Adhesion Copper/Molding Compound: Modeling and Characterization

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Abstract—**Delamination at the resin-copper interface is fully characterized during operative conditions by adopting a combined experimental and numerical approach. Peeling and four-point bending fracture tests are used along with cohesive zone models to reach this purpose. The promising findings are beneficial to analyze the crack propagation at the interface during package-oriented reliability tests, and may therefore be employed to enhance these interfaces in microelectronic plastic packages.**

Keywords— Interfacial fracture, electronic package, peeling, four-point-bending, cohesive zone modeling

I. INTRODUCTION

Electronic packages fulfil two important roles: to provide communication between the environment and the integrated circuits and to protect them from heat, corrosion, and mechanical damage [1]. The structural stability of a package is conferred by an epoxy molding compound (MC) encapsulation. MC is a composite material made of a polymeric cross-linked matrix and a very high ratio of silica filler [1]. In addition to mechanical stability, MC protects the die from any damage or contamination and provides a barrier to limit corrosion due to moisture absorption. On the other hand, the mismatch in the thermo-mechanical properties of the MC and the metallic lead frame may be responsible for a typical failure mechanism observed at the interface between the two materials, called decohesion. Therefore, a detailed thermo-mechanical assessment of the strength of this interface becomes crucial to identify the root cause for failure mechanism and improve package reliability. For this purpose, this work aims to address the study in three phases: macroscopic characterization of materials, MC analysis at the micro-scale, and investigation of interfacial delamination at the copper/MC interface. The latter phase is supported by experimental analysis as well as numerical modelling.

First, the macroscopic thermo-mechanical properties of copper and MC are identified by employing standard experimental methodologies. During this phase, digital image correlation (DIC) is employed as an auxiliary technique for the study of the heterogeneity of the MC. Due to the bi-component nature of the MC, a microscopic resin characterization is also necessary to understand if said heterogeneity can affect the adhesion with copper. Scratch tests are adopted for this purpose. The third step of this work provides an assessment of the copper/MC interfacial delamination rooted in fracture mechanics. The strength and toughness of the interface is quantitatively estimated through experiments, such as peeling and four-point bending (FPB)

tests, on dedicated copper/resin dual beam samples. Load versus displacement curves are collected during each experiment and for different configurations. The measured data serve as reference for the determination of the fracture energy at the interface. Then, finite element analysis (FEA) moves from this experimental estimation of fracture energy to find a set of model parameters able to reproduce the experimental curves. In this stage, the interface between copper and MC is modelled with traction-separation cohesive elements.

Once the interfacial delamination investigation has reached a sufficient maturity level, the validated methodology has the scope to endorse an approach able to optimize the accuracy and efficiency of both experimental characterization and numerical modeling.

II. MATERIALS AND SAMPLES

The interfacial adhesion between pure copper and two different MCs (A and B) is investigated. The choice of two MCs allows for a validation of the robustness of the method. Copper is provided as rolled sheets of two different thicknesses: 0.15mm and 0.25mm. It is cut in rectangular strips 10mm wide and 80mm long. MC samples are obtained through transfer molding process, in the shape of dumbbell specimens for characterization by uniaxial tensile tests. To test adhesion, a resin block is molded on copper strips to obtain a dual beam resin block 75mm long, 8mm wide, and 2mm thick.

III. EXPERIMENTAL METHODS

This section deals with the description of all experimental methodologies and procedures employed in the three phases of the study. For each phase, experimental techniques, test conditions, and post-processing analyses are fully detailed.

A. Macroscopic Material Characterization

The characterization of the tensile properties of the two MCs and copper is a fundamental step before moving on to study the MC/copper interface. MC dumbbell specimens are tested at room temperature, at a load rate of 1mm/min. During these tests DIC is also used to map the strain state of the whole sample to verify if there is an effect of the heterogeneous nature of the material on the deformation pattern. For this reason, samples are sprayed with silver paint as necessary preparation for DIC use. For copper characterization, rectangular strips of the two available thicknesses are tested at room temperature at a speed of 3mm/min, and strain measurement is performed using a video-extensometer.

