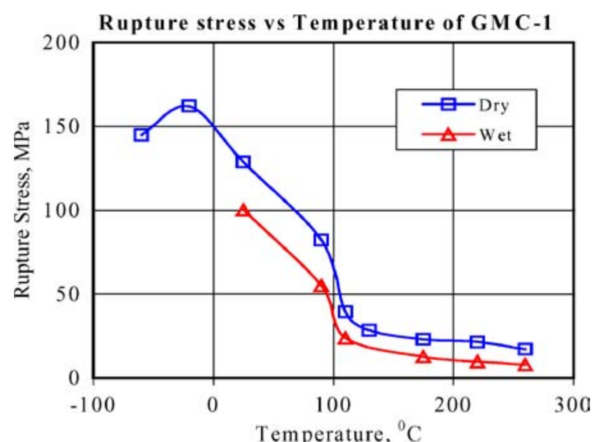

Figure 3 Rupture stress for GMC-1 at different temperatures.

and a further line is drawn accordingly. If the maximum of the load-extension curve falls within these two lines, then $F_{\max}$ shall be called F_Q. If the second line intersects the load curve at F_5 prior to the maximum, then F_5 shall be called F_Q.

The values of G_Q were obtained based on the average of all 4–6 repeated tests under the same testing condition. As the specimen dimension can be well controlled, it is noted that the major variation comes from W_B, work done by external force when the crack starts to propagate.

For flexural tests, modulus, maximum flexural stress and strain can be deduced from the experimental force-deflection readings by following expressions:

$$\text{Flexural stress}, \sigma_{\mathrm{f}} = \frac{3PL}{2wh^2} \quad (2)$$

$$\text{Flexural strain}, \epsilon_{\mathrm{f}} = \frac{6h}{L^2} \cdot s \quad (3)$$

$$\text{Deflection}, s_i = \frac{\varepsilon_{\mathrm{f}_i} L^2}{6h}, \quad (i = 1, 2) \quad (4)$$

$$\text{Flexural modulus}, E_{\mathrm{f}} = \frac{\sigma_{\mathrm{f}_2} - \sigma_{\mathrm{f}_1}}{\varepsilon_{\mathrm{f}_2} - \varepsilon_{\mathrm{f}_1}} \quad (5)$$

where P is applied load, $\varepsilon_{\mathrm{f}}, \sigma_{\mathrm{f}}$, and E_{f} are flexural strain, stress, and modulus, respectively. S_i $(i = 1, 2)$ is the deflection of the beam specimen at two locations in the initial range of load-deflection curve.

Fig. 3 displays the fracture stress-temperature plots of GMC-1 which follow the similar trend for both dry and wet materials. The profile for dry condition lies above the profile for wet specimens, meaning that the rupture stress at wet condition is always smaller than that for dry materials at all temperature points. Rupture stress for wet specimens is 53% lower than that for dry specimens at 260 °C. Table II shows the flexural property changes at different temperature points.

As in Ref. [1], moisture also causes the reduction of modulus of MCs. As a result, the stresses in the MCs could be reduced. However, fracture strength of the MCs deteriorates much more, thus compared with dry MCs, wet MCs will become less resistant to load.

In general, fracture strain at wet condition is lower than those at dry condition, meaning that increasing the moisture will lead to a reduction in rupture strain. Practically, this means a smaller warpage is permitted for wet packages.

The load-displacement readings for both GMC-1 GMC-2 shows linear elastic fracture behavior when temperature is far away from glass transition temperature, T_{g}. However, they also exhibit non-linear fracture behavior in the glass transition range, for example the curve at 110 °C, where some special attention should be paid to clarify the crack initiation. In slightly non-linear cases, G_Q offset values, $G_{Q,5\%}$ were obtained.

