Acoustic properties of composites containing multiple heterogeneities: micromechanics modelling

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Abstract: The acoustic properties of composites containing multiple distinct heterogeneities (spheres, platelets, voids, straight and/or wavy fibres, etc.) are predicted by a micromechanics modelling using a modified Mori-Tanaka and self-consistent methods. The influences of reinforcement geometries, elastic material properties and distinct acoustic properties of each constituent on the effective composite acoustic properties are investigated for tungsten/epoxy, tungsten/EPO-TEK 301 and alumina/EPO-TEK 301 composites. The influence of voids of dry entrained air on the acoustic properties of cements paste materials is also investigated. The predicted composite acoustic properties obtained from the current model agree reasonably well with experimental results from the literature.

Keywords: micromechanics; acoustic property; multiple heterogeneities; composites; platelets; spheres; voids; agglomerates.


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1 Introduction

Polymer matrix composites (PMCs) are widely used in aero/automotive and electronics applications due to their desirable elastic properties, tailorability, and multi-functionality (Hussain et al., 2006; Jones, 1999; Nielsen and Landel, 1994). Recently, PMCs reinforced with particles have shown a significant enhancement in mechanical, thermal and acoustic properties, which expands their application. These composites are used in the field of ultrasonics due to their wide range of specific acoustic properties (Sugawara et al., 2005). For example, PMCs tend to attenuate sound waves more than other materials due to a decrease in cross-linkage or crystallinity in the structure (Grewe, 1990). In most cases, these composites are used as a layer or backing of transducers.

Different models and analytical formation have been proposed to estimate and predict the mechanical, thermal and acoustic properties of PMCs reinforced with particles (Leszczynski and Shukla, 2010; Liu and Brinson, 2008). Grewe et al. (1990) used the theoretical models, such as the Reuss, Voigt, and logarithmic models (Pelmore, 1979) to predict acoustic impedances in composite materials. Wang et al. (2001) experimentally measured acoustic properties of both alumina/EPO-TEK 301 and tungsten/EPO-TEK 301 composites and used the model developed by Devaney and Levine (1980) to compare their result. Maalej et al. (2010) investigated the influence of porosity on ultrasonic wave velocities of dry entrained air cement paste materials, and compared their measured acoustic data to micromechanical models such as the dilute inclusion, the Mori-Tanaka method (MTM), and self-consistent method (SCM). All models described, however, are based on two-phase composite system that contains only a matrix and reinforcements. Usually composite contains nano-scale or microscale defects and other entities such as voids, carbon clusters, and reinforcement agglomerates as shown by Yu et al. (2012a) in Figure 1. These defects on the composites can be developed either during fabrication or curing process. For example, an increase in the primary reinforcement volume fraction and/or aspect ratio can result in a significant increase in the liquid resin viscosity, resulting in an increase in the composite’s void content. Such flaws or poorly dispersed or agglomerated reinforcements can degrade composite elastic properties drastically (Yu et al., 2011, 2012a, 2012b) which can affect composite acoustic properties. In addition, the interphase property and volume fraction between a matrix and reinforcement play a crucial role in determining bulk composite properties (Yu et al., 2011, 2012a, 2012b). Thus, in order to estimate the acoustic properties more accurately, a multi-phase analytical and numerical material model that accounts for voids and other defects in a matrix is required.

In the present study, the effective continuum micromechanics analysis code (EC-MAC) was developed to estimate acoustic properties of composites containing multiple heterogeneities (spheres, platelets, voids, etc.), using the modified Mori-Tanaka or self-consistent micromechanical models. Agglomeration of reinforcements can be approximated as void-like structures of another material phase in our micromechanical models, which is a reasonable assumption since there is often a very poor reinforcement wetting inside of the agglomerates. Particular/polymer composite made of tungsten/epoxy, tungsten/EPO-TEK 301, and alumina/EPO-TEK 301 has been investigated and the influence of reinforcement material properties and distinct acoustic properties is addressed. The effect of voids in the elastic and acoustic properties of composites has also been investigated.
2 Basic of elastic wave propagation in bulk materials

The properties of elastic waves that propagate in heterogeneous materials are directly related to their elastic parameters. If the medium is isotropic (the material has the same mechanical properties in all directions), the attenuation which characterises scattering issue is independent of propagation direction. For isotropic materials, it is assumed that the microstructures are small compared to the wavelength, the wave equation can be given as (Kolsky, 1953; Graff, 1975).