B. Microscopic MC Characterization

A preliminary analysis on the heterogeneity of the MC is carried out to understand possible influences of the filler presence on the adhesion with copper. For this reason, in addition to the DIC test mentioned above, scratch tests are performed to measure the tip penetration and residual depth on the MC samples, to verify for possible correlation with the spatial distribution of filler into the MC itself. The scratch test leads to a controlled surface damage of the analyzed material. 3mm long scratches are applied on the MC surface at a speed of 5mm/min and a contact load of 10N. Data are analyzed to detect any periodicity which could be associated with the filler presence.

C. Interface Characterization

Two different types of tests are used for the characterization of the MC/copper interface. The dual beams with a copper thickness of 0.15mm are analyzed with a peeling configuration, while for the thicker ones a FPB test is chosen. The setup of these experiments are sketched in Fig. 1 and Fig. 2.

For what concerns the peeling tests, specimens are glued to a low friction roller and the copper strip is clamped to the movable part of the testing machine after a small preload is imposed to the system. Tests are performed at room temperature at a speed of 10mm/min. The same test is repeated for three different peeling angles: 45°, 90°, and 130°. Peeling of copper off the resin block occurs in a steady state way during the tests, with a nearly constant force measured during the analysis. Knowledge of the imposed angle, the peeling force, and the constitutive behavior of the peel arm material, it is possible to estimate the fracture energy of the interface [2,3,4,5,6,7,8]. The adhesion energy can then be computed by subtracting the contribution due to elastic/plastic deformation of the peel arms from the total energy input to the system [2,4].
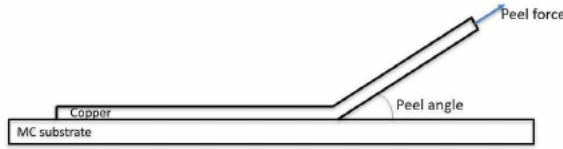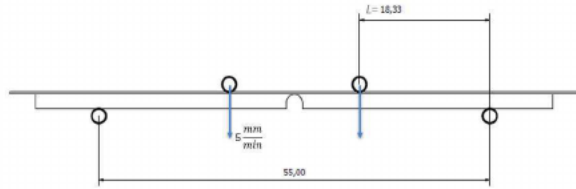

Fig. 1. Peeling test setup scheme.

Fig. 2. FPB test setup.

FPB bending test requires a notch realized in the middle of the MC block of the dual beam, introduced using a diamond saw. Resin is removed by the sawing process to leave approximately 0.3mm of MC material covering the copper surface. The chosen setup has a lower span of 55mm and an upper span of one third that distance. Pins used as loading points have a diameter of 6mm. Tests are carried out at room temperature at a speed of 5mm/min. Thanks to the notch realized in the middle of the MC block of the dual beam, twin cracks originate in the MC and then propagate to the MC/copper interface. Stable propagation occurs thanks to the constant bending moment applied in the region between the upper pins [9,10,11]. For this reason, the recorded force is also supposed to be constant, and its value can be related to the fracture energy G_c of the interface according to [9]:

$$G_c = \frac{(1-\nu_{Cu}^2)P^2L^2}{8E_{Cu}b^2}\left(\frac{1}{I_{Cu}} - \frac{\lambda}{I_c}\right) \tag{1}$$

where:

$$\lambda = \frac{E_{Cu}(1-\nu_{MC}^2)}{(1-\nu_{MC}^2)E_{MC}}, \tag{2}$$

$$I_c = \lambda I_{Cu} + \frac{t_{MC}^3}{12} + \frac{\lambda t_{Cu} t_{MC}(t_{Cu}+t_{MC})^2}{4(\lambda t_{Cu}+t_{MC})}, \tag{3}$$

and: ν_{Cu} and E_{Cu} are the copper Poisson ratio and Young's modulus, respectively; P is the measured force; L is the distance between the upper and lower pins; b is the width of the beam; I_{Cu} and I_c are the moments of inertia of the copper strip and the entire composite beam, respectively;; ν_{MC} and E_{MC} are the Poisson ratio and Young's modulus of MC, respectively; t_{MC} and t_{Cu} are the thicknesses of MC and copper. The specimens due to the different widths for the copper (b_{Cu}) and the MC (b_{MC}), so the following correction has been applied to the original formulation to account for the actual geometry:

$$G_c = \frac{(1-\nu_{Cu}^2)P^2L^2}{8E_{Cu}b_{MC}b_{Cu}}\left(\frac{1}{I_{Cu}} - \frac{\lambda\prime}{I_c}\right), \tag{4}$$

being:

$$\lambda\prime = \frac{E_{Cu}(1-\nu_{MC}^2)b_{Cu}}{(1-\nu_{MC}^2)E_{MC}b_{MC}}, \tag{5}$$

$$I_c = \lambda\prime I_{Cu} + \frac{t_{MC}^3}{12} + \frac{\lambda\prime t_{Cu} t_{MC}(t_{Cu}+t_{MC})^2}{4(\lambda\prime t_{Cu}+t_{MC})}. \tag{6}$$

