Measuring Acoustic Attenuation of Polymer Materials Using Drop Ball Test

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MEASURING ACOUSTIC ATTENUATION OF POLYMER MATERIALS
USING DROP BALL TEST

by

Yi Zhang

This thesis was prepared under the direction of the candidate’s Thesis Committee Chair, Dr. David J. Sypeck, Associate Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Daewon Kim, Assistant Professor, Daytona Beach Campus, and Dr. Frank J. Radosta, Professor, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Department of Aerospace Engineering in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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Lastly but mostly, I want to thank God and the Lord for giving me a life of hope, training me in perseverance, and stimulating me on the path of discovering truth.
Polymers are often used for vibration damping and energy absorption. The effect of a material in reducing the strength of sound waves traveling through it is called acoustic attenuation. In the past, attenuation has mostly been evaluated in the MHz frequency range, using a pulse generator and transmitting transducer as the wave source. However, most real acoustic activities occur at frequencies up to a few hundred kHz. Here, a simple drop ball mechanism is used to generate acoustic source waves in the kHz range, and the attenuation capacities of several solid materials are measured. The recorded waveforms substantially differ between materials. The results show that among the tested polymers, epoxy attenuates the least, rubbers the most, while polyethylene and polyester are also excellent attenuating materials. The drop ball mechanism is controllable and consistent which may be used for other impact or acoustic emission testing. The effect of mixing in additives for the attenuation capacity of epoxy is also investigated.
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I Introduction

Purpose and Significance of the Study

In solids, sound waves can lead to vibrations that generate noise, cause fatigue, or even abrupt structural failure, which is a crucial issue in aerospace and other industries. Polymers have been widely used as vibration damping and energy absorption materials as they attenuate sound waves more than some other materials such as metals or ceramics.

One common way to quantify attenuation is by measuring the decay rate of the signal amplitude using an ultrasonic source (which may include a pulse generator, function generator, and amplifier), a transmitting transducer, and a receiving transducer that are separated by a known distance. The received signal is then analyzed with an ultrasonic analyzer and displayed on an oscilloscope. With these types of setups, attenuation is typically evaluated at high frequencies, i.e. MHz range. However, most real acoustic activities occur at much lower frequencies, i.e. kHz range. The purpose of this work is to evaluate attenuation in polymers at frequencies of up to a few hundred kHz, using a comparatively simple test setup which includes a simple drop ball mechanism, piezoelectric sensor, charge amplifier, and digital oscilloscope.

This thesis consists of a review on vibration damping in polymers, wave propagation, and ultrasonic testing; test material selection and specimen fabrication; experimental setup and attenuation measurement results; and lastly, the effect of mixing in additives for the attenuation capacity of epoxy resin is also investigated.

The significance of this work is to help better the understanding of wave propagation and attenuation in solids, which is a very complicated science. The knowledge and techniques gained during the experimental setup also provide useful
hands-on advice that can benefit other ultrasonic, acoustic emission (AE) testing as well as structural health monitoring (SHM) applications. The drop ball mechanism presented here can generate fast and recognizable acoustic waves. It is simple, controllable, and very reproducible, which can be used for other impact testing applications, and can be an ideal substitute for the commonly used methods such as breaking pencil leads or glass capillary tubes for generating source waves in acoustic emission testing. As numerical simulation has been the ongoing trend in the engineering research field today, it is also the author’s wish also to gain appreciation for laboratory experimental work through this work.

**List of Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>SHM</td>
<td>Structural Health Monitoring</td>
</tr>
<tr>
<td>tan δ</td>
<td>Mechanical Loss Coefficient</td>
</tr>
<tr>
<td>MLC</td>
<td>Mechanical Loss Coefficient</td>
</tr>
<tr>
<td>NDT</td>
<td>Nondestructive Testing</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>DIA</td>
<td>Diameter</td>
</tr>
<tr>
<td>PH</td>
<td>Precipitation Hardening</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
</tbody>
</table>
II Vibration Damping in Polymers

Vibration Damping

A vibration is a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed [1]. In solids, pressure waves can lead to vibrations that generate noise, cause fatigue, or even abrupt structural failure, which is a crucial issue in aerospace and other industries. Vibration damping, i.e. reduction of pressure wave intensity, can be achieved by various ways, i.e. active, passive, and semi-active control. While active control involves the use of active elements such as speakers, actuations or microprocessors [2], here passive control is the topic of interest.

Passive vibration damping is usually achieved by using absorbers, barriers and silencers, etc., which are able to convert wave energy into heat [2]. This can also be referred to as energy absorption. Polymers, due to their viscoelastic properties, have long been used as energy absorption materials. This chapter will give an overview of the viscoelasticity of polymers in vibration damping/energy absorption as well as their applications.

Viscoelastic Behavior of Polymers

A polymer is a material consisting of very large chain-like molecules based upon H and C. In each molecule, an atomic group, or “repeat unit”, can be repeated hundreds or thousands of times. Conventionally, the term “polymer” includes materials consisting of long-chain molecules, which may be arranged in a crystalline (atoms, molecules, or ions arranged in an ordered pattern extending in all three dimensions) or noncrystalline manner (lacking long-range order); or materials consisting of a noncrystalline space
network joined by primary bonds [3]. A symbolic representation of a flexible polymer molecule is shown in Figure 1 below.

![Symbolic representation of a flexible polymer molecule](image)

Figure 1. Symbolic representation of a flexible polymer molecule (polyisobutylene) [4].

Polymers are normally viscoelastic. Viscoelasticity may be defined as a material behavior which exhibits characteristics of both a viscous liquid and an elastic solid. When being stressed, a viscoelastic material can return to its original shape (elastic behavior), but does it slowly enough to oppose any potential next cycle of vibration (viscous behavior) [2]. When under stress, each flexible threadlike molecule of a polymer constantly changes the shape of its contour as it wriggles and writhes with its thermal energy, and a new assortment of configurations can be obtained. Rearrangements on the local scale are rapid, but slow on the long-range scale, which contributes to its viscoelastic behavior [4]. For many materials of classical physics interest, viscoelastic behavior is negligible; however, for polymers this is the dominating mechanical behavior [4]. Consider that the degree to which a viscoelastic material behaves either viscously or
elastically mainly depends on temperature and frequency of loading, which will be explained later in Chapter III.

**Polymers Used as Vibration Damping Materials**

Material-wise, various polymers have been used as vibration damping/energy absorption materials due to their viscoelasticity. Rubber is particularly popular in vibration damping application. Other polymers that have good damping capacity include polytetrafluoroethylene (PTFE, or Teflon®), polyurethane, polymethylmethacrylate (PMMA), polyvinyl acetate and asphaltics [5,6]. A new class of polymers, Interpenetrating Polymer Networks, or IPNs, have been reported to exhibit broad-band damping properties. They are intimate mixtures of two or more network polymers that can bring up the desired morphology.

Several U.S. Patents have described the use of polymers in vibration damping applications. U.S. Pat. No. 3,640,836 describes the combination of ethylene, vinyl acetate and acrylic and/or methacrylic acid as the viscoelastic layer of a vibration-damping laminate [7]. U.S. Pat. No. 3,847,726 describes an adhesive composition made of polyepoxide, polyether amine, heterocyclic amine and phenol useful as damping material over -25° to +60 °C range [8]. U.S. Pat. No. 5,262,232 describes a damping composition comprising an IPN consisting essentially of 5-95% by weight of a polyalkyl acrylate elastomer, and 95-5% by weight of a plastic [9]. Pat. No. 4,839,387 demonstrates the use of polyurethane soft foam as sound insulation materials [10]. These are just a few of the many examples.
Structure-wise, polymers have been used to enhance damping in a structure in primarily three ways: free-layer damping, constrained-layer damping and tuned mass damping [2], shown in Figure 2 below.

