Ultrasonic propagation in metal powder-viscous liquid suspensions

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The need to measure the volume fraction of metal powder during the slurry casting synthesis of metal matrix composites has stimulated a new interest in ultrasonic propagation in metal powder-viscous liquid suspensions. Using model slurries, a systematic series of ultrasonic tests have been conducted to experimentally identify the frequency dependent relationships between ultrasonic velocity/attenuation and the particle volume fraction, the suspending liquid’s viscosity and the particle’s shape. For slurries with the compositions and viscosities typical of those used in slurry casting, the velocity decreases and the attenuation increases with particle fraction. The data have been compared to predictions of the Harker–Temple hydrodynamic model for these systems. The velocity measurements were well predicted by the model with a difference between measured and predicted velocities of about 0.25%. The ultrasonic attenuation was underpredicted by this model in part by its use of a rule of mixtures and by its failure to incorporate the intrinsic absorption/scattering within the powder phase. © 1998 Acoustical Society of America.

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INTRODUCTION

Metal matrix composites (MMCs) consisting of light, high melting temperature metals (such as titanium) reinforced with stiff, strong SiC or Al₂O₃ fibers are expanding the limits of engineering design. They allow the synthesis of aerospace components with property profiles (i.e., combinations of specific modulus, strength, toughness, and creep rupture strength, etc.) that are unachievable with monolithic metal alloys or ceramics. However, the insertion of these materials into many applications has been hindered by the limitations of current processing technologies which must avoid the aggressive chemical reactions between constituents that can lead to fiber-matrix interface damage, fiber dissolution, and a degradation of matrix and fiber properties. The recent emergence of a continuous slurry (tape) casting technique now promises a low cost, solid state synthesis route for MMC manufacture that completely eliminates liquid-metal-ceramic fiber contact.

The attributes of the finished composite components fabricated using a slurry casting technique depend strongly on the characteristics of the initial slurry system. Thus particle volume fraction, particle size distribution, slurry viscosity, and slurry homogeneity can all affect macro-, meso-, and microscopic characteristics of composite components. For instance, a high particle loading in the slurry beneficially reduces macro-shape change during subsequent hot isostatic pressing, but at the expense of an increased slurry viscosity which decreases slurry infiltration of the fiber mat and results in the touching of fibers in completed components. Because local variations in particle fraction can also be harmful during the processing of MMC components, the best composites are obtained when particle volume fractions and slurry viscosities are constantly maintained near optimized values. This requires that the slurry system remains homogeneously mixed throughout the casting process. The ability to maintain a homogeneous, controlled particle loading is limited by many factors, including particle settling due to gravity clustering, and/or incomplete mixing, selective pick-up of particles during infiltration and solvent evaporation. It is believed that these problems could be controlled by on-line sensing of the slurries’ composition.

Both ultrasonic velocity and attenuation measurements might enable in situ determination of the particle volume fraction, particle size distribution, slurry viscosity, and slurry homogeneity during slurry casting. When the ultrasonic wavelength is much longer than the particle size, a slurry can be approximated as an ultrasonically homogeneous medium. In this case, the ultrasonic velocity, \( v = \frac{1}{\sqrt{\beta \rho}} \) where \( \beta \) is its effective compressibility (the inverse of the bulk modulus), and \( \rho \) is its density. Since the density of metal particles (\( \sim 5 \text{ kg m}^{-3} \)) is greater than that of the liquid (\( \sim 1.5 \text{ kg m}^{-3} \), the overall density of such a slurry increases with the particle volume fraction. However, the effective compressibility of the suspension decreases with the particle volume fraction since the compressibility of solid particles (\( 2 \times 10^{-3} - 40 \times 10^{-3} \text{ m}^2/\text{GN} \)) is much smaller than that of the liquid (0.2–1.0 m²/GN). When the particle volume fraction is relatively low (say less than 40%), the increase in the overall density with particle fraction is more than offset by the decrease in overall compressibility, and the ultrasonic velocity decreases monotonically with the particle fraction. Since most slurries for tape casting have particle loadings of 25%–30% or less (otherwise they are too viscous to rapidly cast), the existence of a monotonic velocity-particle fraction correlation is believed to be a useful on-line measurement tool.

