Determination of Copper/EMC Interface Fracture Toughness during Manufacturing, Moisture Preconditioning and Solder Reflow Process of Semiconductor Packages

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Abstract
Interfacial adhesion is of important concern for multilayered structures such as microelectronic packages. Environmental effects, *i.e.*, high temperatures and moisture diffusion, change the mechanical properties of polymeric materials and, more importantly, degrade the adhesion between the polymeric adhesives and substrates. Delamination between the Epoxy Molding Compound (EMC) and the copper-based leadframe during the solder reflow process is a common failure mechanism in plastic encapsulated IC devices.
This work shows the influence of aging in dry and humid conditions on the adhesion between EMC and copper. Bi-layer Copper / EMC beams were exposed to moist environments to reach the saturation condition. Standard fracture tests were performed for the determination of the critical force at the moment of crack onset. The effects of thermal residual stresses, hygroscopic swelling and viscoelasticity on the measured interfacial fracture toughness for a specific mode angle were investigated by Finite Element Analysis (FEA).

1. Introduction

Bimaterial interfaces are widely available in many engineering applications, including fiber-reinforced composites, thermal barrier coatings and microelectronics devices. The latter is a multilayered structure that typically undergoes complex failure modes such as interfacial delamination. Plastic Encapsulated Microcircuits (PEMs) use organic packaging materials such as Epoxy Molding Compounds (EMCs) for environmental protection. PEMs are prone to failure mechanisms caused by moisture contamination and corrosion occurring during long-term storage and extreme temperature cycles. These failure mechanisms are further escalated by fractures caused by steep temperature gradient during solder reflow process for the assembly of these devices on the printed circuit board. The reliability problems get worse when environmental considerations force the use of higher temperature lead-free solders.
In order to characterize the onset and growth of interface delamination, the use of fracture mechanics has become common over the past years [1-4]. A crack at an interface is subjected to mixed mode conditions and propagates in mixed mode while the preferred fracture path is in the interface. The mode mixity is the relative proportion of tractions ahead of the crack tip in mode II and mode I fracture. Typically, the total fracture toughness depends on the mode mixity and it increases as the contribution of the mode II fracture increases. Failure is expected

when, for a given mode mixity, the calculated strain energy release rate, G, exceeds the interfacial fracture toughness, G_C.

This work investigates the intrinsic interfacial adhesion change between the copper leadframe and the EMC due to temperature rise and moisture absorption. The required material parameters are summarized in Section 2. In Section 3 the experimental setup for the determination of interfacial fracture toughness at different aging environments is described. Section 4 summarizes the results followed by conclusions in Section 5.

2. Materials Characterization

Static measurements of Young's modulus were performed using Three-Point Bending (3PB) of bare EMC bars by applying the beam theory approach. Table 1 shows the influence of temperature on the elastic modulus of the EMC. The EMC bars were placed in a moisture chamber (85°C/85% relative humidity (r.h.)) and their elastic modulus was measured with the same method. No significant change in the elastic modulus was observed. Some tests showed even a slight increase in the elastic modulus of the samples exposed to humid conditions which could possibly be attributed to the effect of thermal aging that increases the elastic modulus. Viscoelastic material properties of EMC were determined by multi-frequency Dynamic Mechanical Analyzer (DMA).

The Coefficients of Thermal Expansion (CTE) of the materials were found using a Thermal Mechanical Analyzer (TMA) and Poisson's ratio, ν, was determined by image correlation during the tensile loading of the specimen. The coefficient of moisture diffusion, D, and the Coefficient of Hygroscopic Swelling (CHS) were determined in previous work [5].

Table 1 Material parameters.