![Figure 2: (a) Free-layer; (b) Constrained-layer; (c) Tuned mass [2].](image)

Among the different configurations, free-layer damping can be seen in the undercoatings of automobiles to provide noise and vibration damping. Here, a polymer is
sprayed or bonded directly to the structure surface. With constraint-layer damping, when the base structure undergoes bending vibration, the polymer is forced to deform in shear because of the upper constraint layer, and mechanical energy is converted to heat. Tuned mass damping, on the other hand, can be used to eliminate an unwanted resonance when properly tuned. Here, the viscoelastic material is added between the structure and tuned mass to dissipate vibrational energy [2].

Reducing interior noise and vibration has been a major issue for high quality road vehicles. Several families of constraint-layer damping products have been commercially available to achieve this purpose, i.e. Quiet Steel®, Dynalam, and LVDS, etc. [11,12]. These products have been used on automobile parts such as engine covers, timing belt covers, dash panels, door panels, floor panels, brake insulators, and steering brackets [2].

In aerospace industries, viscoelastic materials have been used for damping sound and vibrations in military aircraft and spacecraft since the early 1960s. For example, polymeric damping materials have been added to commercial aircraft to reduce fuselage cabin noise and vibration [2]. Epoxy-based syntactic paste has been used for engine vibration damping [13].

Many other commercially available polymeric materials are also used for vibration damping in household appliances, computer hardware and machine tools, e.g. Ultra-Pure Viscoelastic Damping Polymers by 3M (St. Paul, MN), Polydamp® Extensional Damping Pad by Polymer Technologies Inc. (Newark, DE), and Sorbothane® by Sorbothane Inc. (Kent, OH), which claims to absorb over 50% of the vibration energy over most of its temperature operating range at frequencies from 10 Hz to 30 kHz.
III Technical Background

Fundamentals of Wave Propagation and Attenuation

Wave Propagation

All materials are comprised of atoms, which can be forced into vibrational motion about their equilibrium positions. Though many different patterns of vibrational motion exist, acoustic or ultrasonic studies focus on particles that contain many atoms that move in unison to produce a mechanical wave [14]. Waves that propagate through solids are also known as elastic waves, and their propagation rate depends on the type of wave, the elastic properties of the medium, the density of the medium, and in some cases the frequency and amplitude [15]. There are four principle propagation modes in solids according to the way the particles oscillate: longitudinal, shear, surface, and guided scenarios like plate waves (in thin plate-like materials) [14]. Among these, longitudinal and shear waves are more often studied in the ultrasonic field [14]. Note that wave propagation in solids is inherently more complex than fluids because fluids do not support shearing or shear waves.

When a normal force is rapidly applied perpendicular to a surface, a longitudinal wave is launched. As the longitudinal wave travels through the material, particles in the vicinity of the wave move parallel to the direction of wave propagation (described by what are called rays) and can be forced back and forth by oscillations of the wave. Longitudinal waves can also be referred to as compressional or pressure waves as compressional force is active in these waves. Longitudinal waves can exist in either solids or fluids (liquids or gases) [16].
On the other hand, if a shearing force is rapidly applied to a surface, a shear wave will be formed. In this case, the particle motion is perpendicular to the direction of the wave propagation [16]. Shear waves can also be referred to as transverse waves, and they only exist in solids. Shear waves are normally much weaker (less energy) than longitudinal waves, and in fact they are usually generated by part of the energy from longitudinal waves [14]. An illustration of longitudinal and shear waves is shown in Figure 3.

![Figure 3. Longitudinal and shear waves [14].](image)

For experiments performed for this work, longitudinal waves are the dominant propagation mode.
Acoustic Attenuation

As a sound wave propagates through a medium, its intensity decreases with the distance travelled. This phenomenon is referred to as sound attenuation (or acoustic attenuation). The amplitude change of a decaying wave can be expressed as:

\[ A = A_0 e^{-\alpha d} \]  

Where:
\( A_0 \) = Amplitude of the propagating wave at a given location  
\( A \) = Reduced amplitude at another location  
\( d \) = Distance traveled between the two locations  
\( \alpha \) = Attenuation coefficient in Neper (Np)/length (can be converted to dB/length by dividing by 0.1151)

The two major mechanisms that cause the attenuation of sound energy are absorption and scattering (these will be further discussed in the following sections). When measuring attenuation, other effects can also cause loss of strength, such as reflection and refraction at interfaces. However, these are sensitive to the inherent phenomena of the wave field [15] and they cannot suggest the attenuating capacity of the medium in interest. Other phenomena such as frequency-dependent spreading, called dispersion, can also have an effect.

Sound attenuation has become an increasingly important issue in many fields. In the air-borne case, attenuation is desirable in sound insulation and noise reduction.
applications. In underwater acoustics studies, attenuation is important for sonar systems as well as the reduction of sound radiation from ships and submarines. For solid structures, sound attenuation materials are often used as damping layers to reduce the vibration of structural components [16]. Currently, the most frequently used attenuating materials are viscoelastic polymers, where attenuation is achieved by converting vibrational energy to heat during molecular relaxation processes [16].

**Energy Absorption**

Absorption is a key mechanism that causes attenuation of sound energy. Here sound energy is converted to heat by the elastic motion of particles, viscosity, relaxation, heat flow etc., where energy can be lost as it is dissipated in the medium. Energy absorption is the same mechanism as vibration damping in a material. This section will give a review on energy absorption in polymers, mostly summarized from Bruce Hartmann’s article “Relation of Polymer Chemical Composition to Acoustic Damping” [17] in the book “Sound and Vibration Damping with Polymers” compiled by R. D. Corsaro and L.H. Sperling.

When a material is elastically loaded, it stores an elastic energy; when it is unloaded, some of the mechanical energy is lost and converted to heat. This is referred to as energy dissipation or absorption. A physical representation can be seen from a stress – strain curve during the loading and unloading of a material, Figure 4 (a). The fraction of the energy lost/energy stored is expressed by the damping coefficient $\eta$, also known as $\tan \delta$, the loss factor, or mechanical loss coefficient, which signifies the degree to which a material dissipates or absorbs vibrational energy. $\tan \delta$ can also be thought of as the ratio...
of the loss modulus $E''$ to storage modulus $E'$ during the loading and unloading of a material shown in Figure 4 (b), as expressed by Eq. (2).

Figure 4. (a) Stress - strain curve during loading and unloading in the elastic region; (b) Phase angle $\delta$ of loss modulus and storage modulus.
\[ \tan \delta = \frac{E''}{E'} \]  

(2)

Where:

\( \delta \) = The phase lag angle between strain and applied stress (in time) when there is energy absorption

\( E'' \) = Complex part of the modulus, also called the loss modulus as it is a measure of absorption

\( E' \) = Real part of the modulus, also known as storage modulus as it represents the elastic storage of mechanical energy

Here the modulus has been treated as a complex number:

\[ E^* = E' + iE'' \]  

(3)

Since \( \tan \delta \) expresses the energy absorption/vibration damping characteristic of a material, it is one of the key parameters that are taken into consideration when it comes to the selection of polymer testing materials later on, which will be discussed in next Chapter.

