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Evaluation of the Elastic Mechanical Properties of a Hybrid Adhesive Material

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Abstract—Adhesive materials and adhesion have been the focal point of multiple research works related to numerous applications, particularly, aerospace, and aviation industries. To enhance the properties of conventional adhesive materials, additives have been introduced to the mix in order to enhance their mechanical and physical properties by creating a hybrid adhesive material. The evaluation of the mechanical properties of such hybrid adhesive materials is thus of an essential requirement for the purpose of properly modeling their behavior accurately. This paper presents an approach/tool to simulate the behavior such hybrid adhesives in a way that will allow researchers to better understand their behavior while in service.

***Keywords*—**Adhesive materials, analysis, hybrid adhesives, mechanical properties, simulation.

I. Introduction

HYBRID adhesives were introduced to modern industries as an answer to the challenges involved when using conventional adhesive materials. Issues such as strength, durability, ease of use, and conductivity are among many mechanical/physical properties that compose an important factor when selecting the right adhesive.

A popular example on hybrid adhesives is a carbon nanotube (CNT) filled adhesive joint. The strength of such joints is multi-folds higher than those bonded with a conventional epoxy resin. Multi-wall CNTs (MWCNTs) increase the toughness and strength of the epoxy resin, which increases the interface bond strength between two similar matching surfaces [1]. The addition of MWNTs in the epoxy matrix increases Young's modulus of MWNTs/epoxy nanocomposites 51.8% for a nanocomposite with 5 wt.% of MWNTs when compared with the epoxy specimen. Tensile strength of the MWNTs/epoxy nanocomposites increases 17.5% for 3 wt.% of MWNTs additive. For higher content of MWNTs considered, the increase of Young's modulus becomes slow, while the tensile strength decreases due to non-uniform dispersion for higher volume of MWNTs in epoxy [2]. Another aspect of property enhancement was durability. The essential improvement introduced by adding CNTs to the mix of the adhesive used to make up the joint is the enhanced durability which is essentially credited to the high mechanical properties of the CNTs themselves and to their ability not to absorb water [3].

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Another significant property of a hybrid adhesive is electrical conductivity which can be exploited for monitoring the different joints in a structure. The performance of CNTs filled conductive adhesive is comparable with solder joints in high frequency [4]; however, applying a high voltage was found to irreversibly decrease the resistivity of polymer composites filled with short carbon fibers [5] and it was found that the behavior at low voltage and above the percolation threshold follows an ohmic-type law at room temperature [6].

Micrometric silver flakes and nanometric CNTs exhibit high electrical conductivity. These properties, in addition to their mechanical properties, are measured at room temperature. It was reported that tiny clusters and free MWCNTs spread in the silver/epoxy composites increase the electrical conductivity and an interactive effect between MWCNTs and micro sized silver flakes is observed in a hybrid composite [7], isotropical conductive adhesives (ICAs) filled with Silver Coated CNTs (SCCNT) shows the lowest conductive resistivity of $2.2\times10^{-4}\ \Omega$ cm. ICAs filled with both CNT and SCCNT exhibit shear strength about (19.6 MPa) [8]. However, there is still a long way to go in terms of ICA advancement, the corresponding process development and infrastructure built, before ICAs become complete solder replacement [9]. Yet, from ICA evolution history and the current technological breakthroughs, it is certain that ICAs will be more widely utilized and will play an important role in the future electronics industry.

II. Theoretical Formulation

The work presented in this paper is based on a hybrid adhesive with components than can be separated by physical means, so the chemical compound of the basic material in the adhesives is not affected, actually if the hybrid adhesives are enlarged enough using microscope, different types of component can be extinguished from each other as shown in Fig. 1.

In general, the response of a typical adhesive material is usually dependent on temperature, strain history, and loading rate. Furthermore, it is noted that such adhesive materials have various segmental zones of mechanical behavior, referred to as `glassy,' `viscoelastic' and `rubbery.' These zones can be identified for a particular adhesive material by applying a sinusoidal variation of shear stress to the bulk form of the material and then measuring the resulting shear strain amplitude.