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relation near these particle loadings could provide an ideal basis for ultrasonic particle volume fraction determination.

The ultrasonic attenuation coefficient also depends on the particle volume fraction. This dependence is thought to result from ultrasonic scattering by the particles, by acoustic energy dissipation in the viscous liquid near the particle surface and from heat conduction between the liquid and the solid particles.\(^\text{13}\) The attenuation contributions of these processes are all likely to increase with particle loading and the liquid’s viscosity. Thus the ultrasonic attenuation might also provide a way of sensing either particle volume fraction or the suspending liquid’s viscosity (i.e., its composition). Thus both ultrasonic velocity and attenuation measurements might be of use for the on-line sensing of tape casting processes.\(^\text{14}\)

Ultrasonic propagation models that involve a detailed analysis of particle loading effects are important both for interpreting ultrasonic measurements and for ensuring that all significant physical contributions have been properly considered in the design of a sensor. The development of predictive models for ultrasonic propagation in suspensions involves two steps: first the interaction between the surrounding viscous liquid and a single solid particle is solved and then the collective effects of a volume of particles on ultrasonic propagation are determined. Good predictive models for the ultrasonic velocity in suspensions have been developed for wavelength regions that are much larger than the particle size.\(^\text{15}\) McClements and Povey\(^\text{16}\) have recently completed a comprehensive review of the other models. It should be noted that ultrasonic attenuation has been more difficult to accurately predict, and, sometimes, as much as an order of magnitude difference is observed between the predicted and measured attenuation coefficients.

There are two approaches available for the formal development of a model based either on a wave scattering\(^\text{17–21}\) or a hydrodynamic approach.\(^\text{22,23}\) To determine the interaction between the viscous liquid and a single solid particle, the wave scattering approach decomposes the total wave field into incident and scattered wave fields. Both the incident and the scattered fields are expressed as infinite eigenfunction series and the expansion coefficients are obtained by matching the displacement, velocity, tractions, temperature, and heat flux at the liquid—solid particle interface. After obtaining the scattered field, the collective effects of a volume of particles on ultrasonic propagation are obtained by a summation over the total number of particles. Since particle—particle interactions are ignored, the approach is an independent scattering one, and can only strictly be applied to dilute suspensions. In the hydrodynamic approach, the Stokes formula\(^\text{24}\) is used to describe the interaction between a single solid particle and a surrounding Newtonian viscous liquid. For this model, the collective effects of a high particle fraction on ultrasonic propagation have been approximated using a rule of mixtures and so this approach may better represent the behavior of the concentrated slurries encountered in composite processing.

Here we experimentally investigate the use of ultrasound for the noninvasive sensing of a slurry’s particle volume fraction and effective viscosity, and examine the predictive accuracy of the hydrodynamic modelling approach.\(^\text{22}\) Using a model laboratory slurry system consisting of Ti-alloy particles (of known shape and size distribution) suspended in liquid mixtures of glycerol and water whose viscosity could be varied over the range of typical tape casting slurries, we have evaluated the feasibility of using a piezoelectric ultrasonic sensor methodology for measuring ultrasonic velocity and attenuation for a variety of suspensions. Both velocity and attenuation measurements are found to be sensitive to the particle volume fraction, and either can be used to sense local particle fraction variations in slurries. While the Harker and Temple hydrodynamic model (the H-T model)\(^\text{22}\) appears to incorporate the phenomena that govern the ultrasonic velocity dependence on particle volume fraction up to particle fractions of 0.35, the model can only predict ultrasonic attenuation for the particle volume fractions below 20% due to the use of a rule of mixtures in the model and the failure to incorporate the intrinsic scattering and absorption of the powder itself.