Furthermore, \( \tan \delta \) is found to depend on temperature and frequency of loading. The effect of temperature on damping for a typical polymer can be seen in Figure 5, where \( G \) signifies shear modulus.
In Figure 5, the temperature at which $\tan \delta$ reaches maximum and shear modulus significantly drops, is known as the glass transition temperature, or $T_g$. At the glass transition temperature of an amorphous polymer, major changes in physical and acoustic properties occur, and the material transitions from a hard and relatively brittle state into a molten or rubber-like state. The vibration damping characteristics of a polymer are dominated by the glass transition occurring in its amorphous (lacking long-range order) portions.

The absorption, or damping in a polymer also depends on the frequency of waves. It is observed that both longitudinal and shear wave absorption increase linearly with frequency. The absorption of polyethylene evaluated at different frequencies is shown in Figure 6. The absorption of some rubbers often used for vibration damping evaluated at different frequencies is shown in Figure 7.
Figure 6. Absorption vs. frequency for polyethylene [17].

Figure 7. Absorption vs. frequency for commonly used rubbers [17].
Scattering

Another mechanism that causes attenuation is scattering, which is a result of inhomogeneities in a material such as crystal discontinuities, grain boundaries, inclusions, particles and voids [15]. Here, the energy of the coherent, collimated waves is converted into incoherent, divergent waves through reflection and refraction. In general, scattering increases with increasing frequency and is a strong function of wavelength [15]. Note that scattering from inclusions in a medium does not become significant until the dimensions of the inclusions are comparable to the wavelength of sound in the medium [16]. Small waves bounce off of ships while large waves move ships. For polycrystalline metals and ceramics, scattering is the major mechanism that causes attenuation. However, for liquids and polymers, absorption dominates.
**Ultrasonic Testing**

**Ultrasound**

Ultrasound is a form of mechanical energy, a vibration or wave-field that propagates through solids, liquids and gases [15]. Ultrasound is a specific branch of acoustics that deals with vibrational waves above the upper frequency range of human hearing, i.e. 16 to 20 kHz. Ultrasonics is used for medical, industrial, electronics, nondestructive testing (NDT) purposes [15]. Some examples of ultrasonic systems at different operating frequencies are shown in Figure 8.

![Figure 8. Ultrasound applications at different frequency ranges [15].](image)

Although many ultrasonic applications are performed at MHz range, in reality, most natural acoustic activities occur in kHz range. For example, with structural composite materials under tensile loading, pure matrix cracking is reported to generate waves having frequencies ranging from 150 to 250 kHz, while fiber breakage from 350 to 450 kHz [18]. General purpose sensors manufactured by Physical Acoustics Corporation
(Princeton Junction, NJ) have rated operating frequencies ranging from 30 kHz to 1 MHz. This work is interested in acoustic events occurring in the kHz range.

**Piezoelectric Transducer**

Piezoelectric transducers can detect mechanical energy and convert it to an electrical signal, or vice versa, which is the heart of ultrasonic testing. They can be used at a wide range of ultrasonic frequencies (16 kHz to 100 GHz) as senders or receivers [15]. The construction of a typical piezoelectric transducer is illustrated in Figure 9.

![Figure 9. Basic structure of a piezoelectric transducer [15].](image)

Their operating principle is the so-called “piezoelectric effect”, which can be defined as “the phenomena of separation of charge in a crystal by mechanical stresses and the converse” by the American Institute of Physics Handbook [15]. When the crystals are subjected to a mechanical force, they become electronically polarized. Voltages of opposite polarity are generated by tension or compression, in proportion to the magnitude of the force applied. Shearing can also generate voltage in some crystals. The converse of this relationship is also true: if these crystals are exposed to an electric field, they lengthen or shorten according to the polarity of the field, in proportion to the strength of
the field. These behaviors are referred to as piezoelectric effect and the inverse piezoelectric effect, respectively [19].

The design of a piezoelectric transducer must be concerned with the electrical and acoustic characteristics of the transducer in relation to its corresponding electrical equipment (such as power sources or receiver amplifiers), as well as its mechanical properties in relation to its vibrational performance. Nowadays there are a vast variety of shapes, sizes and thicknesses of piezoelectric materials one can chose from to make piezoelectric transducers [15].

**Acoustic Impedance and Reflection**

When an ultrasonic wave travels through an interface of different materials, the wave energy will be reflected back when the two materials have different acoustic impedance (Z) values. This difference is referred to as the impedance mismatch. The amount of the wave energy reflected at the boundary is dependent on the degree of acoustic mismatch. The greater the impedance mismatch is, the greater the percentage of energy that will be reflected, and vice versa. Thus, in ultrasonic testing it is important to know the acoustic impedance of the materials involved.

Acoustic impedance describes how the particles of a material behave when subjected to a wave; it measures the resistance of a material against the wave propagating through it [20]. It is calculated by the product of the material’s density and its longitudinal wave speed as shown in Eq. (4). The wave speeds and acoustic impedance of some common materials are given in Table 1.
\[ Z = \rho c \]  \hspace{2cm} (4)

Where:

\( Z \) = Acoustic impedance (Rayl = kg/m\(^3\)·m/s)

\( \rho \) = Density

\( c \) = Longitudinal wave speed
### Table 1. Acoustic properties of common materials [21].

<table>
<thead>
<tr>
<th>Material</th>
<th>Wave Speed</th>
<th>Acoustic Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal (km/s)</td>
<td>Transverse (Shear) (km/s)</td>
</tr>
<tr>
<td><strong>Solids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>3.251</td>
<td>1.194</td>
</tr>
<tr>
<td>Nickel (CP)</td>
<td>5.639</td>
<td>2.972</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>10.846</td>
<td>-</td>
</tr>
<tr>
<td>Copper (CP)</td>
<td>4.75</td>
<td>2.337</td>
</tr>
<tr>
<td>Silver (0.99 Fine)</td>
<td>3.607</td>
<td>1.6</td>
</tr>
<tr>
<td>Bronze (Phosphor 5%)</td>
<td>3.531</td>
<td>2.235</td>
</tr>
<tr>
<td>Titanium, 6Al-4V</td>
<td>6.172</td>
<td>3.302</td>
</tr>
<tr>
<td>Iron (Cast), Various</td>
<td>3.505-5.588</td>
<td>2.210-3.200</td>
</tr>
<tr>
<td>Aluminum 2024-T4</td>
<td>6.375</td>
<td>3.15</td>
</tr>
<tr>
<td>Glass (Plate)</td>
<td>5.766</td>
<td>-</td>
</tr>
<tr>
<td>Concrete</td>
<td>4.242-5.258</td>
<td>3.429</td>
</tr>
<tr>
<td>Acrylics</td>
<td>2.667-2.769</td>
<td>1.118-1.448</td>
</tr>
<tr>
<td>Teflon</td>
<td>1.372</td>
<td>6.35</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.667</td>
<td>-</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>2.286</td>
<td>-</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.388</td>
<td>1.143</td>
</tr>
<tr>
<td>Rubber (Natural)</td>
<td>1.549</td>
<td>-</td>
</tr>
<tr>
<td>Rubber (Silicone)</td>
<td>0.94</td>
<td>-</td>
</tr>
<tr>
<td><strong>Liquids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glycerin</td>
<td>1.93</td>
<td>-</td>
</tr>
<tr>
<td>Ethylene Glycol</td>
<td>1.626</td>
<td>-</td>
</tr>
<tr>
<td>Oil (SAE 20)</td>
<td>1.753</td>
<td>-</td>
</tr>
<tr>
<td>Water (20°C)</td>
<td>1.473</td>
<td>-</td>
</tr>
<tr>
<td><strong>Gases</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen (20°C)</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>Air (20°C)</td>
<td>0.356</td>
<td>-</td>
</tr>
<tr>
<td>Nitrogen (20°C)</td>
<td>0.356</td>
<td>-</td>
</tr>
</tbody>
</table>
As mentioned above, the degree of impedance mismatch determines the percentage of energy reflected. The intensity reflection coefficient \( R \) is calculated using Eq. (5) [20]:

\[
R = \left( \frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2
\]  