\[
\frac{\rho}{\partial t} \frac{\partial^2 u_i}{\partial t^2} = \mu \frac{\partial^2 u_i}{\partial x_k^2} + \left( K + \frac{3}{4} \mu \right) \frac{\partial^2 u_i}{\partial x_k \partial x_l} \tag{1}
\]

where \( \rho \) is the density, \( u_i \) are the components of the displacement vectors, \( K \) is the bulk modulus, and \( \mu \) is the shear modulus of the material.
The longitudinal wave speed ($V_L$) that are propagating through an unbounded isotropic medium can be related to the material property as given by equation (2). For heterogenous materials, the average longitudinal wave velocities can be expressed as

$$V_L = \sqrt{\frac{K + (4/3)\mu}{\rho_c}}$$

where $\rho_c$ is the average composite density given by

$$\rho_c = c_0 \rho_0 + c_k \rho_k$$

where $c_0$ is a matrix volume fraction, $\rho_0$ is a matrix density, $c_k$ are the volume fractions of heterogeneities ($k = 1, 2, \ldots, m$), and $\rho_k$ are the densities of heterogeneities ($k = 1, 2, \ldots, m$).

The acoustic impedance of a material determines the transmission and reflection of waves in a material and hence assesses the absorption of sound energy in the material. It is an important material property for equipment like ultrasonic transducers, where measuring the ultrasound energy being transmitted into the medium is important. The characteristic impedance, $Z_L$, of a material can be calculated from the product of longitudinal velocity and density as given by equation (4)

$$Z_L = \rho V_L$$

where $\rho$ is the density of the material and $V_L$ is the wave velocities in the longitudinal direction. In this study the longitudinal wave velocity and the corresponding density calculated above is used to determine the characteristic impedance.

### 3 Estimation of an effective material property using mean field micromechanical approaches

A number of mean field micromechanics approaches, such as the MTM (Mori and Tanaka, 1973; Benveniste, 1987), the SCM (Hill, 1965), and various coated inclusion techniques (Mura, 1987; Nemat-Nasser and Hori, 1993) have been developed to predict the effective heterogeneous material properties, particularly for composites containing low volume fractions of reinforcements in an elastic matrix. These approaches are based on the classic Eshelby (1957) solution that gives stress and strain fields for an infinite domain with an ellipsoidal inclusion and subjected to uniform far-field loading.

These homogenisation methods can only take into account a single heterogeneity (i.e., single type of reinforcement in a matrix) without the effect of interphase between reinforcement and matrix. These two-phase composite models do not show a matrix-inclusion micro-topology at some or all of the volume fractions of interest. In real composites, where unexpected constituents such as voids, carbon clusters, and agglomeration are created during material processing, and different thicknesses and material properties of interphase region are developed, the two phase material mode cannot be used. This is crucial in determining the effective acoustic properties of composites accurately specially when the difference in volume fraction and material properties between each constituent’s is large. In such cases, modifying the micromechanics model and account multiple heterogeneity is essential.
Recently, Yu et al. (2011) developed a modified MTM and SCM models for predicting effective elastic properties of nano-composites containing hollow wavy nano-fibres surrounded by an arbitrary number of coating layers. Now, these micromechanical models are extended and modified to estimate the acoustic properties of composites containing multiple heterogeneities with arbitrary shapes and orientations using an approach first developed by Nemat-Nasser and Hori (1993). The EC-MAC was developed using MATLAB for predicting:

a. effective elastic properties
b. acoustic properties for composites containing multiple heterogeneities,

each with an arbitrary number of coating layers based upon modified versions of the MTM and SCM.

The acoustic properties were calculated using the homogeneous composite property obtained from these micromechanical models. A detail discussion of the basic features, capabilities, and computational procedures associated the modified method can be obtained in the paper by Yu et al. (2011), and briefly discussed below.