IV. NUMERICAL MODELS

As mentioned before, the experimental analysis of this work is tightly connected to numerical modeling. FEA is employed for the investigation of delamination at the copper/MC interface. Numerical simulations of the performed experimental fracture tests (peeling and FPB) are run to validate the procedure and devise a prognostic procedure for this type of applications.

The cohesive zone model (CZM) is widely used for the numerical simulation of crack initiation and propagation in quasi-brittle materials [12]. In pure mode I, this fracture model requires two fundamental parameters: the interfacial strength $\sigma_{\max}$, and the fracture energy G_c. The displacement-based FEA framework also requires a (fictive) initial stiffness K at the interface to be introduced. According to CZM, the interface behaves elastically until the maximum stress reaches $\sigma_{\max}$. Afterwards, softening and damage ensue until the fracture energy G_c is dissipated [12]. In all the models described here, the interface is represented by a layer of cohesive elements between the two materials; the CZM law is applied as shown in Fig. 3, and delamination can therefore only occur there.
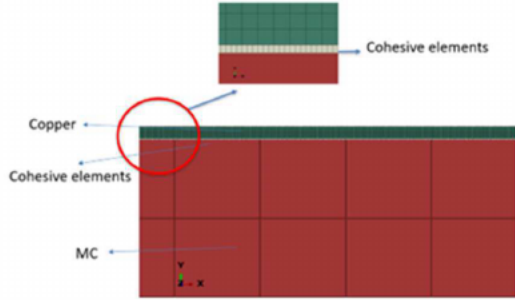
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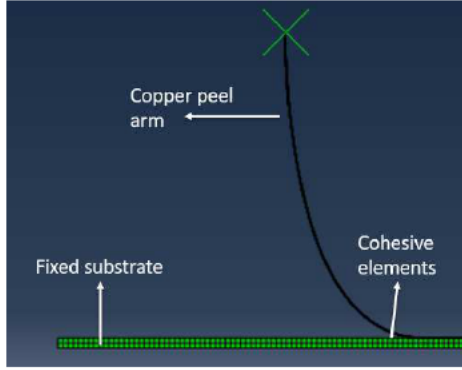Fig. 3. Representation of dual beam structure with the copper/MC interface described by cohesive elements.
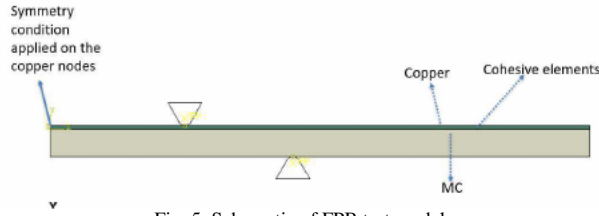

Fig. 4. Schematic of peeling test numerical model.

Fig. 5. Schematic of FPB test model.

A. Peeling Test

Due to the relatively large specimen width, 2D plane strain conditions are enforced to the simulation of the peeling test. The copper strip is modeled as an elastic-perfectly plastic material with a yielding stress of 337MPa and a Young's modulus of 124GPa. The MC substrate is instead assumed to be rigid, neglecting tensile strains across the thickness direction. Finally, a layer of cohesive elements is inserted between copper and MC, as depicted in Fig. 3. CZM parameters are identified directly from the experiments (G_c) or by searching for a good match with the experimental results (σ_{max}). During the investigation, the substrate is assumed fixed while the left end of the peel arm is displaced upwards in the peeling direction (see Fig. 4).

B. Four-Point Bending Test

FPB test is simulated in accordance with the former model assumptions. Further than that, the MC substrate is modeled as an elastic material. As per peeling test, a layer of cohesive elements is inserted between the two parts. To account for the symmetry conditions, only one half of the laminae is modeled [11], as depicted in Fig. 5.

V. RESULTS AND DISCUSSION

Having described the experimental techniques and the numerical modeling setup for all the phases of the present work, we next focus on the assessment of the findings coming out of the copper/MC adhesion investigation.