Where:

\( Z_1, Z_2 \) = Acoustic impedance of the two adjacent materials

Since energy that is not reflected back will be transmitted into the adjoining second material, the coefficient of transmission is obtained by simply subtracting the reflection coefficient from one. Take the interface of standard air and aluminum alloy 2024 as an example; standard air has an acoustic impedance of 0.00041 MRayl, while for aluminum it is 17.6 MRayl. Using Eq. (5), the percentage of the wave energy reflected will be almost 100%, which means there is almost no energy transmitted into aluminum. This is why in ultrasonic type testing, where air can be present between the transducer and the testing object, it is necessary to apply a couplant at the interface to fill the air gap between them and to facilitate signal transmission.

**Couplant Effect**

As demonstrated in the previous section, the impedance mismatch between air and solids is large, thus there is almost no transmission of ultrasonic waves between the two. Therefore, in ultrasonic testing, it is often required to apply a couplant at the transducer and the testing specimen interface to facilitate signal transmission. There are a
variety of couplant materials one can choose from, e.g. ultrasonic gel, grease, paste etc. The acoustic impedance values of several couplants are listed in Table 2. Besides acoustic impedance, the viscosity, wetting capability, hazard, and reaction with the testing material should all be considered when it comes to couplant selection.

Table 2. Acoustic impedance of various couplant materials.

<table>
<thead>
<tr>
<th>Couplants</th>
<th>Acoustic Impedance (MRayl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honey</td>
<td>2.89 [22]</td>
</tr>
<tr>
<td>Glycerine</td>
<td>2.43 [22]</td>
</tr>
<tr>
<td>Ultragel II</td>
<td>1.8 [23]</td>
</tr>
<tr>
<td>Motor oil SAE 20</td>
<td>1.51 [22]</td>
</tr>
<tr>
<td>Sunflower oil</td>
<td>1.35 [22]</td>
</tr>
<tr>
<td>Baby oil</td>
<td>1.17 [22]</td>
</tr>
<tr>
<td>Silicone spray lubricant</td>
<td>0.983 [24]</td>
</tr>
</tbody>
</table>

To ensure the consistency of the ultrasonic testing, a thin, uniform film of couplant should be applied to the surface(s). The application of the couplant should also be kept consistent in each test. To achieve this, the technique of immersion is often used, where both the transducer and testing specimen are immersed in the couplant, which is usually water (Figure 10). This method makes the couplant effect consistent if moving and handling the transducer or the specimen.
Previous Technique in Attenuation Measurement

This work is interested in the measurement of attenuation in an ultrasonic system. Attenuation is measured by evaluating the decay rate of multiple back surface reflection signals. A conventional method to achieve this consists of an ultrasonic source (pulse generator, amplifier), transmitting transducer, and receiving transducer that are separated by a known distance; the received signal is then analyzed and displayed [26]. A typical setup is shown in Figure 11 below.
With the typical setup shown above, attenuation is typically evaluated at high frequencies, i.e. MHz range. However, most real acoustic activities occur at much lower frequencies, i.e. kHz range. Here, the attenuation measurement setup is designed to evaluate attenuation in polymers at frequencies of up to a few hundred kHz. It also
features a comparatively simple test setup which only utilizes a transducer, charge amplifier, digital oscilloscope, and simple drop ball mechanism. The setup used here will be explained further in Chapter V.

**ASTM Standards on Ensuring the Consistency of Acoustic Emission Testing**

The ultrasonic testing presented in this work can also be referred to as an acoustic emission (AE) testing. For this testing system, consistency is crucial. Several ASTM standards are available on this topic, and were carefully reviewed. The ASTM standards have served as a guideline and reference for the author to set up her own experiment. This Chapter will summarize the important findings in ASTM E976, E2075, and E650 which cover the procedure of verifying the consistency of acoustic emission sensor response and the sensor mounting techniques.

**ASTM E976-10**

ASTM E976-10 (“Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response”) defines simple procedures for testing or comparing the performance of AE sensors [27]. Among all the parameters and components that affect the sensitivity of an AE test system, the AE sensor is the one most subject to variation, which can also be affected by damage or aging. This standard gives procedures on how to measure the response of a sensor to an arbitrary but repeatable acoustic wave, thus allowing users to check for degradation of a sensor or to select sets of sensors with similar performances. However, these procedures are not capable of providing an absolute calibration of the sensor.
Besides the AE sensor under test, the essential elements of the apparatus for these procedures are: (1) a test block or rod; (2) a signal source; and (3) measuring and recording equipment.

(1) Test block or rod

A test block or rod can provide a convenient mounting surface for the AE sensor under test while providing a stable medium for wave propagation. They also provide mechanical loading of the sensor which should be similar to that experienced in actual use. However, when using these devices, one needs to pay attention to minimize the structural resonances so the sensor response will not be masked by them. A conical “nonresonant” block (Beattie block) can be used, since its conic geometry and lack of any parallel surfaces reduce the number of mechanical resonances the block can support. The experimental setup using Beattie block is shown in Figure 12. A gas-jet test block, on which a gas-jet is fixed, is another option. Acrylic rod can be used with the sensor mounted on the end of the rod, and the acoustic excitation is applied by pencil lead (graphite) break at a consistent distance from the sensor end of the rod (Figure 13). This technique will be further discussed in ASTM E2075.
(2) Signal source

In order to compare sensor responses, it is required to have a source capable of producing repeatable acoustic waves. The characteristics of waves do not need to be known as long as the waves can be reproduced. Three sources are recommended: an electrically driven ultrasonic transducer, a gas jet, or an impulsive source produced by breaking a pencil lead or glass capillary tube. An ultrasonic transducer can transmit acoustic signals when it is driven by a white noise generator, sweep generator or a pulse generator. A gas jet can project extra dry air, helium, etc., at a pressure of 150 to 200 kPa onto the test block surface as the signal source. Pencil lead breaks, which are commonly used in AE testing, are performed by carefully breaking a pencil lead (usually 0.3 mm in diameter) against the test block or rod (Figure 13). When the lead breaks, the sudden release of compressive stress at and near the surface will generate an acoustic wave on
and into the block or rod where the lead is touching. Care should be taken to always break the same length (2 to 3 mm) and same type of lead to ensure better consistency.