TABLE II Change of flexural properties (%) of GMC-1

Temp, °C	Diff. stress	Diff. strain	Diff. modulus
90.0	−33.1	103.1	−22.3
175.0	−44.9	−29.2	−20.6
260.0	−53.5	−39.0	−24.1

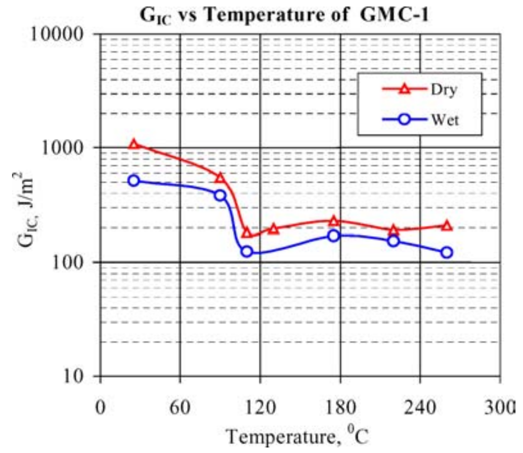

Figure 4 Fracture toughness of GMC-1.

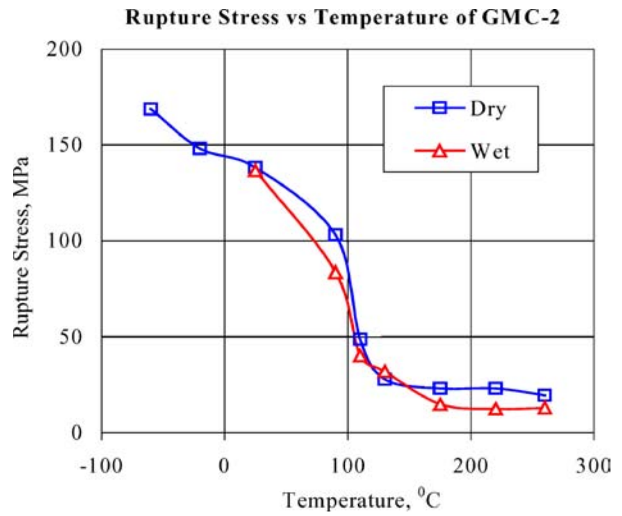

Figure 5 Rupture stress for GMC-2.

Fig. 4 shows the fracture toughness of molding compound GMC-1 with respect to temperature. It is seen that fracture toughness reduces with moisture condition at both high and low temperatures. G_{IC} at wet condition is 53% lower at room temperature or 41% at 260 °C than the value at dry condition. It is also seen that fracture toughness drops abruptly with temperature, especially in the T_{g} range. Above and below T_{g}, G_{IC} changes with T much slowly.

Figs 5 and 6 plot the fracture stress—temperature and fracture toughness—temperature curves of molding

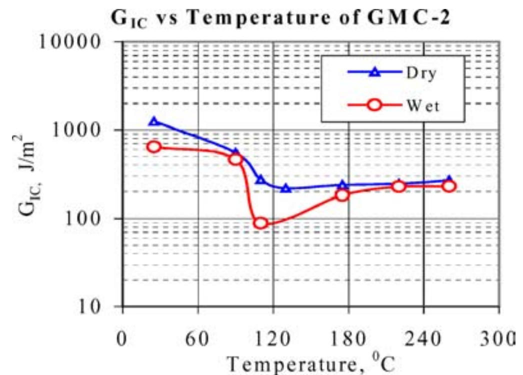

Figure 6 Fracture toughness of GMC-2.

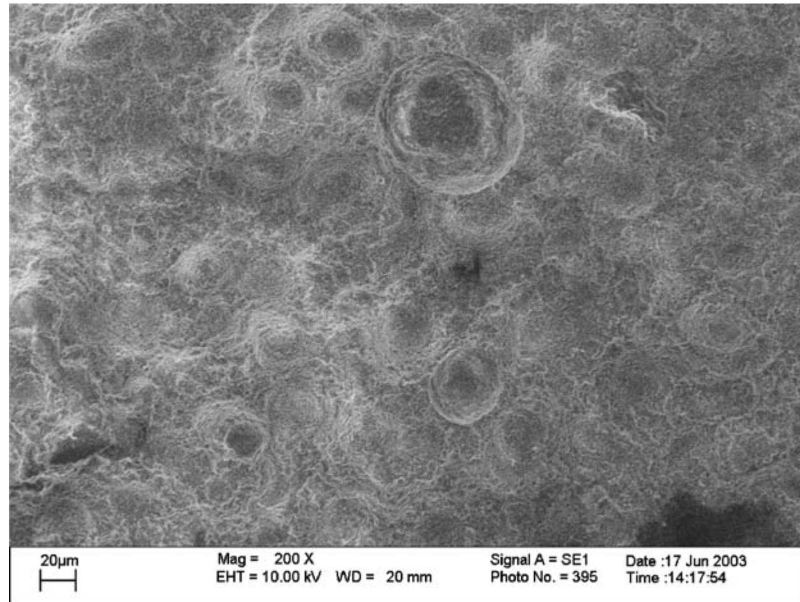

Figure 7 SEM analysis shows the fracture surface of dry GMC-2.