	EMC	Leadframe
E (GPa)	30 @ T=25°C 25 @ T=85°C 2 @ T=140°C 1.4 @ T=200°C 1 @ T=250°C	135
CTE (10^{-6}/°C)	7 for $T < T_g$ 25 for $T > T_g$	17
ν	0.24	0.33
D (mm^2/s)	$0.7 \cdot 10^{-6}$	0
CHS (mm^3/g)	129	0

Test Matrix

Test specimens were divided into eight groups. The aim was to investigate the effects of moisture absorption, temperature aging, and tests at elevated temperature. A summary of the experimental test matrix is given in Table 2. Test group 1 was the control test group which shows the fracture toughness of the samples just after manufacturing. Test group 2 was used to investigate the effect of thermal aging at 85°C on the adhesion between EMC and Cu. At this temperature samples undergo a high residual stress because of warpage induced by the mismatch between the CTEs of the copper and the EMC. In contrast to test group 2, samples of test group 3 were aged at the mold temperature (175°C) at which the so-called stress-free temperature (*i.e.*, almost no warpage) can be assumed.

Table 2 Test matrix.

Test Group	Aging Environment	Test Temperature
1	-	Room Temperature
2	2 weeks in dry condition at 85°C	Room Temperature
3	2 weeks in dry condition at 175°C	Room Temperature
4	2 weeks at 85°C/85%r.h.	Room Temperature
5a	2 weeks at 85°C/85% r.h. followed by baking at 125°C for 24 h	Room Temperature
5b	4 weeks at 85°C/85% r.h. followed by baking at 125°C for 24 h	Room Temperature
6	-	175°C
7	-	210°C
8	-	250°C

Test group 4 identifies the effect of moisture absorption on the adhesion between EMC and Cu. By using the data of moisture diffusion and running a transient moisture absorption of the specimen, it revealed that after two weeks of exposure to humid environment a virtual saturation [5] and after 4 weeks a second phase saturation [5, 12] will be achieved. Test groups 5a and 5b were aimed at studying the possible adhesion recoverability upon baking after two and four weeks moisture aging, respectively. Test groups 6, 7, and 8 were used for the investigation of the effect of elevated temperatures on the interfacial fracture toughness.

3. Fracture Experiments

3.1 Sample Preparation

Copper substrates were machined into 50×10×0.4 mm^3 strips. After cleaning with acetone, the substrates were placed in the cavity of a molding machine. Pellets of a commercial EMC were introduced into the cavity of a pre-heated mold at about 175 °C and kept under a pressure of 60 Bars for 90 s; the molding compound was dispensed automatically on the copper surface at 175 °C. After molding, the samples were placed in an environmental chamber for post-mold curing at 175 °C for six hours to complete the polymerization process of the epoxy molding compound. Fig. 1 shows the dimensions of the bimaterial beam. t_{EMC} and t_{Cu} are the thicknesses of EMC and Cu, respectively.

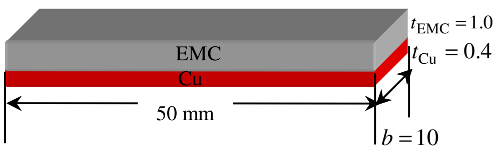
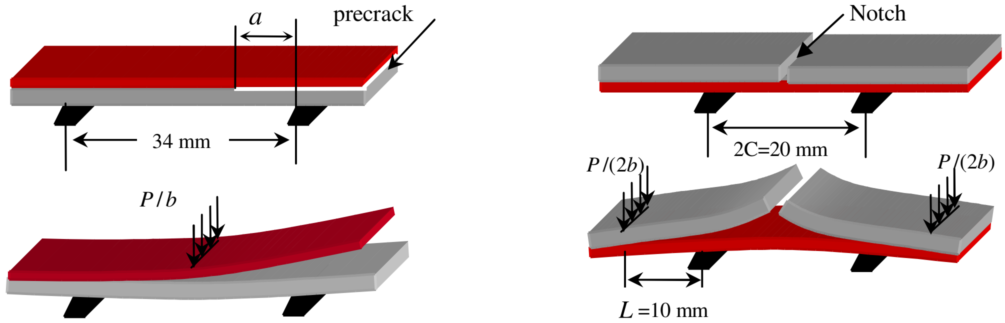


Fig.1 Bimaterial beam sample (dimensions in mm).