### I. SLURRY SYSTEM

A typical MMC tape casting slurry consists of a mixture of viscous liquids with an effective shear viscosity of about 0.15 Pa s containing 10–200 \(\mu\)m diameter solid metal particles with a volume fraction of about 20%. The suspending liquids used here consisted of mixtures of (highly viscous) glycerol and water. The glycerol and water mixtures were chosen because of their similar viscosities to the binder/solvent combinations used in tape casting slurries. Since the glycerol/water volume fractions (and thus the viscosity) of such mixtures can be easily manipulated, this system allowed the effects of liquid viscosity upon the ultrasonic velocity and attenuation to be systematically studied. The viscosity, density, and sound velocity of the components and their mixtures studied are listed in Table I.\(^\text{25,26}\)

<table>
<thead>
<tr>
<th>Fluids (volume % of constituents)</th>
<th>Bulk modulus (GPa)</th>
<th>Density (kg/m³)</th>
<th>Velocity (m/s)</th>
<th>Viscosity (Pa s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% water</td>
<td>2.24</td>
<td>1000</td>
<td>1497</td>
<td>0.001</td>
</tr>
<tr>
<td>10% water</td>
<td>2.39</td>
<td>1000</td>
<td>1467</td>
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<td>1000</td>
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</tr>
<tr>
<td>100% glycerol</td>
<td>4.37</td>
<td>1250</td>
<td>1870</td>
<td>0.58</td>
</tr>
<tr>
<td>95% glycerol + 5% water</td>
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<td>1870</td>
<td>0.58</td>
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<td>1828</td>
<td>0.25</td>
</tr>
<tr>
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<td>1228</td>
<td>1798</td>
<td>0.13</td>
</tr>
<tr>
<td>80% glycerol + 20% water</td>
<td>3.79</td>
<td>1217</td>
<td>1765</td>
<td>0.076</td>
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<td>1205</td>
<td>1738</td>
<td>0.046</td>
</tr>
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<td>1000</td>
<td>1497</td>
<td>0.001</td>
</tr>
<tr>
<td>Suspending liquids for tape casting</td>
<td>1.7</td>
<td>1100</td>
<td>1545</td>
<td>0.15</td>
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Two types of metal powder particles were used in the study. The first were Ti-3 wt. % Al powders with a nearly spherical shape: Fig. 1(a). Their theoretical density, \(\rho_0 = 4.459\) kg/cm\(^3\), while their bulk modulus, \(B = 141\) GPa. A cross sectional analysis of the particles revealed that a few contained closed pores. Overall the particle porosity was determined to be 2.2%, and so an effective density, \(\rho = 0.978\) kg/cm\(^3\), was used in subsequent calculations. The second system consisted of nonspherical Ti-6 wt. % Al-4 wt. % V; Fig. 1(b). Their theoretical density, \(\rho_0 = 4.361\) kg/cm\(^3\), was used in subsequent calculations.
5.457 g/cm$^3$ and their bulk modulus, $B = 141$ GPa. A cross sectional analysis of these particles indicated negligible porosity. Both particles sets had a fairly broad size/volume distribution; Fig. 2. The spherical Ti-3 Al particle system was chosen for ease in modeling, while the nonspherical Ti-6 Al-4 V powders were selected to assess the effects of particle shape which is not always spherical in practice.