A. Macroscopic Material Characterization

The resulting stress-strain curve for the three materials tested are shown in Figs. 6 and 7. Copper displays an almost perfectly plastic behavior, with a yield stress of around 337MPa (Fig. 6). Fig. 7 depicts the mechanical behavior of the two MCs under uniaxial tensile test: results report similar Young's moduli for both A and B. The strain state on a MC A sample is depicted in Fig. 8, as obtained with the DIC: no strain concentration along the specimen is observed during the test. The longitudinal strain is plotted as a function of the length of the sample, along the path represented in Fig. 8, for different levels of average strain (0.002, 0.004, and 0.006). Results for both MCs show oscillations of the strain values which are not associated with the spatial periodicity of the filler.
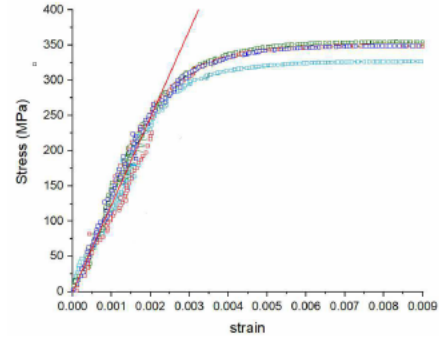

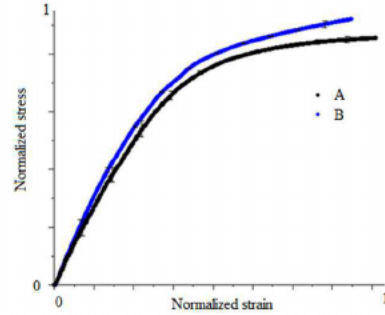Fig. 6. Copper stress-strain curves.

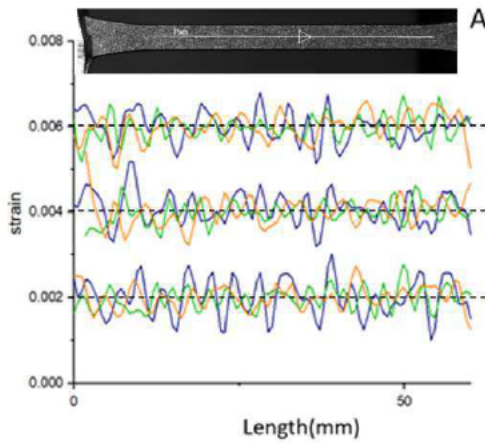Fig. 7. Normalized MCs stress-strain curves.

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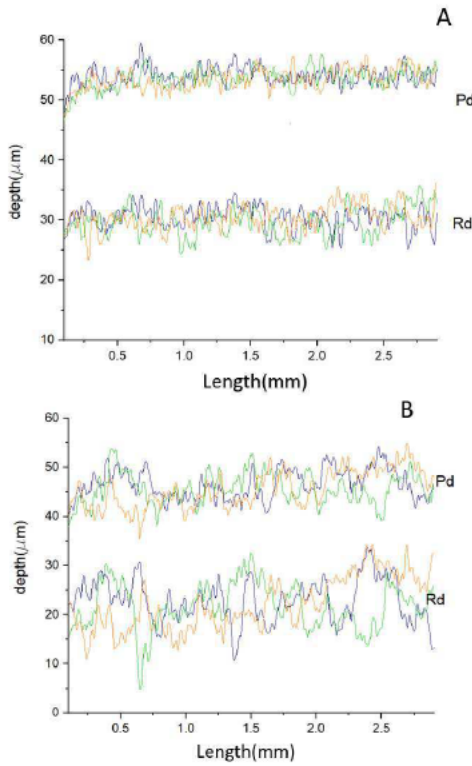Fig. 8. DIC results for MC A. Strain is plotted along path representing the length of the sample (57 mm).