3.2 Fracture Tests

Since the interfacial fracture toughness is a mode-dependent parameter, two test methods were performed. The End-Notched Flexure (ENF) test [6] has been widely used to characterize the mode II fracture toughness. A typical ENF testing setup for the bimaterial interface is essentially a 3PB with an initial crack of length a at one end of the beam as shown on Fig. 2a. Since the upper layer undergoes a larger deflection, the sample was positioned with the copper side facing up.



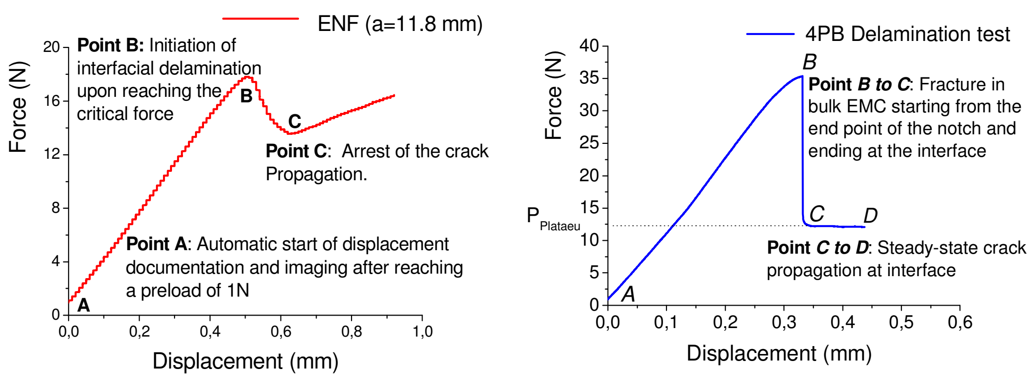
(2a) (2b)

Fig.2 Fracture Tests (2a): ENF (2b): 4PB.

According to beam theory and by assuming Linear Elastic Fracture Mechanics (LEFM), the energy release rate of ENF test can be found by the following formula [6]:

$$G = \frac{3}{2}\frac{P^2 a^2}{b^2}\left[\frac{1}{t_{\mathrm{EMC}}^3 E_{\mathrm{EMC}} + t_{\mathrm{Cu}}^3 E_{\mathrm{Cu}}} - \frac{(t_{\mathrm{EMC}} E_{\mathrm{EMC}} + t_{\mathrm{Cu}} E_{\mathrm{Cu}})}{k}\right]$$

where, $k = 4 t_{\mathrm{EMC}} t_{\mathrm{Cu}} E_{\mathrm{EMC}} E_{\mathrm{Cu}} (t_{\mathrm{EMC}} + t_{\mathrm{Cu}})^2 + (t_{\mathrm{EMC}}^2 E_{\mathrm{EMC}} - t_{\mathrm{Cu}}^2 E_{\mathrm{Cu}})^2$.



(3a) (3b)

Fig.3 A typical load-displacement curve (3a): ENF, (3b): 4PB.

A typical load-displacement curve of an ENF test is shown in Fig. 3a. At the early stages of applying load (Point A to B in Fig. 3a), a linear relation between force and displacement can be observed. The slope of the curve at this stage represents the bending stiffness of the composite Cu/EMC structure. The peak of the load profile corresponds to the critical force and the initiation of the interfacial delamination. This force was used later as the critical force in the finite element analysis. After reaching the peak load (Point B in Fig. 3a) the delamination propagates until it stops at a point (Point C). After the crack propagation stops at point C, the load increases again linearly.

Four-Point Bending (4PB) delamination tests [13] were also applied for the determination of the mixed-mode fracture toughness. Fig. 2b shows a schematic picture of a 4PB setup. The top layer of the EMC was carefully notched vertically with a diamond wafering blade. The notch depth was approximately 80% of the whole thickness of the EMC. The beams were placed in 4PB fixtures with adjustable inner and outer symmetrical loading pin positions.