II. MEASUREMENT SYSTEM

A. Ultrasonic test cell

The ultrasonic test cell consisted of two collinear transducers in a pitch-catch arrangement; Fig. 3. To increase the signal strength in these sometimes very lossy slurries, a focused piezoelectric transducer was used to generate ultrasonic pulses and an unfocused transducer with a matching central frequency was used to receive ultrasonic signals. Four pairs of 1-in. diameter (Panametrics) transducers with center frequencies of 0.46 MHz, 0.87 MHz, 2.10 MHz, and 4.80 MHz were used for the ultrasonic testing. The transmitting transducer was mounted on a three point adjustable plate allowing for precise collinear alignment of the two transducers; the receiving transducer was fixed to a piston controlled by a micrometer allowing the distance between the transmitter and the receiver to be continuously varied. The measured distance between the two transducers had a precision of about $\pm 10$ $\mu$m. Parallelism between the two transducers was considered achieved by maximizing the amplitude of the detected signal. The ultrasonic test system used in conjunction with the test cell consisted of a MATEC MBS 8000 velocity and attenuation measurement system, a Marconi 2022C signal generator, a LeCroy 9400 digital oscilloscope (8 bits vertical resolution, 1-ns sampling resolution) and a 15-MHz low-pass filter to eliminate high-frequency noise. A theoretical model due to Lu et al. for focused transducers was used to calculate the acoustic field intensity for each combination of transducers and mixtures of glycerol and water; the acoustic intensity was then used to correct attenuation measurements for beam spreading or convergence.

B. Data collection

The test cell micrometer position was set to zero at a reference propagation distance, $L_0$. Velocity and attenuation measurements were then made as the distance between transducers was increased in steps of about 3.0 $\pm 0.1$ cm. A slurry sample was then placed in the test cell and the reading of the micrometer was recorded. This, together with the reference distance, $L_0$, gave the distance between the transmitter and the receiver. The raw data were collected in the form of receiver transducer waveforms on a digital oscilloscope. The entire data acquisition process was automated using a data acquisition program LABVIEW at a rate of about one wave-
form every 2 s to allowed experiments to be conducted rapidly and to avoid potential settling of the slurry during the measurement. All measurements were taken at the ambient temperature.

C. Velocity/attenuation determination

The ultrasonic velocity was determined by measuring the travel time of the first peak in each waveform. If \( L \) was the distance between two transducers and \( t \) the time lapse between the trigger time and the first peak in the waveform, then the ultrasonic velocity \( v = \frac{L}{t} \). We obtained a linear relationship between the measured time interval, \( t \), and the propagation distance, \( L \), with an estimated error of \( \pm 2.5 \text{ m/s} \), or about 0.14\% for a typical velocity of 1800 m/s.

A differential scheme was used to determine the attenuation. The maximum amplitudes, \( A_1, A_2, A_3 \), of three waveforms corresponding to three different propagation distances, \( L_1, L_2, L_3 \), (for the same frequency and slurry composition) were measured. The attenuation was obtained as:

\[
\alpha_{\text{liq}} = \frac{20 \log (A_3/A_1)}{L_3/L_1},
\]

where \( \omega = 2\pi f \) is the angular frequency, \( f \) is the sound frequency, \( v \) is the velocity, \( \rho' \) is the effective liquid density, and

\[
\omega_v = \frac{2B}{\eta_v + \frac{4}{3} \eta_s},
\]

is the characteristic frequency of the mixtures.

The measured ultrasonic velocity and attenuation of glycerol/water mixtures are shown in Fig. 4 and Fig. 5. Equation (1) was used to predict both the velocity and the attenuation. The shear viscosity of the mixture was taken from Ref. 26, and the volume viscosity was determined to be \( \eta_v = 0.8 \eta_s \) by fitting experimental data with Eq. (1). There is an excellent match between the measured velocity and the predicted velocity; Fig. 4(b). Since the velocity for the mixture of either 90\% glycerol and 10\% water or 80\% glycerol and 20\% water is almost constant at all test frequencies (\( v = 1828 \text{ m/s} \) for 90\% glycerol and 10\% water, and \( = 1763 \text{ m/s} \) for 80\% glycerol and 20\% water), we conclude that both the ultrasonic frequency and the viscosity have a vanishing effect on the velocity, and the increase in the velocity is a result of an increase in the bulk modulus due to the increasing glycerol volume fraction (see Table I).