![Figure 13. Pencil lead break on acrylic rod [27].](image)

(3) Measuring and recording equipment

The output of the AE sensor must be amplified by a preamplifier before it can be measured. After that, the results can be measured and stored by a transient recorder, digital oscilloscope, or a waveform-based acoustic emission system if the source signal is a single pulse or a pencil lead break. When comparing waveforms, emphasis should be placed on the initial few cycles and on the large amplitude features. Small variations later in the waveform for consistent tests and geometries are often produced by slight changes in the coupling or position of the sensor. If the source signals are generated by an ultrasonic transducer driven by some kind of generators or by gas-jet sources, the signals should be captured by a transient recorder and replayed into the spectrum analyzer.

With the testing apparatus ready, one should perform the test by placing the sensors under test on the test block or rod in as identical positions as possible. Identical
force should be applied to hold the sensor and block or rod together. A low-viscosity
couplant is desirable to ensure reproducible signals.

**ASTM E2075**

ASTM E2075 ("Standard Practice for Verifying the Consistency of AE-Sensor
Response Using an Acrylic Rod") gives details on using acrylic rod in verifying sensor
response [28]. While there are different kinds of test blocks one can choose for the same
purpose, an acrylic rod offers the best all-around combination of suitable acoustic
properties. A description of the rod used here is shown in Figure 14.

![Figure 14. Acrylic rod description [28].](image)

The actual material of the acrylic polymer rod here is polymethylmethacrylate
(PMMA). The Hsu-Nielsen pencil lead break should be used as the signal source. A
permanent reference mark should be placed on the rod at a distance of 10.2 cm (4 in)
from one end. A very small spotface, for example, 0.8 mm (0.03 in) DIA and 0.1 mm
(0.004 in) deep at the reference mark point should be provided. The rod should be placed
horizontally on a suitable hard, flat surface, with the reference mark facing vertically up.
The rod may be secured with tape or other means. The sensor should be mounted on the
flat end of the rod using a prescribed couplant and good application techniques (explained in detail in ASTM E650). It should be mounted in the six o’clock position so that it is resting on the same surface supporting the acrylic rod.

**ASTM E650**

ASTM E650 (“Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors”) provides guidelines for mounting piezoelectric AE sensors [29]. The purpose of mounting is to hold the sensor in a fixed position on a structure and to ensure that the coupling between the sensor and the structure is adequate and constant.

Before mounting, the contact surfaces should be cleaned and mechanically prepared. The sensor can be mounted either by a compressive force or adhesive bonding. A compressive force can be supplied by springs, torqued-screw threads, magnets, tape, elastic bands, or other suitable means. A couplant is necessary for this case. The thickness of the couplant layer may alter the effective sensitivity of the sensor, thus the layer should be as thin as possible. A good way to apply the couplant is to place a small amount of the material in the center of the sensor face, then carefully press the sensor to the structure surface spreading the couplant uniformly from the center to the outside. When using either a compressive force with a couplant, or adhesive bonding, one needs to consider the temperature and pressure in the environment, chemical compatibility with the structure (to avoid corrosion), whether it can be totally removed or not in order to select the right type of couplant or bonding agent.

Mounting fixtures should also be constructed carefully so that they do not create any extra acoustic emission to mask the valid AE response. If direction contact of the AE
sensor and test structure is not desirable, a waveguide can be used to convey the acoustic signal (i.e. waves) from the structure to the sensor.

**Impact Testing**

Various impact testing systems have been used for different purposes. Impact testing that is similar to the one presented in this work, which utilizes the ball drop as the impact load, has been used in the optical industry to test the impact-resistance of lenses. Eyeglasses and sunglasses are required to be fitted with impact-resistant lenses as they reduce eye injury possibilities. Furthermore, each finished impact-resistant glass lens for prescription use shall be individually tested for impact resistance as described in the Code of Federal Regulations Title 21, Section 801.410 [30]:

> “In the impact test, a 5/8 inch steel ball weighing approximately 0.56 ounce is dropped from a height of 50 inches upon the horizontal upper surface of the lens. The ball shall strike within a 5/8 inch diameter circle located at the geometric center of the lens. The ball may be guided but not restricted in its fall by being dropped through a tube extending to within approximately 4 inches of the lens. To pass the test, the lens must not fracture; for the purpose of this section, a lens will be considered to have fractured if it cracks through its entire thickness, including a laminar layer, if any, and across a complete diameter into two or more separate pieces, or if any lens material visible to the naked eyes becomes detached from the ocular surface.”

In this work, chrome steel drop balls will be used but of much smaller size, i.e. 3.18 mm (0.125 in) and 4.76 mm (0.188 in) DIA. It is released by simply rotating a
release screw. The ball drop is used to generate the acoustic signal for the ultrasonic system, which will be explained further in Chapter V.
IV Material Selection and Test Specimen Preparation

Materials of Various tan δ and Acoustic Attenuation

Various polymers were selected, from which test specimens were made. A drop ball test was later performed on each specimen to investigate its attenuation characteristics, which is explained in detail in next section. Before acoustic attenuation was fully investigated, tan δ (Mechanical Loss Coefficient) was used as a guiding property for selecting test polymers, since tan δ measures the degree to which a material dissipates vibrational energy. Granta CES EduPack 2012 [31] was used to find materials of different tan δ. Plots of tan δ vs. Price and tan δ vs. Density were generated for polymer materials using the software, shown in Figures 15 and Figure 16 below. From the plots, it can be seen that desirable vibration damping materials are flexible PVC (Shore A60) and butyl rubber, which are both inexpensive and light weight, while epoxy with carbon fiber composite has the poorest vibration damping capability.
Figure 15. $\tan \delta$ vs. Price for polymers.
Figure 16. tan δ vs. Density for polymers.

*Note:* From the plots above it can be seen that some materials have tan δ value higher than 1, which is practically impossible, as the energy lost cannot be more than the energy stored in; however, the reason to this is unknown.

The tan δ values were further detailed for various common polymers, summarized in Table 3 (again there is tan δ higher than 1, which is unreasonable). In order to make the drop ball attenuation measurement results more distinct, it is preferable to select polymer materials having a range of different tan δ values.
Table 3. $\tan \delta$ of common polymer materials [31].