3.1 Modified MTM for composites containing multiple heterogeneities

The MTM assumes that a single ellipsoidal heterogeneity is embedded within a homogeneous matrix domain, whose strain field has been perturbed by other heterogeneities in the system. The MTM uses the continuum-averaged stress and strain fields to predict effective material properties for composites containing arbitrary ellipsoidal heterogeneities (Mori and Tanaka, 1973; Benveniste, 1987; Mura, 1987; Nemat-Nasser and Hori, 1993). For a composite with matrix phase (0) and heterogeneity phase (1), the effective fourth order elastic stiffness tensor, $C^e$, can be expressed (Nemat-Nasser and Hori, 1993) as

$$C^e = \frac{1}{1 - c_1} \left( L(0)I : (A(1) - S(1): I) : \left(A(1) - S(1): I\right)^{-1} \right)$$

where

$$A(1) = \left( L(0) - L(1) \right)^{-1} : L(0)$$

$A(1)$ is the local strain concentration tensor for the heterogeneity. $L(0)$ and $L(1)$ are the fourth rank elastic stiffness tensors for the matrix and heterogeneity, $c_1$ is the heterogeneity volume fraction, $S(1)$ is the fourth rank Eshelby tensor for the heterogeneity, and $I$ is the fourth rank identity tensor. Here a colon `:` is used to denote the tensor double dot product. The Eshelby tensor ($S(1)$) accounts for the influence of the aspect ratio/geometry of the heterogeneity on the local strain field. Eshelby tensors for specific reinforcement shapes (spheres, platelets, fibres, etc.) are readily available in the literature (Mura, 1987; Nemat-Nasser and Hori, 1993). The fourth rank effective compliance tensor, $C^e$, can be determined by inverting the effective stiffness tensor given by equation (5). After performing requisite orientation averaging to account for the effect of two- and three-dimensional randomly oriented heterogeneities on the calculated effective properties (Mura, 1987; Nemat-Nasser and Hori, 1993), the effective compliance tensor can be expressed as a $6 \times 6$ matrix using Voigt notation. For composites containing
parallel platelets, the effective composite moduli in the longitudinal ($E_L$) and transverse ($E_T$) directions can be expressed as equations (7) and (8)

$$E_L = \frac{1}{\tilde{M}_{11}} = \frac{1}{\tilde{M}_{22}},$$

$$E_T = \frac{1}{\tilde{M}_{33}},$$

where $\tilde{M}_{11}$, $\tilde{M}_{22}$, and $\tilde{M}_{33}$ are components of the effective compliance tensor. Similar expressions can be used to define effective elastic moduli for composites containing aligned or two- and three-dimensional randomly oriented heterogeneities of arbitrary shape (fibres, ellipsoids, etc.).

Figure 2  Schematic of a composite containing five ($m = 5$) distinct types of heterogeneities ($k = 1, 2, \ldots, 5$) each with a single coating layer ($n_k = 2$) (see online version for colours)

Source:  Yu et al. (2012a)

This approach is extended to the case for composites containing multiple distinct heterogeneities, such as the matrix contains $m$ distinct types of ellipsoidal heterogeneities ($k = 1, 2, \ldots, m$) and each consisting of $n_k$ layers ($\alpha_k = 1, 2, \ldots, n_k$; $k = 1, 2, \ldots, m$). For example, Figure 2 shows a composite containing five ($m = 5$) distinct types of heterogeneities ($k = 1, 2, \ldots, 5$) each with a single coating layer ($n_k = 2$, defines the total number of layers for the $k^{th}$ heterogeneity, i.e., particle plus one coating layer). Each type of heterogeneity has distinct elastic properties, shape, and orientation distribution. Based on a composite containing $m$ distinct types of heterogeneities ($k = 1, 2, \ldots, m$) and each are having an arbitrary number of layers ($n_k$) in a matrix (0), the overall elasticity tensor, $\tilde{L}$, can be expressed (Nemat-Nasser and Hori, 1993) as

$$\tilde{L} = L^{(0)} + \left\{ I + \sum_{k=1}^{m} \sum_{\alpha_k=1}^{n_k} \frac{c_{(k)\alpha_k}}{E_L} \left( S_{(k)} - I \right) \left( A_{(k)}^{(\alpha_k)} - S_{(k)} \right)^{-1} \right\}^{-1} + \left\{ I + \sum_{k=1}^{m} \sum_{\alpha_k=1}^{n_k} \frac{c_{(k)\alpha_k}}{E_T} S_{(k)} \left( A_{(k)}^{(\alpha_k)} - S_{(k)} \right)^{-1} \right\}^{-1}.$$  