The attenuation was found to rapidly increase with the glycerol volume fraction and the test frequency; Fig. 5. We found that Eq. (1) fits measured attenuation data well by taking \( \eta_v = 0.8 \eta_s \). It severely underestimated the measured data if \( \eta_v = 0.0 \), confirming that the volume viscosity plays a
very significant role in ultrasonic propagation in viscous liquids, and its effects should not be neglected in attenuation predictions for slurries.

IV. POWDER SLURRY BEHAVIOR

A. Results

Figures 6 and 7 show typical examples of the measured ultrasonic velocity of both spherical Ti-3 Al and nonspherical Ti-6 Al-4 V particles suspended in two glycerol and water mixtures (90% glycerol + 10% water and 80% glycerol + 20% water) as a function of particle volume fraction for test frequencies 0.46 and 2.1 MHz. For particle volume fractions up to 0.35, the velocity decreased monotonically with the particle volume fraction. The slope was steepest near the volume fraction of 0.25—fortuitously close to the value used in many slurry casting processes. The velocity for Ti-3 Al powder suspensions was always greater than that for Ti-6 Al-4 V powder particles, principally because of the (often hollow) Ti-3 Al powders’ smaller effective density. The velocity of the slurries were also strongly affected by the suspending liquid’s composition. For example, Fig. 8 displays the measured velocity-glycerol volume fraction relationship for a slurry containing a 20% volume fraction of Ti-3 Al powders at a test frequency of 0.87 MHz. The velocity is a strong, monotonic functions of the suspending liquid’s composition.

The ultrasonic attenuation as a function of particle volume fraction is shown in Figs. 9 and 10 at test frequencies of 0.46 and 2.1 MHz. The attenuation was a strongly increasing function of both particle fraction and test frequency. The size of the particles appears to affect the attenuation, with the larger Ti-6 Al-4 V powder particles (the average particle radius was 47.5 μm, deduced from the particle volume measurements) exhibiting a higher attenuation than the Ti-3 Al powder particles (the average particle size was 37.5 μm).

The ultrasonic attenuation exhibits a strong monotonic increase as particle volume fraction and/or ultrasonic frequency increase; Figs. 9 and 10. The attenuation also monotonically increases with the liquid’s viscosity; Fig. 8. Figure 8 shows attenuation as a function of volume percentage of glycerol for a 20% volume fraction of Ti-3 Al particles at 0.87-MHz frequency. Clearly, the attenuation is a strong monotonic function of the suspending liquid’s composition. In particular, it is clear that as the suspending liquid’s viscosity increases (glycerol content rises), the attenuation of the slurry rises exponentially. A comparison of Figs. 5 and 8 reveals that the presence of powder synergistically increases the attenuation contribution of the liquid, and clearly reveals the very strong effect of viscosity upon ultrasonic attenuation by suspended particles.
B. Discussion

1. Sensor opportunities

Within the 0.0–0.35 particle volume fraction range, the measured velocity is a monotonic function of powder particle fraction (Figs. 6 and 7) and is consistent with the dominance of increase in slurry density over the compensating decrease in slurry compressibility. The ultrasonic velocity also monotonically increases with the suspending liquid’s or the powder particle’s velocity (e.g., see Figs. 8 and 6). Changes in the particle volume fraction, particle size, ultrasonic frequency, and liquid viscosity all affect the ultrasonic attenuation.

The experimental velocity/attenuation trends with particle volume fraction shown above can be empirically fitted by simple monotonic relationships. Thus once provided with premeasured calibration data relating either the ultrasonic velocity or attenuation to the particle volume fraction, a subsequent ultrasonic measurement during slurry casting could be converted to particle fraction, providing the basis for a real time ultrasonic particle volume measurement. Because of the relatively small error in measured velocity (± 2.5 m/s) and the fairly strong dependence of velocity upon particle volume fraction, the particle volume fraction could be obtained to within 5% from the velocity measurement near the 0.2 volume fraction region of practical interest.