The strain energy release rate of 4PB delamination tests exhibits steady-state characteristics when the interfacial crack reaches a minimum length and does not exceed the distance between the inner supports (2C). Applying beam theory and by assuming LEFM, the energy release rate for a 4PB test can be calculated as [13]:

$$G = \frac{M^2(1-\nu_{\mathrm{Cu}}^2)}{2E_{\mathrm{Cu}}}\left(\frac{1}{I_{\mathrm{Cu}}} - \frac{\lambda}{I_{\mathrm{c}}}\right),$$

where $\lambda = \frac{E_{\mathrm{Cu}}(1-\nu_{\mathrm{EMC}}^2)}{E_{\mathrm{EMC}}(1-\nu_{\mathrm{Cu}}^2)}$ and $M = PL/2b$.

I_{c} and I_{Cu} denote quantities which are proportional to the moments of inertia of the composite beam and of the Cu, respectively, and they can be calculated from

$$I_{\mathrm{c}} = \frac{t_{\mathrm{EMC}}^3}{12} + \frac{\lambda t_{\mathrm{Cu}}^3}{12} + \frac{\lambda t_{\mathrm{EMC}} t_{\mathrm{Cu}} (t_{\mathrm{EMC}} + t_{\mathrm{Cu}})^2}{4(t_{\mathrm{EMC}} + \lambda t_{\mathrm{Cu}})}, \text{ and } I_{\mathrm{Cu}} = \frac{t_{\mathrm{Cu}}^3}{12}.$$

Fig. 3b shows a typical curve of the 4PB fracture test. The slope of the linear part of the curve (point *A* to *B* in Fig. 3b) corresponds to the stiffness of the whole beam. The force at point B represents the required force for fracture in the upper bulk EMC through the notch. This force is primarily a function of the shape and length of the notch and does not provide any information about the interface. When a vertical crack originating from the end of the notch had formed, it moved very fast, reached the interface, and kinked into it (point *C*). Afterwards, the crack advanced along the interface (Point *C* to *D*). The constant force during crack propagation (P_{plateau}) represents the critical force required to propagate the crack.

3.3 Effect of Thermal Aging

In order to determine whether the exposure to different temperatures will result in any change in the adhesion between EMC and leadframe, samples were exposed to two different temperatures for the period of 2 weeks. Two aging temperatures of 85°C and 175°C were selected, as described in Section 2.

3.4 Effect of Moisture Diffusion

Moisture can influence the interfacial adhesion by three mechanisms. The first mechanism is the intrinsic aggregating effect of water molecules upon direct presence at the interfaces and degrading the interfacial adhesion by bonding to the polymer chains [7]. The second mechanism is that the absorbed moisture changes the mechanical properties of polymeric materials [8, 12]. For example moisture can change the elastic modulus and shift the glass transition temperature of polymers to lower values. This mechanism leads normally to a slight difference in the mode mixity of the measured fracture toughness of moist sample when compared to that of dry sample. The third mechanism is the swelling of polymeric materials upon exposure to moist environments and causing an additional mismatch between volumetric expansions of substrate and adhesives [5]. In order to measure the intrinsic fracture toughness of a moisture preconditioned sample, the influence of hygroscopic swelling which induces an apparent change in the measured fracture toughness should be isolated.