(9)
Acoustic properties of composites containing multiple heterogeneities

where

\[ A_{(\alpha k)}^{(\alpha)} = \left( L^{(\alpha)} - L_{(\alpha k)}^{(\alpha)} \right)^{-1} : L^{(\alpha)} \]  \hspace{1cm} (10)

\( A_{(\alpha k)}^{(\alpha)} \) is the local strain concentration tensor for the \( \alpha_k \)th layer of the \( k \)th heterogeneity \( (\alpha_k = 1, 2, \ldots, n_k, k = 1, 2, \ldots, m) \). Here \( L_{(\alpha k)}^{(\alpha)} \) is the fourth rank elastic stiffness tensor for the \( \alpha_k \)th layer of the \( k \)th heterogeneity, \( c_{(\alpha k)\alpha} \) is the volume fraction of the \( \alpha_k \)th layer of the \( k \)th heterogeneity, and \( S(k) \) is the fourth rank Eshelby tensor, which is common to the heterogeneity and all layers of the \( k \)th heterogeneity. Once the overall elasticity tensor, \( \bar{L} \), is determined for composites containing aligned or randomly oriented heterogeneities, the relevant elastic moduli can be determined using relationships similar to equation (7) and equation (9).

3.2 Modified SCM for composites containing multiple heterogeneities

The SCM assumes that a single ellipsoidal heterogeneity is embedded within a homogeneous matrix with an unknown effective stiffness tensor, \( \bar{L} \) (Hill, 1965; Mura, 1987; Nemat-Nasser and Hori, 1993). For a composite with a matrix phase (0) and heterogeneity phase (1), the effective fourth rank elastic stiffness tensor can be determined iteratively (Mura, 1987) from

\[ \bar{L} = \bar{L} : \left\{ I + c_1 \left( S^{(1)} - I \right) : \left( \bar{A}^{(1)} - S^{(1)} \right)^{-1} \right\} : \left\{ I + c_2 S^{(0)} : \left( \bar{A}^{(0)} - S^{(0)} \right)^{-1} \right\}^{-1} \]  \hspace{1cm} (11)

where

\[ \bar{A}^{(1)} = \bar{L} - L^{(1)} \]  \hspace{1cm} (12)

Here, \( \bar{A}^{(1)} \) is the strain concentration tensor for the heterogeneity (1) based on the effective composite properties. The effective stiffness tensor given by equation (11) can be determined in an iterative fashion. The fourth rank effective compliance tensor, \( \bar{M} \), can be determined by inverting the effective stiffness tensor given by equation (11), and the effective elastic moduli of composites containing parallel platelets for the longitudinal \( (E_L) \) and transverse \( (E_T) \) directions can be determined using similar procedure used in MTM.

The SCM is also extended to the case for composites containing multiple distinct heterogeneities. Suppose that the effective homogeneous medium with elastic stiffness tensor, \( \bar{L} \), contains \( m \) distinct types of ellipsoidal heterogeneities \( (k = 1, 2, \ldots, m) \) each consisting of \( n_k \) layers \( (\alpha_k = 1, 2, \ldots, n_k) \) in a matrix (0). Then the overall elasticity tensor, \( \bar{L} \), can be determined (Mura, 1987) from

\[ \bar{L} = \bar{L} : \left\{ I + \sum_{k=1}^{m} \left[ \sum_{\alpha_k=1}^{n_k} c_{(k\alpha)\alpha} \left( S_{(k\alpha)} - I \right) : \left( A_{(k\alpha)}^{(\alpha)} - S_{(k\alpha)} \right)^{-1} \right] \right\} : \left\{ I + \sum_{k=1}^{m} \left[ \sum_{\alpha_k=1}^{n_k} c_{(k\alpha)\alpha} S_{(k\alpha)} : \left( A_{(k\alpha)}^{(\alpha)} - S_{(k\alpha)} \right)^{-1} \right] \right\}^{-1} \]  \hspace{1cm} (13)
where

\[
A_{(\alpha_k)} = \left( L - I_{(\alpha_k)}^{(\alpha_k)} \right)^{-1} : L
\]

\(A_{(\alpha_k)}^{(\alpha_k)}\) is the global strain concentration tensor for the \(\alpha_k\)th layer of the \(k\)th heterogeneity \((\alpha_k = 1, 2, \ldots, n_k, k = 1, 2, \ldots, m)\).