Changes in the particle volume fraction, particle size, ultrasonic frequency, and liquid viscosity all affect the ultrasonic attenuation.

The attenuation relationship (e.g., Figs. 9 and 10) could also be used for sensing volume fraction. However, attenuation measurements have relatively larger uncertainties (the largest measurement error was about ± 1 dB/cm), and a weaker dependence upon particle fraction around the 0.2 volume fraction region of interest. The attenuation is also a strong function of the suspending liquid’s viscosity. This, together with the difficulty of avoiding signal losses from other causes, may pose additional practical problems for a particle volume fraction sensor based solely on amplitude measurements. It is of interest to note that since the velocity measurements give a good indication of particle volume fraction, the ability to make reliable attenuation measurements would provide a potential method to determine the viscosity of the suspending liquid. This then provides a pract-
tical way to monitor changes in the liquid’s composition through relationships between viscosity and composition (e.g., Fig. 8).

2. Wave propagation predictions

In Harker and Temple’s (H-T) hydrodynamic model\textsuperscript{22,23} the complex effective wave number, $k$, is used to determine the velocity and attenuation. The effective wave number is given by

$$ k = \sqrt{\omega^2 (1 - \varphi) \beta i + \varphi \beta_s} $$

$$ \times \frac{\rho_s (1 - \varphi + \varphi S) + \rho_s S (1 - \varphi)}{\rho_s (1 - \varphi)^2 + \rho_s [S + \varphi (1 - \varphi)]}. $$

(3)

where

$$ S = \frac{1}{2} \left[ \frac{1 + 2 \varphi}{1 - \varphi} \right] + \frac{9}{4} \sqrt{\frac{2 \eta_s}{\rho_s \omega}} $$

$$ + \frac{9}{4} \sqrt{\frac{2 \eta_s}{\rho_s \omega} + \frac{2 \eta_s}{\rho_s \omega}}. $$

(4)

The velocity and the attenuation coefficient are obtained from Eqs. (3) and (4) using:

$$ v = \frac{\omega}{\text{Re}(k)}, \quad \alpha (\text{dB}) = 20 (\log_{10} e) \text{Im}(k). $$

(5)

The measured ultrasonic velocity and attenuation data have been compared to predictions of the H-T model using the thermophysical data for the liquids found in Table II. Since the H-T model strictly applies only to spherical particles, the volume, $V$, of the Ti-6 Al-4 V particles was used to deduce an equivalent particle radius $a = \sqrt{3 V/4 \pi}$. The predicted velocity values are shown and compared with measurements in Figs. 6 and 7. Overall the comparison between the predicted and measured velocity values is very good. It is clear from both Figs. 6 and 7 that the velocity is a function both of particle and glycerol volume fractions; neither the test frequency nor the viscosity significantly affect the velocity. At lower frequencies, the H-T model slightly overestimates the rate of the velocity decrease with the powder particle volume fraction. As the frequency increases the agreement between the experimentally determined ultrasonic

<table>
<thead>
<tr>
<th>Property (Symbol)</th>
<th>Glycerol (C\textsubscript{3}H\textsubscript{8}O\textsubscript{3})</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.6071 W/m</td>
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<tr>
<td>Viscosity ($\eta$)</td>
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<td>0.893 mPa s</td>
</tr>
<tr>
<td>Density ($\rho$)</td>
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<td>1.0 g/cm\textsuperscript{3}</td>
</tr>
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<td>Specific heat at the constant pressure ($C_p$)\textsuperscript{a}</td>
<td>218.9 J mol\textsuperscript{-1} K\textsuperscript{-1}</td>
<td>75.3 J mol\textsuperscript{-1} K\textsuperscript{-1}</td>
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<td>Thermal expansion coefficient ($\alpha$)</td>
<td>0.52$\times$10\textsuperscript{-11}/°C</td>
<td>0.206$\times$10\textsuperscript{-11}/°C</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Basic Laboratory and Industrial Chemicals, A CRC Quick Reference Handbook, edited by D. R. Lide (CRC, Boca Raton, 1993).
velocities and the model becomes excellent. Generally, the relative error between the measured and predicted velocities is around 0.25%.