<table>
<thead>
<tr>
<th>Material</th>
<th>$\tan \delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermoplastics</strong></td>
<td></td>
</tr>
<tr>
<td>EEA (Ethylene Ethyl Acrylate)</td>
<td>0.774</td>
</tr>
<tr>
<td>PVC, soft, A60</td>
<td>0.68 - 1.6</td>
</tr>
<tr>
<td>EMA (Ethylene Methyl Acrylate)</td>
<td>0.585</td>
</tr>
<tr>
<td>EVA (Ethylene Vinyl Acetate)</td>
<td>0.5</td>
</tr>
<tr>
<td>EBA (Ethylene Butyl Acrylate)</td>
<td>0.48</td>
</tr>
<tr>
<td>FEP (Fluorinated Ethylene Propylene)</td>
<td>0.11</td>
</tr>
<tr>
<td>Ionomer</td>
<td>0.1</td>
</tr>
<tr>
<td>PTFE (Teflon®)</td>
<td>0.07 - 0.1</td>
</tr>
<tr>
<td>UHMWP (Ultra High Molecular Weight Polyethylene)</td>
<td>0.041 - 0.045</td>
</tr>
<tr>
<td>PP (Polypropylene)</td>
<td>0.03 - 0.04</td>
</tr>
<tr>
<td>ASA (Acrylonitrile Styrene Acrylate)</td>
<td>0.0184</td>
</tr>
<tr>
<td>PC (Polycarbonate)</td>
<td>0.016 - 0.017</td>
</tr>
<tr>
<td>PVC (Polyvinyl Chloride), rigid</td>
<td>0.016 - 0.017</td>
</tr>
<tr>
<td>ABS (Acrylonitrile Butadiene Styrene)</td>
<td>0.0145 - 0.0183</td>
</tr>
<tr>
<td><strong>Thermosets</strong></td>
<td></td>
</tr>
<tr>
<td>Polyester, flexible</td>
<td>0.13 - 0.137</td>
</tr>
<tr>
<td>Epoxy, standard</td>
<td>0.016 - 0.017</td>
</tr>
<tr>
<td><strong>Thermoplastic Elastomers (TPE)</strong></td>
<td></td>
</tr>
<tr>
<td>PVC elastomer</td>
<td>0.2 - 0.5</td>
</tr>
<tr>
<td><strong>Thermoset Elastomers (Rubber)</strong></td>
<td></td>
</tr>
<tr>
<td>Fluoro elastomer</td>
<td>1.34</td>
</tr>
<tr>
<td>Butadiene rubber</td>
<td>0.065 - 0.13</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>0.06 - 0.17</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>0.05 - 0.1</td>
</tr>
</tbody>
</table>
When the cause of the reduction of the intensity of pressure waves as they travel through a medium became more clear, the acoustic attenuation property of a material was also taken into consideration. The acoustic properties of common materials are shown in Table 4. However, the quoted attenuation values can only serve as a rough reference. This is because attenuation is generally proportional to the square of sound frequency, yet the quoted attenuation values are evaluated at 5 MHz, which is much higher than the frequency range of interest in this work; also, the values are highly dependent on how the material is manufactured [32].

Table 4. Acoustic properties of common polymer materials [33-35].

<table>
<thead>
<tr>
<th>Material</th>
<th>Longitudinal Velocity m/s</th>
<th>Acoustic Impedance MRayl</th>
<th>Attenuation dB/cm @ 5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane rubber</td>
<td>2090</td>
<td>2.36</td>
<td>27.6 - 100</td>
</tr>
<tr>
<td>Polycarbonate (Lexan)</td>
<td>2300</td>
<td>2.75</td>
<td>23.2</td>
</tr>
<tr>
<td>Epoxy</td>
<td>2360</td>
<td>2.86</td>
<td>15 - 20 [36]</td>
</tr>
<tr>
<td>Nylon 6-6</td>
<td>2600</td>
<td>2.9</td>
<td>12.9</td>
</tr>
<tr>
<td>Acrylic, clear</td>
<td>2750</td>
<td>2.32</td>
<td>11.3</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>2270</td>
<td>3.27</td>
<td>11.2</td>
</tr>
<tr>
<td>Polyester</td>
<td>2290</td>
<td>2.86</td>
<td>10 - 20 [37]</td>
</tr>
<tr>
<td>UHMWP</td>
<td>2364</td>
<td>2.33</td>
<td>8 [38]</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2740</td>
<td>2.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Teflon®</td>
<td>1390</td>
<td>3</td>
<td>3.9</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2400</td>
<td>2.52</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Considering both the tan δ and attenuation property, together with the availability and cost, epoxy, polyester, Teflon®, UHMWP (Ultra High Molecular Weight Polyethylene), Type I PVC, Type II PVC, Neoprene rubber and polyurethane rubber were selected. Among these materials, epoxy and polyester are common matrix materials for fibrous composites, Type II PVC is used for parts subject to shock, and polyurethane has good vibration damping and energy absorption characteristics. Annealed type 17-4 PH stainless steel (precipitation hardening alloy 630) was also chosen to compare with polymer materials, as metal attenuates much less than polymers. All selected materials are listed in Table 5, note that the density values are obtained from the actual specimens whose fabrication is described later on. All commercially available materials were ordered in the form of approximately 31.8 mm (1.25 in) DIA rod, except for epoxy and polyester specimens which were hand cast by the author by mixing resin and hardener and then casting into molds. Materials were later machined and made into specimens of 50 mm (1.97 in) thickness and 31.8 mm (1.25 in) DIA.
### Table 5. All selected materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Comment</th>
<th>Density (g/cm³)</th>
<th>( \tan \delta )</th>
<th>Attenuation (dB/cm @ 5 MHz)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>Bondo® Fiberglass Resin</td>
<td>1.21</td>
<td>0.13 - 0.137</td>
<td>10 - 20</td>
<td>3M (St. Paul, MN)</td>
</tr>
<tr>
<td>Teflon®</td>
<td>Very slippery</td>
<td>2.17</td>
<td>0.07 - 0.1</td>
<td>3.9</td>
<td>United States Plastic Corp. (Lima, OH)</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>Durometer 75A</td>
<td>1.39</td>
<td>0.06 - 0.17</td>
<td>-</td>
<td>McMaster-Carr Supply Co. (Elmhurst, IL)</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>Durometer 80A</td>
<td>1.24</td>
<td>0.05 - 0.1</td>
<td>27.6 - 100</td>
<td>W.W. Grainger Inc. (Lake Forest, IL)</td>
</tr>
<tr>
<td>UHWMP</td>
<td>Slippery, high impact</td>
<td>0.91</td>
<td>0.041 - 0.045</td>
<td>8</td>
<td>Aircraft Spruce &amp; Specialty Corp. (Peachtree City, GA)</td>
</tr>
<tr>
<td>Epoxy</td>
<td>Poly Epoxy</td>
<td>1.15</td>
<td>0.016 - 0.017</td>
<td>15 - 20</td>
<td>McMaster-Carr Supply Co. (Elmhurst, IL)</td>
</tr>
<tr>
<td>Type II PVC</td>
<td>Chemically resistant, high impact</td>
<td>1.39</td>
<td>0.01 - 0.017</td>
<td>-</td>
<td>Speedy Metals (New Berlin, WI)</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>Chemically resistant, normal impact</td>
<td>1.36</td>
<td>0.01 - 0.016</td>
<td>11.2</td>
<td>McMaster-Carr Supply Co. (Elmhurst, IL)</td>
</tr>
<tr>
<td>Type 17-4 PH stainless steel</td>
<td>Precipitation hardenable</td>
<td>7.61</td>
<td>0.0003 - 0.00066</td>
<td>-</td>
<td>Speedy Metals (New Berlin, WI)</td>
</tr>
</tbody>
</table>

**Test Specimen Preparation**

*Fabrication of Epoxy and Polyester Specimens*

Next, epoxy and polyester specimens were made. The epoxy was Poly Epoxy Advanced Resin System obtained from Aircraft Spruce & Specialty Corp. (Peachtree City, GA) but made by System Three Resins, Inc. (Auburn, WA). It is a two part epoxy system that has high tensile, compressive, and flexural strengths [39]. It has a 105 min
pot life, and two cure cycles. At room temperature, the mixed epoxy cures in 6 hr; a post curing is accomplished by heating at 60°C (140°F) in air for 2 hr [39]. Poly Epoxy is also used later on by mixing in different additives. The as received two part Poly Epoxy system is shown in Figure 17 and its properties are listed in Table 6.