For arbitrary distributions of reinforcements, the symmetric fourth rank stiffness tensors calculated using equations (5), (9), (11), and (13) will be generally anisotropic. For the case of aligned, two-dimensional randomly oriented and three-dimensional randomly oriented heterogeneities the calculated elasticity tensor will display orthotropic, transversely isotropic, and isotropic material symmetries, respectively. In such case the longitudinal, in-plane and transverse moduli can be calculated. However, in the present study, spherical shape particles are mainly considered and hence the elastic property will remain same in all direction.

4 Effective elastic moduli and acoustic properties for composites containing multiple heterogeneities

In this study, mean field approaches have been used to investigate the effect of multi-phases material inhomogeneity on bulk composite properties and acoustic properties. In order to estimate the composite elastic and acoustic properties accurately, detail information of each constituent is required. Particularly, voids or defects in polymer composites reinforced with nano-, or micro-scale fillers can be investigated using scanning electron microscopy (SEM) or transmission electron microscopy (TEM). The material properties, such as stiffness and strength of the interface layer can be obtained using atomic force microscopy (AFM). The interface thickness, number of layers and properties of each layer can also be determined using molecular dynamics (MD) simulation. In this study, material properties of each constituent of different particle/polymer composites obtained from the literature are used as numerical examples.

Table 1 contains a summary of relevant mechanical properties of materials used in the calculation. The effective elastic moduli for composites containing alumina, tungsten and voids obtained from the current model are shown in Figure 3. This effective modulus along with the effective density is used to calculate the longitudinal wave velocity and characteristic impedance. In all calculations, the composites’ acoustic properties in the longitudinal \(V_L\) direction were normalised by their respective matrix acoustic property, \(V_{mm}\), in order to clearly illustrate the effect of the heterogeneities. As shown in Figure 3, the results obtained from MTM and SCM are very close, within the range of 4% difference, and hence for the rest of the paper the result obtained from MTM is presented.
Table 1  Selective material properties and geometries of different reinforcements and matrixes

<table>
<thead>
<tr>
<th>Reinforcement/matrix</th>
<th>Reinforcement dimensions</th>
<th>Young’s modulus (GPa)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten powder/Epoxy</td>
<td>$D_t = N/A$</td>
<td>$E_t = 413.0$</td>
<td>$\rho_t = 19,300.0$ (Sugawara et al., 2005)</td>
</tr>
<tr>
<td>Epoxy</td>
<td></td>
<td>$E_m = 4.6$</td>
<td>$\rho_m = 1,150.0$ (Sugawara et al., 2005)</td>
</tr>
<tr>
<td>Alumina powder/EPO-TEK 301</td>
<td>$D_a = 3 \mu m$ (Wang et al., 2001)</td>
<td>$E_a = 300.0$</td>
<td>$\rho_a = 3,690.0$ (Wang et al., 2001)</td>
</tr>
<tr>
<td>EPO-TEK 301</td>
<td></td>
<td>$E_m = 5.8$</td>
<td>$\rho_m = 1,150.0$ (Wang et al., 2001)</td>
</tr>
<tr>
<td>Tungsten powder/EPO-TEK 301</td>
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</tr>
<tr>
<td>EPO-TEK 301</td>
<td></td>
<td>$E_m = 5.8$</td>
<td>$\rho_m = 1,150.0$ (Wang et al., 2001)</td>
</tr>
<tr>
<td>Void</td>
<td>$D_v = \text{various}$ (Maalej et al., 2010)</td>
<td>$E_v = 0$</td>
<td>$\rho_v = 0.0$ (assumed value)</td>
</tr>
<tr>
<td>Cement</td>
<td></td>
<td>$E_m = 22.8$</td>
<td>$\rho_m = 1,770.7$ (Maalej et al., 2010)</td>
</tr>
</tbody>
</table>

Figure 3  Normalised elastic moduli for (a) tungsten/epoxy composites (b) tungsten/EPO-TEK 301 composites (c) alumina/EPO-TEK 301 composites and (d) cement paste materials with porosity
Figure 3 Normalised elastic moduli for (a) tungsten/epoxy composites (b) tungsten/EPO-TEK 301 composites (c) alumina/EPO-TEK 301 composites and (d) cement paste materials with porosity (continued)

4.1 Acoustic properties of composites containing particles

EC-MAC was used to estimate the acoustic properties of particle/polymer composites comprised of different particles and matrices. The two main acoustic properties, longitudinal wave velocity and acoustic impedance, are investigated as a function of particle content.