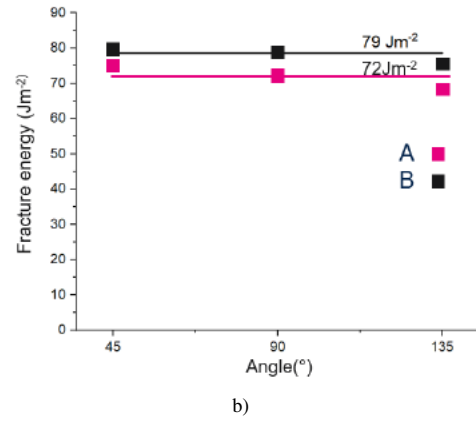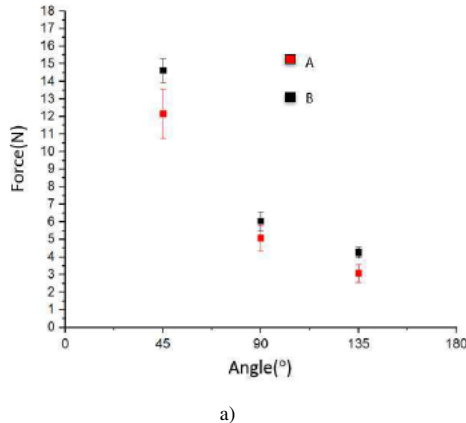Fig. 9. Penetration and residual depth along 3mm scratch for MC A and B.

a)

b)

Fig. 10. a) Peeling forces and b) corresponding computed fracture energies for the two MCs.

B. Microscopic MC Characterization

The results obtained with DIC didn't show any effect associated with the distribution of the MCs. A more comprehensive picture of the phenomenon can be provided by scratch tests, in which the following parameters are investigated: friction, penetration depth (Pd), residual depth (Rd), and acoustic emission. In fact, none of the above parameters show peaks at spatial frequencies associated with the filler dimensions. The results are represented in Fig. 9 for Pd and Rd along the scratch length on both MC A and B. Considering these findings, it is reasonable to assume that MC behaves as a homogeneous material for the purpose of its adhesion with copper at this scale. Other works which account for the presence of the filler into the polymer matrix could be helpful to understand the influence of filler particles on the MC/copper adhesion at the microscopic scale [13].

C. Copper/MC Interfacial Adhesion

Peeling and FPB tests on dedicated copper/resin dual beam samples are chosen as representative test cases.

As anticipated, peeling tests are carried out for three different angles. As shown in Fig. 10a the peeling force increases as the angle decreases for both the MCs investigated. Peeling angle is recorded during the test by employing a camera, to verify that its value remains constant during the test. The results are very similar for the two analyzed MCs, with a slightly higher value of peeling force for material B, for all the configurations. Combining peeling results with those of the copper tensile tests, the fracture energy of the copper/MC interface can be calculated. An open-source tool, called IC peel [14], is employed for this purpose. A bilinear function is selected to describe the almost perfectly plastic behavior of copper with a modulus of 124GPa and a yielding stress of 337MPa. The ratio between the stress-strain curve slopes before and after yielding for the bilinear function is 0.00337. To compute G_c, the width of the sample is considered as the one of the copper strips (10mm) so that the energy dissipated by the copper plastic bending, which is the most relevant contribution, is correctly computed. Given that the copper/MC interface has instead a 8mm width, the results obtained as G_c should be corrected by a factor of 1.25 equal to the ratio of the two widths. The same approach can be repeated for the estimation of G_c, which uses a 2D approximation of the specimen geometry. Fracture energy estimation is consistent among the different testing configurations and, as expected,

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the evaluated interfacial energy is almost angle independent. As for the peeling force, the values of fracture energy for the two materials A and B are very similar (see Fig. 10b).

For FPB tests the average measured forces and the fracture energies turn out to be again rather similar for both MCs investigated. The results are shown in Table 1, with the estimation of fracture energies obtained with (4).

TABLE I.   MEASURED FORCES BY FPB TESTS AND FRACTURE ENERGIES ESTIMATION.

MC	*Average F (N)*	G_c *(J/m²)*
A	4.95	70.69
B	4.90	69.27

Starting from the estimated experimental values, different simulations are run by varying the parameters of the cohesive zone law to match at best the experimental forces measured. Finally, a good match is found for the three peeling angles configurations with these parameters: $\sigma_{max} = 40$MPa, $G_c = 85$Jm^{-2}, and $K = 50000$MPa/mm for MC A; $\sigma_{max} = 40$MPa, $G_c = 95$Jm^{-2}, and $K = 50000$MPa/mm for MC B. Experimental peeling test results at 45° and 90° are very well matched with simulation results by employing the same set of values, while the 135° configuration shows forces slightly overestimated (Fig. 11). This trend is observed for both the investigated MCs and is repeatable meaning that best peeling angle configurations for G_c estimation are 45° and 90°.