![Figure 17. Poly Epoxy resin (left, quart size) and hardener (right).](image)

**Table 6.** Poly Epoxy properties [39].

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>With Post Cure</th>
<th>Without Post Cure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, psi</td>
<td>9600</td>
<td>8800</td>
</tr>
<tr>
<td>Elongation at Break, %</td>
<td>7.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>470,000</td>
<td>460,000</td>
</tr>
<tr>
<td>Flexural Strength, psi</td>
<td>19,000</td>
<td>14,500</td>
</tr>
<tr>
<td>Flexural Modulus, psi</td>
<td>515,000</td>
<td>500,000</td>
</tr>
<tr>
<td>Compressive Strength, psi</td>
<td>32,000</td>
<td>33,000</td>
</tr>
<tr>
<td>Shore D Hardness</td>
<td>82</td>
<td>70</td>
</tr>
<tr>
<td>Glass Transition Temp., °C</td>
<td>72</td>
<td>62</td>
</tr>
<tr>
<td>Heat Distortion Temp., °C</td>
<td>64</td>
<td>50</td>
</tr>
</tbody>
</table>
The resin system has a mixing ratio of 3 parts resin to 1 part hardener by weight. 50 mm (1.97 in) tall specimens were made using the fabrication procedure shown in Figure 18 below.

Figure 18. (a) Pour resin into cup; (b) Pour hardener into cup; (c) Thoroughly mix resin and hardener; (d) Pour the mixture into the molding cup.
Note that in Figure 18 (d), the molding cup is made of polycarbonate, which gives a clear view of the mixture inside. However, a polycarbonate molding cup was only used for the initial trials because it was virtually impossible to remove the hardened sample from the polycarbonate cup. A more slippery material is preferred as a molding cup, for example, polyethylene, which was used later on in epoxy sample casting.

The mixture was then positioned in a desiccator which was then placed under vacuum in order to remove air bubbles within. The desiccator was the Economy Glass Vacuum Desiccators Model 2277-60 by Ted Pella, Inc. (Redding, CA). It is made of thick wall glass, and has an inside storage dimensions of 240 mm (9.34 in) by 140 mm (5.90 in). The desiccator and its stopcock are shown in Figure 19. Dow Corning (Midland, MI) High Vacuum Grease was used as the vacuum sealant.

![Desiccator](image)

Figure 19. (a) Desiccator; (b) Stopcock on the lid.

The vacuum pump was a Robinair (Owatonna, MN) High Performance Vacuum Pump Model 15600, which has a 6 CFM capacity and can pull a vacuum in the $10^{-3}$ Torr range, shown in Figure 20.
The epoxy mixture was placed in the desiccator, which was then evacuated. The setup is shown in Figure 21. After several minutes, the pressure inside desiccator dropped to nearly 0 Torr (gauge), as shown by the vacuum gage in Figure 22 (a). Bubbles began to rise up and escape from within the mixture as shown in Figure 22 (b). It is unclear whether all of these were trapped bubbles or possibly air dissolved within the mixture.
Figure 21. Sample within the desiccator and vacuum pumping setup.

Figure 22. (a) Gage reads 0 Torr (gauge); (b) Bubbles foaming up.
After 6 hr under vacuum, the epoxy sample was totally cured. It was then
removed from the molding cup and heated to 60°C (140°F) in air for 2 hr for post curing.

There are a few tips learned from making epoxy samples:

1. In order for the air bubbles to escape more easily, it is better to preheat the epoxy
   resin to 40°C (104°F) before mixing, which makes the resin warm and less viscous.

2. The waiting time between epoxy being mixed and placed into desiccator needs to be
   kept as short as possible. As the mixture gets more viscous (hardening), it becomes
   more difficult for the air bubbles to come out, in which case the desiccator system
   may very possibly produce a foam like product.

3. Only a few materials can be used as molding cups, for example, polyethylene which
   is slippery and possesses self-releasing characteristics. Other materials, for example,
   polycarbonate as shown in Figure 18 (d), will stick to the epoxy and it becomes
   virtually impossible to remove the sample.

4. One can spray the molding cup’s surface with lubricant before pouring epoxy mixture
   into the cup which helps prevent the epoxy from sticking to the mold. However, too
   much lubricant appears to cause the epoxy mixture to not cure properly. Here,
   “B’laster” Silicone Spray Lubricant by Blaster Corporation (Valley View, OH) was
   used.

A 50 mm (1.97 in) tall polyester specimen was also made. The polyester used was
Bondo® Fiberglass Resin Kit by 3M, which contains a can of resin and tube of hardener
(Figure 23). The mixing ratio by weight of resin to hardener is 78.7 to 1, which is
equivalent to 4 g of resin to 1 drop of hardener. The resin has a cure cycle of 1 to 1.5 hr.

The procedure for making this specimen is shown in Figure 24.
Figure 23. Bondo Fiber Glass Resin Kit (quart size resin).
However, since this polyester hardens really quickly (1.5 hr or less), the bubbles won’t be able to totally escape, which results in a foam like final product. Therefore, it was decided to not use the desiccator for making polyester samples and to just let the mixture harden in air. Also note that when this polyester hardened, it generated large amounts of heat, which required special attention in handling and choosing of the molding cup material.
Making Other Polymer Specimens

Other polymer materials, i.e., Teflon®, UHMWP, Type I PVC and Type II PVC in approximately 31.8 mm (1.25 in) DIA rods were also obtained, cut and sanded into desired 50 mm (1.97 in) tall specimens. A 50 mm type 17-4 PH stainless steel sample was also made for comparison. A 15 mm (0.591 in) thick heat treated type 17-4 PH stainless steel disk was made as the target for ball drop, which will be explained in the next Chapter. All of the specimens that were made are shown in Figure 25, and their properties are shown in Table 7. It can be seen that among all of the polymers selected here, UHMWP has the lowest density, while Teflon® has the highest.

Figure 25. All samples that were made.
Table 7. Specimen properties.

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass (g)</th>
<th>Thickness (mm)</th>
<th>Diameter (mm)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 17-4 PH stainless steel</td>
<td>304.9</td>
<td>49.8</td>
<td>32.0</td>
<td>7.61</td>
</tr>
<tr>
<td>Teflon®</td>
<td>86.3</td>
<td>49.8</td>
<td>31.9</td>
<td>2.17</td>
</tr>
<tr>
<td>Type II PVC</td>
<td>55.3</td>
<td>49.8</td>
<td>31.9</td>
<td>1.39</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>51.3</td>
<td>49.9</td>
<td>30.7</td>
<td>1.39</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>53.5</td>
<td>49.6</td>
<td>31.8</td>
<td>1.36</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>50.5</td>
<td>51.1</td>
<td>31.8</td>
<td>1.24</td>
</tr>
<tr>
<td>Polyester</td>
<td>43.3</td>
<td>48.9</td>
<td>30.5</td>
<td>1.21</td>
</tr>
<tr>
<td>Epoxy</td>
<td>44.7</td>
<td>49.7</td>
<td>31.6</td>
<td>1.15</td>
</tr>
<tr>
<td>UHMWP</td>
<td>36.1</td>
<td>49.6</td>
<td>31.9</td>
<td>0.91</td>
</tr>
</tbody>
</table>

In ultrasonic testing, preparation of test specimens is extremely important to ensure the validity and consistency of the test. The preparation process can be very meticulous and time consuming. The lessons and tips learned for this process are:

1. The dimensions of all the specimens have to be as identical as possible. Here, the thicknesses of all specimens ranged from 48.9 mm (1.93 in) to 51.3 mm (2.02 in), and the diameters ranged from 30.7 mm (1.21 in) to 32.0 mm (1.26 in).