4.1.1 Longitudinal wave velocity

Figure 4 shows a plot of normalised longitudinal wave velocity \( (V_L / V_m) \) for tungsten/epoxy composites as a function of tungsten particle volume fraction, comparing the predicted obtained using the current MTM module, and experimentally measured values by Sugawara et al. (2005). While there was a fair degree of scatter in the experimental results, the modified MTM micromechanical solutions agree reasonably well with the mean experimental values over wide range of volume fractions. The longitudinal wave velocity decreases with an increase in tungsten volume fraction. This seems a surprising result as the elastic modulus of tungsten is higher than that of the matrix. However, even though the elastic modulus of the composites increases with an
increase in tungsten content, the high density of tungsten particles results in the reduction of longitudinal wave velocity with increase in the tungsten content.

Figure 4  Normalised longitudinal wave velocity ($V_L / V_m$) for tungsten/epoxy composites

Similarly, the acoustic properties of particle/polymer composites comprised of tungsten particles in an EPO-TEK 301 matrix are investigated. In this calculation, a well dispersed 5 μm particle size tungsten powder was considered in an EPO-TEK 301 matrix. Figure 5 shows a plot of normalised longitudinal wave velocity ($V_L / V_m$) as a function of tungsten volume fraction. Similarly to tungsten/epoxy, for tungsten/EPO-TEK 301 matrix composites, the longitudinal wave velocity non-linearly decreases with an increase in volume fraction of tungsten particles. A 40% reduction in the acoustic longitudinal wave velocity is observed for composites containing 25% volume of tungsten particles (sphere shape) in an EPO-TEK 301 matrix. The longitudinal wave velocities for composites containing prolate (fibre shape) and platelet (penny shape) are also shown in the figure for comparison. The predicted acoustic properties obtained from the MTM model is slightly lower compared with those obtained from the experiment (Wang et al., 2001). The disparity between the predicted and measured acoustic properties is likely due to the reality of composite’s defects such as combination of void content or other heterogeneities which were not known to use in the model.

Figure 5  Normalised longitudinal wave velocity ($V_L / V_m$) for tungsten/ EPO-TEK 301 composites
As shown above, due to similarity in their elastic and physical properties, the variation in the matrix does not change the acoustic properties of polymer composites with tungsten particles. To understand the effect of particles in the acoustic properties of polymer composites, different type of particle was considered. Acoustic properties of composites comprised of alumina particles in an EPO-TEK 301 matrix were obtained using the same procedure discussed above. In our numerical model, an alumina powder with a 3 $\mu$m particle size was considered. On the other hand, Wang et al. (2001) measured experimentally the acoustic properties of composite materials contained alumina particles, at room temperature, using ultrasonic spectroscopy. Figure 6 shows a plot of the measured (Wang et al., 2001) and predicted composite normalised longitudinal wave velocity ($V_L / V_m$) as a function of reinforcement volume fraction. In contrast to the previous two cases that involve tungsten particles, the acoustic properties for composite contain alumina increases non-linearly with increase in alumina particle volume fraction. This is due to the fact that alumina has relatively low density ($\rho_a = 3.69 \times 10^3$ kg/m$^3$) compared to tungsten ($\rho_t = 19.3 \times 10^3$ kg/m$^3$). The predicted acoustic property for composites with 25% volume of alumina particles has shown a 3% increase, and was only 1% off from experimentally measured value. The longitudinal wave velocities for composites reinforced with fibres and platelets are also plotted in Figure 6 for comparison.

Figure 6  Normalised longitudinal wave velocity ($V_L / V_m$) for alumina/EPO-TEK 301 composites

4.1.2 Acoustic impedance

Figure 7(a) shows a plot of acoustic impedances of EPO-TEK 301 composites containing alumina particle as a function of volume fraction of alumina continent. Both experimental results from Wang et al. (2001) and numerical results predicted from the current study demonstrate an increase in acoustic impedance value with increase in alumina volume fraction.