3.5 Effect of Elevated Test Temperatures

Delamination tests were performed at four temperatures: room temperature, 175°C, 210°C, and 250 °C. At each temperature, constant displacement rate tests were performed. For the test at room temperature the displacement rate was fixed at 0.1 mm/min, while at elevated temperatures higher rates were required to achieve interface delamination. This was due to high stress relaxation of the EMC at elevated temperatures when small rates were applied. For example at 210°C no delamination was observed by using the displacement rates of 0.1 mm/min and 1 mm/min. Consequently the displacement-rate of 10 mm/min was selected for tests at elevated temperatures. Linear elastic fracture mechanics was assumed in the analytical solution for the ENF. However, due to viscoelastic effect of the EMC at high temperatures, finite element analysis should be performed. The maximum force at which the delamination occurs can still be used as crack onset force. It must be noted that for testing at elevated temperature and at time scales where viscoelastic deformation may cause changes in fracture toughness, the use of linear elastic fracture mechanics is believed to be valid because the load-displacement curve will prove to be linear up to the point of delamination propagation [9]. In this case any significant viscoelastic deformation that may be occurring in a specimen is assumed to occur on a very local scale in the crack tip region as part of crack growth process. Other studies [10] show that the time of maximum loads matches exactly with the time of maximum energy release rate if viscoelastic material behavior is considered.

4. Results

Based on the fracture curves obtained from the ENF and 4PB tests, finite element analyses were carried out to determine the resultant interfacial fracture toughness. A 3D finite element model was built with eight-node elements using the FEM tool ANSYS. For the analysis of the ENF model, contact elements without friction were used to avoid element penetrations. The residual stresses during the manufacturing process of the samples were taken into account as follows: First the chemical cure shrinkage during the molding process was introduced in the FEA model. Then the cooling process from mold temperature (175°C) to room temperature (25°C) was taken into account. Finally the introduction of a precrack, which leads to some stress relaxations in the sample, was modeled by decoupling the selected nodes at the interface.

The Virtual Crack Closure Technique (VCCT) has successfully been used to obtain the total Strain Energy Release Rate (SERR) and the mode mixity for both homogenous and interface cracks [11] based on the results of finite element analysis. VCCT requires only one complete analysis of the structure to obtain the deformations. The method yields the total energy release rate in the direction in which the crack is extended virtually. A macro was written for the FEM tool ANSYS that allows to find all three components of the SERR.

Fig.4 shows the influence of mode angle on the interfacial fracture toughness. The scatter of results together with the average value of each test is also shown. The 4PB test measures the mixed mode interfacial fracture toughness with mode I fracture dominating. However, the ENF test measures the interfacial fracture toughness close to mode II fracture. It can be concluded that the interface strength with respect to shear loading is greater than its strength with respect to tensile loading. For the rest of this study, only the ENF test will be used in order to enable comparison between different aging conditions.

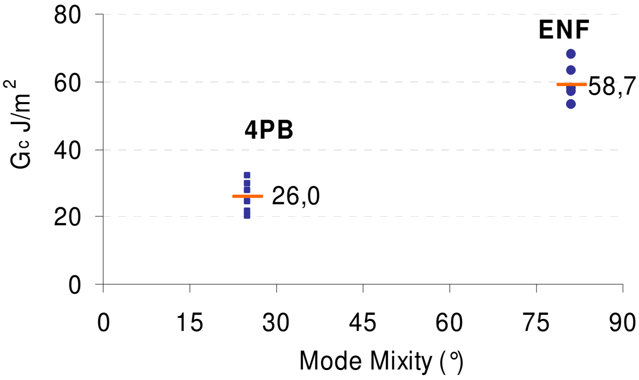


Fig.4 Effect of Mode angle on the interfacial fracture toughness of Cu/EMC.

Fig. 5 shows the influence of residual stresses on the interfacial fracture toughness for an ENF test (Dry sample at room temperature, P=31 N, a=10.9 mm). If only the mechanical load is considered, the total value of G found by VCCT (40.04 J/m^2) agrees very well with G from the analytical formula (39.97 J/m^2), which is the verification of the FEA-based VCCT approach. However, significant influence of the thermal stresses (arising from the CTE-mismatch between EMC and leadframe which induces a warpage because of higher leadframe shrinkage by cooling from mold temperature to room temperature) and chemical cure stresses (due to shrinkage of EMC during the crosslinking of the epoxy, which causes the shrinkage of EMC only) was observed, which suggests that using the analytical solutions or only consideration of the thermal stresses for the calculation of SERR can cause errors. Compressive stresses in general impede the crack propagation while tensile stresses facilitate it. Hence, any determination of energy release rate without considering these stresses should be avoided. Residual stresses contribute to the stored energy in the specimen. Therefore, for the rest of this work, sample history including both cure shrinkage and thermal stresses were considered.