FPB experiment is then simulated by employing a fracture energy of 70J/m^2, which is close to the one obtained analytically, and 90J/m^2, which is instead the one obtained as best estimate with the peeling numerical model. Given the 2D approximation of the numerical model, both the width of the MC beam (8mm) and the copper one (10mm) are considered to set the upper and lower limits of the simulated force. Results are presented in Fig.12. The procedure is repeated by employing the aforementioned values of the fracture energy of 70J/m^2 and 90J/m^2 (blue bars and red bars respectively in Fig.12). The value of the fracture energy tuned with the analytical solution seems to describe well the force trend obtained with the experimental results. Using instead the energy obtained with the peeling simulations, the results seem to slightly overestimate the experimental data if the 10mm thickness is considered, while they match them if the MC thickness is adopted in the analysis. Overall, the identified range of parameters offers a reasonably accurate description of the behaviour of the system under study, providing a very useful toolset to be implemented in more complex models of package delamination.

VI. CONCLUSION AND FUTURE DEVELOPMENTS

The main goal of this work has been the investigation of the interfacial adhesion between copper and MC, via materials characterization as well as numerical modeling. After a macroscopic experimental analysis of two MCs and copper, two delamination tests have been adopted to assess the properties of the interface between the two materials. Peeling and FPB tests prove to be efficient for the adhesion characterization with in-house produced samples and give results consistent with each other. Experimental tests are simulated to tune the CZM coefficients able to describe the response of the MC/copper interface. FPB and peeling tests give comparable results. The coefficients obtained by means

of numerical simulations are fully able to describe the experiments in different configurations.

Future developments of this research activity should be addressed to investigate the MC/copper interface under different conditions like temperature, thermal cycles, and fracture mode type. Finally, the obtained CZM coefficients can be used in a real package test case model to evaluate its ability to predict the failure mode in actual devices.
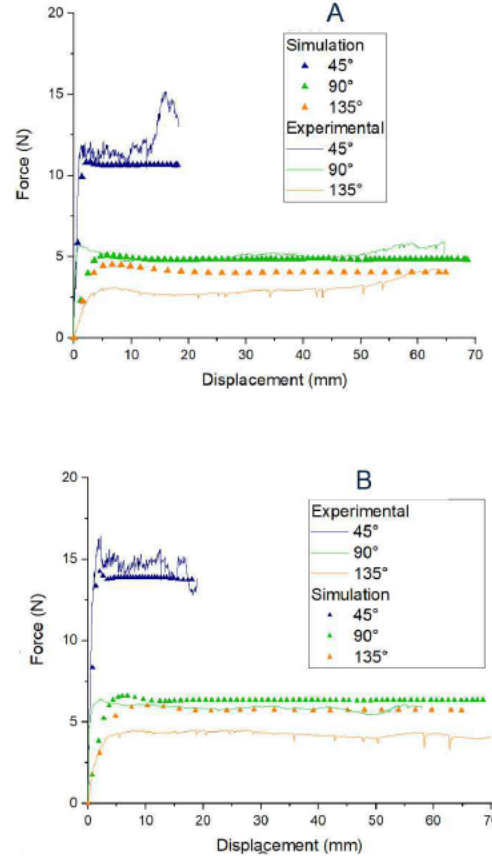

Fig. 11. Simulated versus experimental force-displacement curves for the peeling tests at different angles for MC A and B.
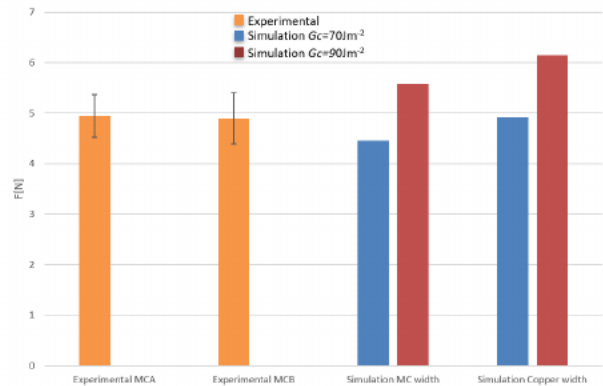

Fig. 12. Four-point bending tests: experimental data versus simulated results.

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