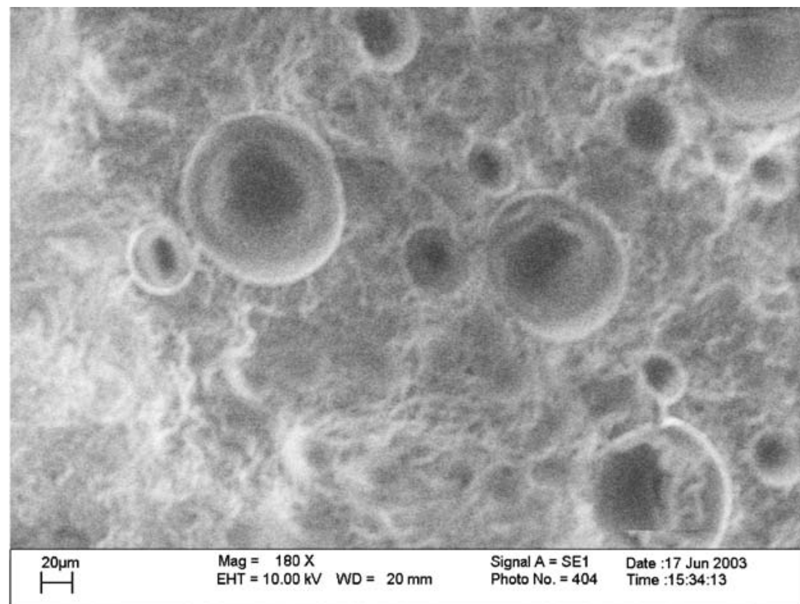

Figure 8 SEM analysis shows the fracture surface of wet GMC-2.

compound GMC-2, respectively, at wet and dry conditions. We can see that both stress and fracture toughness decrease considerably in the glass transition temperature range. With the change of moisture condition rupture/fracture stress decreases 33.6% at 260 °C, while G_{IC} at dry condition could be reduced by 49% at room temperature or 15% at 260 °C compared with that under wet condition.

To explore the mechanism of moisture effect on the material properties of MCs, SEM analysis has been done to the fracture surfaces for wet and dry specimens. Figs 7 and 8 show some of the typical pictures of fracture surfaces of GMC-2 at dry and wet conditions, respectively. For the dry case, fracture surface has only few holes which were formed due to pulling out of fillers from epoxy, however on the fracture surface for the wet specimen many craters were seen in the matrix epoxy. The typical size of the filler(s) is 80 μm. The above observation could be explained as the moisture effect on the interfacial strength between filler and epoxy. In dry condition, the adhesion between Si filler and epoxy was strong enough to resist any interfacial failure that the failure tended to break the epoxy or even cut through the fillers, therefore only very limited fillers whose interface with epoxy may have some voids or other defects will be pulled out. For wet specimens, moisture up-take in the MCs reduced the interfacial adhesion between filler and epoxy, fracture around the granular surface of the filler could be driven easily compared with breaking through the whole compound, therefore many fillers were pulled out from the epoxy.

Conclusions can be made based on the experiments and analysis:

For both GMC-1 and GMC-2, fracture toughness is remarkably lower at wet condition than that under dry condition especially at high T. The moisture-induced

difference could be 53% and 41% for GMC-1, and 49% and 15% for GMC-2 at 25 °C and 260 °C, respectively;

Flexural strength of two green MCs could decrease by up to 50% at 260 °C when comparing wet specimens with dry specimens;

Moisture also changes the feature of fracture surfaces. For wet MCs, more fillers were pulled out from epoxy due to the weakened adhesion between filler and matrix.

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