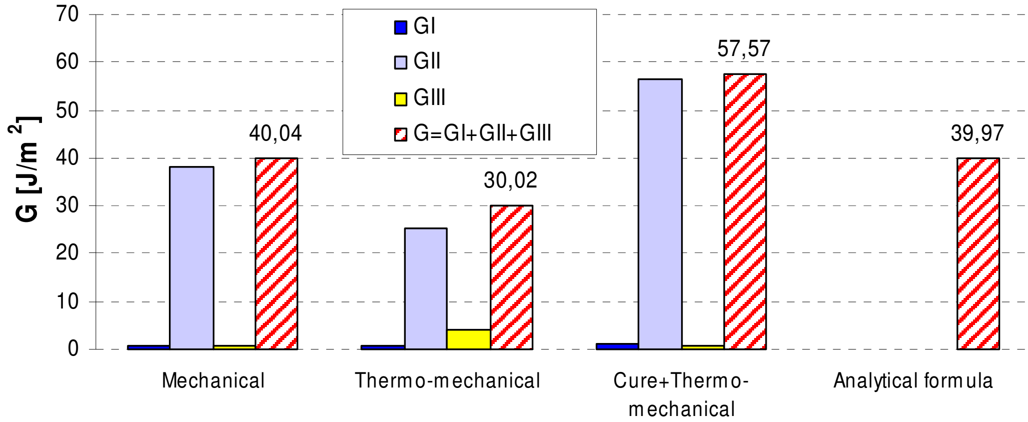


Fig.5 Effect of cure and thermal stresses on the energy release rate of an ENF test.

Fig. 6 shows the effect of aging in dry and moist environment on the adhesion. Test group 1 shows the interfacial fracture toughness at room temperature directly after manufacturing. While aging in dry condition at 85°C (test group 2) has no significant effect on the adhesion, aging at 175°C (test group 3), which is the apparent stress-free temperature of the beam, degrades the adhesion significantly.

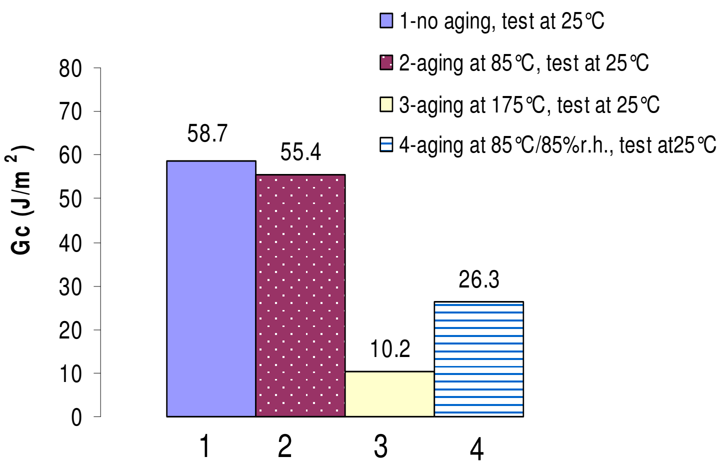


Fig.6 Effect of 2 weeks aging in dry and moist environment on the adhesion of Cu/EMC.

Fig. 7 shows the effect of drying after aging in humid environment on interfacial fracture toughness. Using the diffusion coefficient from the experimental results [2], the time to virtual saturation of the samples was found numerically to be almost two weeks (0.21 % weight gain of the whole sample). Results show that the interfacial fracture toughness initially being 58.7 J/m^2 in dry condition reduced to 26.3 J/m^2 when the virtual saturation level was achieved at interface.