The predicted attenuation values are compared with the data in Figs. 9 and 10. It can be seen that the H-T model compares fairly well for low (say less than 0.2) volume fractions of powder. In general, it underestimates the attenuation of the mixtures. This may be linked to the H-T model’s use of a simple viscosity relation that does not recognize volume viscosity. This term in the constitutive response of associative liquids clearly has a significant effect on attenuation (Fig. 5). However, we also note that while the measured attenuation always increases monotonically with the particle volume fraction, the predicted values peak at about a 30% particle volume fraction. Figure 11 shows the attenuation as a function of particle volume fraction predicted by the H-T model for a volume fraction from zero to unity. Clearly, the model can no longer be valid when the particle volume fraction exceeds the theoretical limit for spherical particle packing (0.67 for a random packing). The drop in predicted attenuation above a volume fraction of 0.3 is a consequence of the zero assumed attenuation of the solid phase and the use of a rule of mixtures in the derivation of the H-T model. The validity of the rule of mixtures relation restricts the validity of the H-T model to particle volume fractions of no more than 20%. The use of the rule of mixtures, combined with the assumption of no solid phase attenuation even reduces the predicted attenuation in the 0.1–0.2 particle volume fraction region, and appears to be a significant contributor to the discrepancy between modeled and measured attenuation.

In spite of the attenuation modeling discrepancy, it is clear that provided the viscosity of the suspending liquid is known, there exists a promising basis for ultrasonic determination of particle volume fraction from either a velocity or an attenuation measurement. The precision of the measurement might be increased by using both attenuation and velocity data at a specific frequency and/or ultrasonic measurements over a range of frequencies. It is interesting to note that Figs. 6 and 7 show that the liquid viscosity has a vanishingly weak effect upon velocity, whereas Figs. 9 and 10 show attenuation measurements are much more viscosity dependent. Thus a combination of the two measurements might enable the determination of both viscosity and the particle volume fraction of a slurry.

V. CONCLUSION

Ultrasonic sensor concepts have been assessed for their potential for monitoring metal particle volume fractions during a slurry casting step in the manufacture of fiber reinforced MMCs via tape casting. Model laboratory slurry systems consisting of two Ti-alloy powders of known size and shape distributions suspended in mixtures of glycerol and water with controllable viscosity were used to investigate the relationship between particle shape, slurry composition, liquid viscosity, and the velocity/attenuation of ultrasound. The slurries had viscosities that spanned those of a typical tape casting slurry. The experiments reveal a monotonic decrease in velocity with increasing particle volume fraction and water content. The attenuation monotonically increased with particle volume fraction, viscosity, and test frequency.

An ultrasonic velocity measurement appears to offer the best precision for determining the particle volume fraction. The use of attenuation data has the potential for additional recovery of the slurry’s viscosity. Because of the relatively small error in velocity measurement (±2.5 m/s) and the fairly strong dependence of velocity upon particle volume fraction, the particle volume fraction could be obtained to within 5% from the velocity measurement. Attenuation measurements have larger uncertainties (the largest measurement error was about ±1 dB/cm) and this may pose potential problems for a sensor technology solely based upon amplitude measurements.

The Harker and Temple hydrodynamic model was used to analyze both the velocity and attenuation results. The velocity measurements were well predicted by the H-T model, the relative error between the measured and predicted velocities is around 0.25%, suggesting that the model could be used to convert velocity data to particle volume fraction. Ultrasonic attenuation trends with particle fraction, liquid viscosity, and test frequency were reproduced well by the model. However, the absolute attenuations were underestimated by the model. This arises in part from the use of a rule of mixtures (which limits its useful range to a particle volume fraction of less than about 20%) and its failure to incorporate scattering/absorption in the metal phase.

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