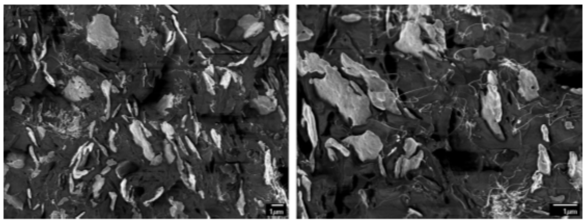

Fig. 1 EM images of cryo-fractured surface area of 0.4 vol.% DWCNTs/20 vol.% Ag hybrid composite [7]

Typically, hyper-elastic material models are constructed in a manner as follows:

1. Stress-strain relationships for the bulk material form is found by specifying its strain energy density "W" as a function of the deformation gradient tensor "W=W(F)". This warrants that the material is perfectly elastic, and thus that a scalar function is in place for the purpose of modelling the material. The general form of the strain energy density is set by the experimental work and the formula for strain energy density will contain material properties that can be adjusted to describe a particular material behavior (in the elastic range).
2. An isotropic behavior is assumed in the undeformed material. In the other words, the behavior of the material is independent of its initial orientation with respect to the direction of loading. If the strain energy density is a function of the Left Cauchy-Green deformation tensor "$B=F.F^T$", the constitutive equation is then automatically isotropic. When B is used a measure of deformation, then the strain energy must be a function of the invariants of B since the invariants of a tensor remain constant under a change of basis.
3. Formulae for stress in terms of strain are then developed by differentiating the strain energy density.

In this work, a model for powder material imbedded into the base material (adhesive) is presented. The model is formulated using finite element method (FEM).

The basic model of the material breaks down into small elements and each element will be given the characteristics of the base material, then a specific number of the elements will be chosen that will represent the additives added to the basic elements, the base material here is an elastic material, considered as a hyper-elastic material, and thus Yeoh's model which is also known the third order reduced polynomial form. The model describes isotropic incompressible rubber-like materials and depends only on the first strain invariant [10], [11]. In this work, it will be used for characterization of the elastic properties of the bulk adhesive material as given in (1).

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 + \frac{1}{d_1}(J - 1)^2 + \frac{1}{d_2}(J - 1)^4 + \frac{1}{d_3}(J - 1)^6 \quad (1)$$

where C_{10}, C_{20}, C_{30} and d_1, d_2, d_3 are material constants.

Yeoh's will be used in the simulation software to represent this material, while the additives are a rigid material which comply with Hook's law in the elastic region.

In this work, it is assumed that hybrid adhesives must have the additives distributed uniformly across the model so that they will not behave in the opposite manner of their main purpose (to avoid having the powder acting as stress constriction points in the model).

The assumption of uniform distribution was applied to the model with circle packing into a given domain, where all the radii of the circle were introduced as equal, each circle represents one element where the number of elements necessary are derived from the ratio used for the hybrid adhesive. Since the number of elements for additives is little, only the principle of circle packing of tangential to each other while keeping the maximum area is covered by circle. When using thin model, the formulation of the elements will have one row of elements in that direction, and using the densities of the base elements and additives alongside the weight ratio for formulation of the material. Based on all these parameters the volume ratio can be obtained, and for dividing it by the thickness, the surface ratio is obtained.

Assuming that all elements are equal in area of the surface, we multiply their number by the surface ratio to give the number of elements needed to represent the additives in the model. Using the circles, number of circles will have the same number of the elements needed for additives, and these circles will need to cover the area of the model as much as possible while having the same radius. If the number of the elements is small, it is best to reduce the number of the cuts in the model, since these circles must be tangential to these cuts as they represent the symmetry of the model.

III. Modelling and Analysis

The geometric model for simulation and analysis is based on ASTM, type IV, D638-03 test specimen [12] as shown in Fig. 2. Symmetry of the geometrical shape was not exploited during the analysis since the mechanical properties are not symmetrical across the test piece.

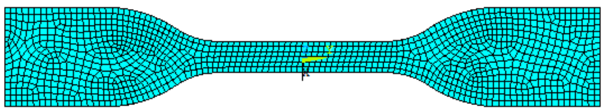

Fig. 2 Element formulation of the model

The model will have uniformly scattered elements that have the same properties as the additives, the method of distribution is shown in Figs. 3 and 4 for additives 2% and 4% weight ratio, respectively.