In order to study the effect of an absorption/desorption cycle on the adhesion, moist samples were baked for 24 h at 125°C to reach a virtual dry state. A longer exposure to moisture was also investigated by 4 weeks aging in humid condition (0.25% weight gain of the sample) followed by baking at 125°C for 24 h. The fracture toughness of these samples was measured again at room temperatures. Some of adhesion loss due to moisture absorption up to virtual saturation was recovered after drying (44.9 J/m^2). However, samples that remained longer in humid conditions (4 weeks) showed almost no recoverability upon the same annealing condition (28.8 J/m^2). This is an important result, which shows the extreme degrading effect of long-term moisture absorption.
It must be noted that due to the significant reduction in the elastic modulus of the EMC at higher temperatures, the mode mixity in the test categories 6, 7, and 8 is different from other test categories. For other tests, the mode mixity remains almost constant, because, as shown in Section 2, the elastic modulus of EMC is almost independent of the moisture content.

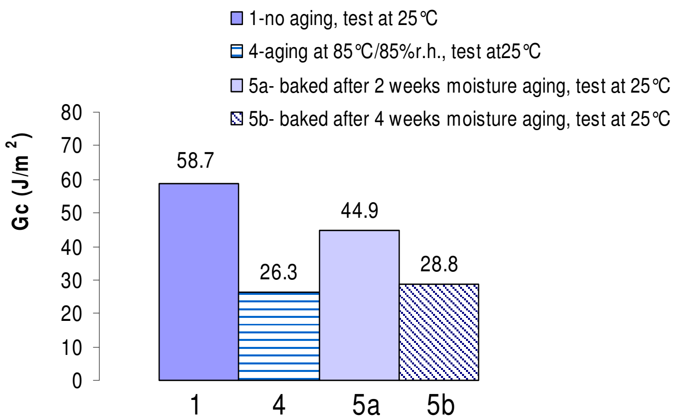


Fig.7 Adhesion recoverability of moist samples upon baking.

Fig. 8 shows the significant reduction of interfacial fracture toughness at elevated temperatures. The general trend is a reduction in fracture toughness at elevated temperatures. However, the fracture toughness data at elevated temperature showed that fracture is a complicated function of time and temperature as was observed in [10, 11].

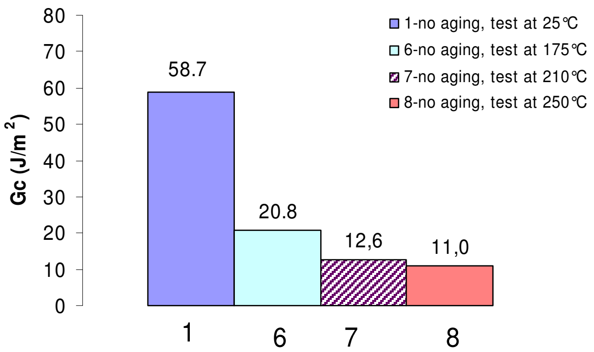


Fig. 8 Effect of elevated temperatures on the adhesion of Cu/EMC interface.

5. Conclusion

In this study we have demonstrated that the exposure of a Copper/EMC bimaterial interface to moisture prior to fracture results in degradation of adhesion. This degradation is the result of the diffusion of water in the interface. For samples that are aged not too long in a humid environment it is partially reversible by applying an appropriate heat treatment at mild annealing conditions. However, long-term aging in humid condition can cause permanent adhesion loss, which may be attributed to effect of hydrogen bonding between water molecules and polymer chains at the interface.

The thermal aging in dry condition showed also two different mechanisms. While aging at 85°C, at which the sample has a high warpage and undergoes large residual thermal stresses, had no remarkable influence on the measured fracture toughness, aging at 175°C had a significant degrading effect. Moreover, fracture tests at elevated temperatures revealed that at higher temperature, *e.g.*, during the solder reflow process, the interfacial adhesion significantly decreases.

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