Figure 7(b) presents a plot of acoustic impedance for tungsten/EPO-TEK 301 composites as a function of volume fraction of tungsten. Similarly, both experimental results from Wang et al. (2001) and the numerical results from the current prediction show an increase in acoustic impedance with an increase in tungsten continent. Note that the acoustic impedance for both composites reinforced with alumina and tungsten particles increased linearly with increase in the volume fraction of the particles. This is due to the fact that impedance is a linear function of density and wave velocity and in this case the density is predominant as the particles are much heavier than the matrix. The
variation rate in acoustic impedance as a function of reinforcements for the composites containing alumina and tungsten particles is dissimilar due to difference in their densities (i.e., $\rho_a = 3.69 \times 10^3 \text{ kg/m}^3$, $\rho_t = 19.3 \times 10^3 \text{ kg/m}^3$). Acoustic impedance is more rapidly increased with increasing volume fraction of tungsten than that of alumina. Furthermore, even though the longitudinal velocity of composites containing tungsten particles decreased with increase in tungsten volume fraction, the density of tungsten is high enough to rise up the impedance as the volume fraction of tungsten increases.

**Figure 7** Characteristic acoustic impedance for (a) alumina/EPO-TEK 301 composites and (b) tungsten/EPO-TEK 301 composites.

![Figure 7](image)

4.2 Acoustic properties of composites containing voids (micro-porosity)

The modified MTM and SCM, a three phase model which accounts for voids, is also used to estimate the acoustic properties of composites with a presence of voids. Figure 8 shows a plot comparing the predicted normalised longitudinal wave velocity ($V_L / V_m$), obtained using both the MTM and SCM modules, as a function of void volume fractions. As shown in the figure, the SCM slightly underestimate the acoustic properties compared to those obtained using the MTM. This is due to the fact that the SCM uses a unified elastic property of matrix assuming homogeneous materials while the MTM uses averaged elastic property of matrix for values perturbed by reinforcements. As shown in the plot, the longitudinal wave velocity decreases with an increase in volume fraction of voids. This is expected as the elastic modulus for composites decreases with increase in
the volume fraction of voids (Figure 3). A presence of 10% voids resulted in roughly a
10% reduction in the composite acoustic properties. In Figure 8, the result from the
present model was compared with experimentally measured acoustic properties from the
literature (Maalej et al., 2010). While there was a large degree of scatter in the measured
experimental properties, both the modified MTM and SCM micromechanical solutions
reasonably matched with the mean experimental response in the low range of voids
volume fraction ($c_v \leq 0.2$). In contrast, for relatively high volume fraction of voids
($c_v \geq 0.2$), the prediction underestimates the acoustic properties. In our model, voids are
loosely idealised as spheres, and usually in micromechanics model all heterogeneities are
assumed to be well dispersed in the matrix and perfectly bonded to the other phases. Our
assumption may be too conservative which may be the reason for underestimating the
acoustic properties especially at larger void concentration.

Figure 8  Normalised longitudinal wave velocity ($V_L / V_m$) for cement paste materials with
porosity

5 Conclusions

The acoustic properties of composites containing multiple distinct heterogeneities
(spheres, platelets, voids, straight and/or wavy fibres, etc.) are predicted using a
micromechanical model. The model was developed for predicting acoustic properties of
composites containing multiple distinct heterogeneities with an arbitrary number of
coating layers based on the modified version of MTM and SCM. In order to estimate
composites elastic and acoustic properties accurately, properties of each constituent
need to be known and practically voids or defects in polymer composites reinforced with
nano-, or micro-scale fillers can be determined using SEM or TEM. In addition, the
interphase’s thickness, number of layers, and material property of each layer can be
investigated through MD simulation. In this study, the acoustic properties for three
different particle/polymer composite, such as tungsten/epoxy, alumina/EPO-TEK 301,
and tungsten/EPO-TEK 301 were predicted using our method, and they matched very
well with experimental results from the literature. The influence of voids on the acoustic
properties was also addressed. This study is a part of development of analytic and
numerical material models that can be used to facilitate composite material design and
fabrication for a specific application.
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