TAYLORING MATERIAL PROPERTIES IN COMPOSITE MATERIAL MANUFACTURING PROCESS

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Abstract: Tailoring mechanical, electrical or thermal properties of particle reinforced composite materials is the big issue in the composite manufacturing industries, due to the fact that has a major impact on the manufacturing costs reducing. Authors experience in the field of particle reinforced composite materials aid the choice of the best theoretical models, based on theoretical-experimental data correlations from previous research, to run a probabilistic simulation to retrieve the sensitivity factors influencing the overall previous mentioned material properties. These factors may help to size the major influencing constitutive properties on each applied property investigated.

Key-Words: elastic, thermal, electric, particle, composite, properties, sensitivity, analysis

1 Introduction
There is no doubt that particle reinforced composite materials are founding a wide spread use in aerospace or non-aerospace applications.

Particle reinforced composites emerged as viable alternatives to the classical materials due to their mechanical, electrical and thermal properties that can be tailored such as to fulfil a wide range or working conditions, from extreme temperatures to normal ones, in applications such as force/pressure sensors, electro-magnetic shields, toothed wheels, etc.

The characterization of these materials is fundamental to their reliable use. Technical literature provides numerous micromechanical models to predict the mechanical, electrical and thermal properties of particle reinforced composites [3]. These simplified expressions are based on mechanics of material approach and can account for few environmental factors such as moisture or temperature change. However, the effective composite properties exhibit scatters due to the uncertainties in constituent material properties, particles volume fraction and fabrication related parameters.

In such circumstances, there is a need for analytical tools that formally account for these influencing factors and quantify the overall composite behaviour.

The objective of the present work is illustrate the way in which can be tailored the composite’s material properties via tailoring its constitutive material properties using a sensitivity analysis developed by the aid of a Monte Carlo simulation. From these sensitivity factors, representing the sensitivity of that particular output variable (e.g. composite modulus, electrical conductivity, etc.) to the selected primitive random variables selected in each case can be tailored the overall properties by controlling the scatter in its output. Such information is very useful for design/test engineers in designing with that material or in interpreting the experimentally measured data and may help to reduce the manufacturing cost.

2 Micromechanical approach
The expressions derived for the elastic modulus, electrical conductivity and coefficient of thermal expansion in case of particle reinforced composite materials using a micromechanical approach are the one corresponding to the models from technical literature that prove to relate closely with the experimental data (see [1],[5]).
With respect to the elastic modulus of the composites the Hashin-Shtrikman bounds proved to be the best choice as a theoretical model, for which the expressions for the superior limits are as follow:

\[
K_{c}^{\text{sup}} = K_{p} + \frac{(K_{m} - K_{p})(3K_{p} + 4G_{p})(1 - V_{p})}{3k_{p} + 4G_{p} + 3(k_{m} - k_{p})V_{p}}
\]

(1)

for the effective bulk modulus,

\[
G_{c}^{\text{sup}} = G_{p} + \frac{5G_{p}(G_{m} - G_{p})(3K_{p} + 4G_{m})(1 - V_{p})}{5G_{p}(3k_{p} + 4G_{m}) + 6(G_{m} - G_{p})(k_{p} + 2G_{p})V_{p}}
\]

(2)

for the effective shear modulus respectively. The Young modulus of composite material, \(E_{c}\), follows easily by knowing the previous moduli. The primitive variables selected herein are: \(K_{p}\) particles’ bulk modulus, \(K_{m}\) matrix bulk modulus, \(G_{p}\) particles’ shear modulus, \(G_{m}\) matrix shear modulus, \(V_{p}\) particles’ volume fraction.