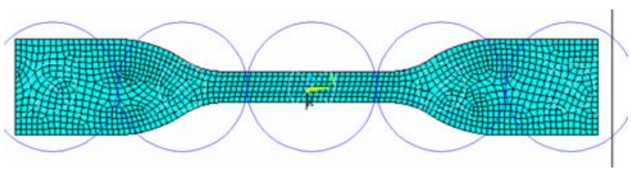

Fig. 3 Elements chosen to represent the additives in the model for 2% weight ratio

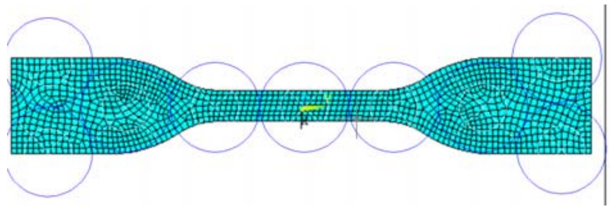

Fig. 4 Elements chosen to represent the additives in the model for 4% weight ratio

The number of elements was obtained after converting the weight ratio to volume ratio and multiplying the latter by the number of elements of the model. The distribution is based on covering the whole area of the model by circle with the same diameter circle then the details of the material properties of these particular elements to that of additives as in Figs. 5 and 6 for additives 2% and 4% weight ratio, respectively.

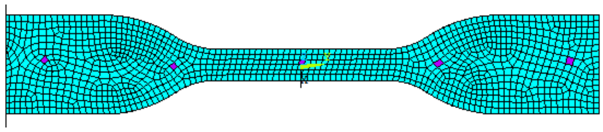

Fig. 5 Elements distribution in the model for 2% weight ratio

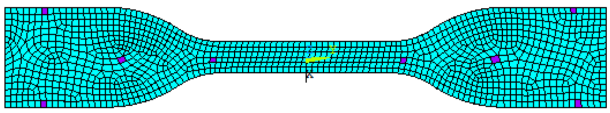

Fig. 6 Elements distribution in the model for 4% weight ratio

As for the boundary conditions, displacement conditions were applied. These boundaries were the same for all models as shown in Figs. 7 and 8.

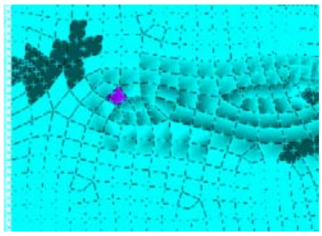

Fig. 7 Roller BC at the end of the model

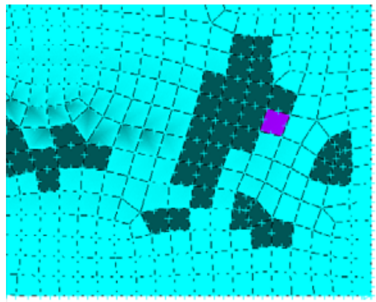

Fig. 8 Displacement BC at the other end of the model

IV. Results and Discussion

Parameters for the Yeoh's 3rd order energy equation were extracted from multiple experimental stress-strain curves from a tensile test. The analysis represents y-direction stress and displacement since the experimental data was acquired from a uniaxial test. Figs. 9 and 10 show the stress distribution for the new model of 2% that was introduced earlier and for the same model but with the base material taken from the experimental data obtained from the 2% mixture. As expected the stress around, the additives is higher because of the difference in element properties.