With respect to the electrical conductivity of the overall composite the best choice is again the Hashin-Shtrikman expression, the superior limit, as follow:

\[
\sigma_{c}^{\text{sup}} = \sigma_{m} V_{m} + \sigma_{p} V_{p} - \frac{V_{p} V_{m} (\sigma_{p} - \sigma_{m})^{2}}{\sigma_{m} V_{p} + \sigma_{p} V_{m} + \sigma_{p}}
\]

(3)

where the primitive variables selected are: \(\sigma_{m}\) electrical conductivity of the matrix material, \(\sigma_{p}\) electrical conductivity of the particles, \(V_{p}\) particles’ volume fraction (the matrix volume fraction can be estimated knowing the particles volume fraction).

With respect to the coefficient of thermal expansion (CTE) a simple series model satisfy all the experimental data, such as:

\[
\alpha_{c} = \alpha_{m} + (\alpha_{p} - \alpha_{m}) V_{p}
\]

(4)

where the primitive variables selected are: \(\alpha_{m}\) matrix coefficient of thermal expansion, \(\alpha_{p}\) particles’ coefficient of thermal expansion, \(V_{p}\) particles volume fraction.

### 3 Probabilistic simulation

The @RISK software from Palisade was used to run the Monte Carlo simulations. For each case the results were obtained running 5 000 iterations and 5 simulations. The selected values are sufficiently to obtain the best results, considering that fact that the aim is to size which is the most influencing intrinsic factor on the overall property analysed.

In section 2 along with the expressions for the overall material property were defined the individual input variables. These variables are uncorrelated and their probability distributions were set to be a normal one. Constituent properties, volume fraction, etc. are independent variables that in turn define a composite property, which was set as an output variable.

The simplified micromechanics expressions for the particle reinforced composite materials define the response function that related the composite properties to the input variables.

The particle reinforced composite considered was made up from Fe particles embedded with a 70% particle volume fraction into an epoxy matrix. The volume fraction selected was a compromise between the experimental and theoretical value of each selected property.

In figure 1 is being plotted the simulated values obtained for the elastic coefficients – longitudinal, shear and bulk ones, using the Hashin-Shtrikman theoretical model along with the experimental values retrieved using an ultrasonic NDT technique (frequencies of 1 MHz and 2 MHz).
In figure 2 and 3 are plotted the sensitivity factors retrieved for the elastic moduli of the particle reinforced composite – bulk and shear. In figure 4 is plotted the sensitivity factors for the effective electrical conductivity of the composite considered whereas in figure 4 the ones for the coefficient of the thermal expansion.

From the sensitivity factors in case of the overall bulk modulus of the composite it is clear that the property is most sensitive to particle bulk modulus, i.e. if one wishes to control the scatter in the composite modulus, the biggest payoff could be realized by controlling the scatter in the particle modulus.

With respect to the shear modulus naturally ones can expect to happen the same, but as it can be seen from figure 3 the effective shear modulus is most sensitive to the matrix modulus. With respect of the sensitivity coefficient plotted in figure 4, electrical conductivity of the polymeric particle reinforced composite material is mainly influenced once again by the matrix conductivity, followed by the electrical conductivity of the particles and their volume fraction.

In figure 5 are being plotted the sensitivity factors at the probability level of 0.5 for the thermal expansion coefficient of the particle reinforced composite analysed, revealing the fact that the CTE of particles is far the most sensitive variable, followed by the CTE of the matrix, particle volume fraction, etc.

4 Conclusion
The sensitivity information can be utilized for tailoring a desired property as mentioned previously, providing qualitative and quantitative information that can be used as a guide in testing or designing with this class of composite materials, particularly and generally, can be extended to any material combinations.

The purpose of this paper was to underline that probabilistic methods can be employed to improve the desired material properties by ranking the sensitivities and utilizing the resulting information as a guidance to appropriate quality control measures. The theoretical and experimental characterization aided sensitivity analysis is fundamental to their reliable use.

Sensitivities factors has to be obtained for each individual effective composite material property due to the fact that each constitutive has its particular influence.

The sign of the sensitivity factor indicates how a specific variable influences the performance function or the scatter in the response variable under consideration. As we obtained only positive values this indicates a decrease in performance with an increase in the mean value of the random value under concern.
References:


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