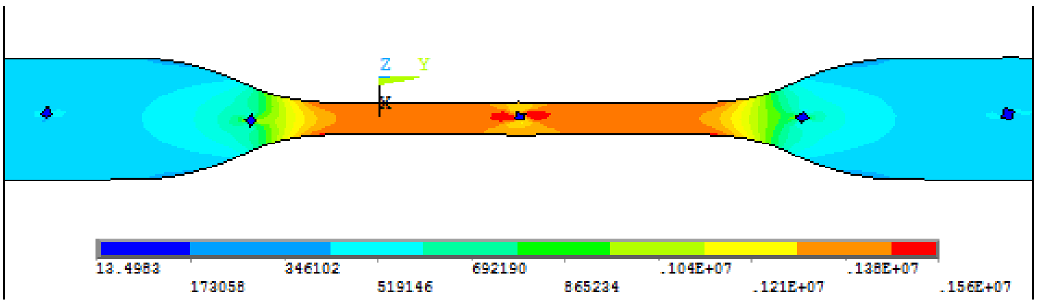

Fig. 9 Stress distribution in the model for 2% weight ratio

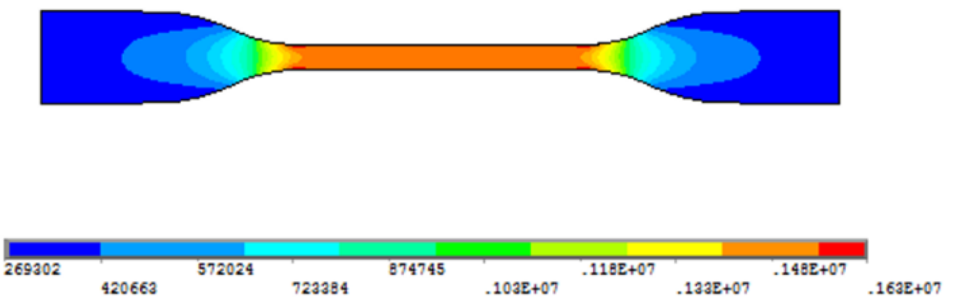

Fig. 10 Stress distribution in the model based on the experimental data input to the model as material properties

Furthermore, the elements highlighted in Fig. 11 were chosen to calculate the average stress and strain in the y-direction. Results are shown in Figs. 12 and 13.

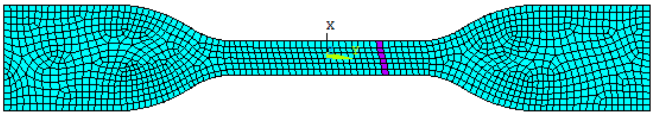

Fig. 11 Elements selected for the calculation of stress

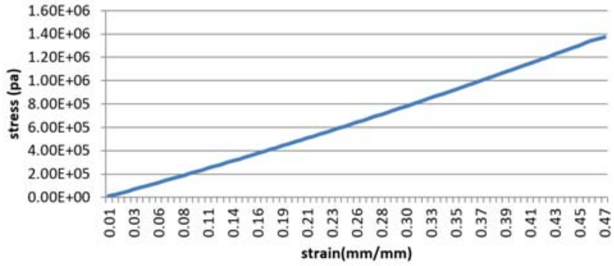

Fig. 12 Stress-strain diagram based on the proposed model

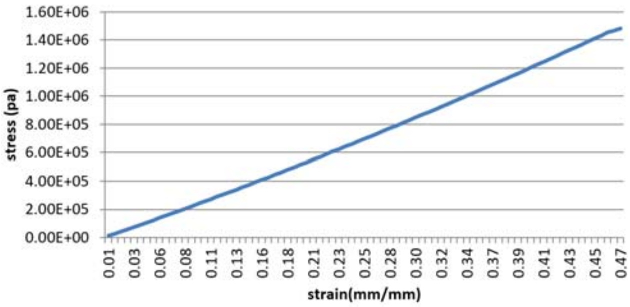

Fig. 13 Stress-strain diagram based on experimental data

Figs. 12 and 13 show a slight difference in the stress-strain results between the proposed model and the experimental data. The percent differences for stress and strain are 7.95% and 0.87%, respectively. The same analysis was repeated for the second model with 4% weight ratio and results between the analysis and experimental data were 11.64% and 1.69% for stress and strain, respectively.

V. Conclusion

The results suggest that the proposed model gives comparatively acceptable values for stresses and strains for a hybrid adhesive. Nevertheless, the model needs to be improved further by considering different distribution of the additive elements and reducing the thickness of additive part in order to find the best ratio of number of elements to each other (base elements and additive elements.

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