2. The specimen surfaces have to be very flat, smooth and parallel to ensure good signal transmission. This was achieved using 600 grit SiC sandpaper lubricated with tap water for consistency of final surface finish.

3. When using a Buehler (Lake Bluff, IL) Beta Twin Variable Speed Grinder-Polisher machine, if the specimen diameter is “thinner” than the spinning specimen holder hole diameter, a slanted surface will be produced from sanding. If this happens, the specimen should be hand sanded to the desired surface finish. A Buehler Handimet 2
Roll Grinder, containing 240, 320, 400, and 600 grit SiC was used for tap water lubricated hand sanding (Figure 26).

Figure 26. Buehler Handimet 2 Roll Grinder (the sandpaper is 7.9 cm = 3.1 in wide).
V  Experimental Setup

Test Configurations

ASTM E976, E2075 and E650 have been reviewed and several suggestions were extracted:

1. The test structure can be a block or a rod, and the resonances of the test structure should be eliminated.
2. A pencil lead break may be used to generate a desired acoustic pulse and signal.
3. A waveguide can be used to facilitate wave transmission.
4. A couplant material should be carefully chosen and its application has to be kept as consistent as possible each time.

A typical setup using an acrylic rod and pencil lead break can be seen in Figure 27 from ASTM E976.

Figure 27. Pencil lead break on an acrylic rod [27].

These ASTM suggestions were taken into consideration when experimenting with test setups. In order to investigate the attenuation characteristics of a material, an acoustic
pulse (sometimes called signal) needs to be generated, which will transmit through the test material, to be possibly attenuated/reduced, and then received on the other side by a sensing device like a piezoelectric sensor. The reduced signal will then be analyzed to evaluate how much it has been attenuated by the test material.

A few mechanisms were experimented to generate the input signal, which include breaking of a pencil lead and tapping. Breaking of a pencil lead or glass capillary tube are common approaches used at the National Institute of Standards and Technology (NIST) and elsewhere for many years. While these types of sources are convenient and controllable, they seem to lack the short duration impulse necessary to generate exceptionally strong, energetic, and detectable pulses as needed to propagate pressure waves over long distances through highly attenuating materials like polymers. Tapping, on the other hand, is manually done and can hardly be consistent. Here, a large magnitude, highly accelerating force applied over a very short duration (rise time) is necessary, and the generating method has to be controllable and consistent. Finally, it was decided to use the dropping of a steel ball as the acoustic signal source since this can produce a very fast and energetic source that can be repeatedly controlled.

In order to achieve the attenuation measurement, several test configurations were experimented. The configuration in Figure 28 is similar to that suggested by ASTM E2075, where a small flat spotface was machined onto the steel rod, and the sensor was held to the end of the rod by a rubber band. However, with this setup, little of the signal can reach the sensor, thus the signal that is captured by the sensor was not strong enough. Also, it was difficult to hold the sensor to the end of the steel rod consistently each time
as well as consistently produce the same signal. Therefore, this setup was not used in the end.

Figure 28. Test configuration using steel rod.

Figure 29 is also similar to one of the common setups used for ultrasonic measurement. However, the signal transmission path to the sensor is also complicated in this case, and it is also difficult to mount the sensor consistently every time. Therefore, this configuration was not used either.
Drop ball Test Setup

The final test configuration was decided to be the one shown in Figure 30, where the drop ball target, the test specimen and sensor are vertically aligned together. The 15 mm (0.591 in) thick type 17-4 PH stainless steel disk was used as the drop ball target and also the wave guiding material, thus the ball will not drop on the test specimen directly and therefore the surface hardness effect of the test specimens is eliminated.
In the setup shown above, the acoustic signal is generated by dropping the steel ball onto the target. The input signal travels through the test specimen, and the reduced outcome signal is received by the piezoelectric sensor and displayed on a digital oscilloscope. The RMS (root mean square) voltage, which is proportional to the average signal power, is recorded for each test. Since the dropping of the steel ball is kept consistent each time, higher RMS results for certain test specimens mean that less signal has been attenuated, which indicates a poorer attenuation capability, and vice versa. Various materials were tested and their attenuation capabilities can be relatively compared with each other. Tested specimens include type 17-4 PH stainless steel.
(untreated), epoxy, polyester, Teflon®, UHMWP, Type I PVC, Type II PVC, Neoprene rubber and polyurethane rubber, all were 50 mm (1.97 in) tall and 31.8 mm (1.25 in) DIA.

**Equipment & Setup Details**

A close up view of the setup is shown in Figure 31. As can be seen, the drop ball test setup mainly consists of a charge amplifier, a digital oscilloscope, a piezoelectric sensor and a steel support stand with a screw release clamp. The equipment used are listed in Table 8 and explained in more detail later in this section.

![Figure 31. Close up view of the test setup.](image-url)
Table 8. Equipment list.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 504E Dual Mode Amplifier</td>
<td>Kistler Instrument Corp. (Novi, MI)</td>
</tr>
<tr>
<td>TDS1012C-EDU Digital Storage Oscilloscope</td>
<td>Tektronix, Inc. (Beaverton, OR)</td>
</tr>
<tr>
<td>R30 General Purpose Acoustic Emission Sensor</td>
<td>Physical Acoustics Corp. (Princeton Junction, NJ)</td>
</tr>
<tr>
<td>Support Stand</td>
<td>Technical Devices Co. (Culver City, CA)</td>
</tr>
<tr>
<td>HDPE Platform</td>
<td>King Plastic Corp. (North Port, FL)</td>
</tr>
<tr>
<td>Castaloy-R Clamps</td>
<td>Thermo Fisher Scientific Inc. (Waltham, MA)</td>
</tr>
<tr>
<td>Petroleum Jelly</td>
<td>Vi-Jon Laboratories, Inc. (St. Louis, MO)</td>
</tr>
<tr>
<td>Chrome Steel Bearing Balls</td>
<td>Tool Supply, Inc. (Tualatin, OR)</td>
</tr>
<tr>
<td>B’laster Silicone Spray Lubricant</td>
<td>Blaster Corporation (Valley View, OH)</td>
</tr>
</tbody>
</table>

The amplifier used here is a Model 504E Dual Mode Amplifier by Kistler Instrument Corp., shown in Figure 32. It is a multi-range amplifier especially designed to follow piezoelectric pickups or transducers, and oscilloscopes. It converts electrostatic charge input to standard voltage output in any of the twelve range positions [40]. For this setup, the OPERATE pushbutton is pressed, the Time Constant switch is set to SHORT, the TRANSDUCER SENSETIVITY is selected to be the highest which is 11.0 pC/psi, g, lb. The RANGE is dialed to a proper setting to optimize the signal display on the oscilloscope. If the RANGE is not set high enough, the signal might be saturated and won’t be fully displayed on the oscilloscope screen; when the RANGE setting is doubled, the signal magnitude is halved. The amplifier is connected with the sensor to receive the signal, and connected with the oscilloscope to output the signal.
Figure 32. Model 504E Dual Mode Amplifier connected to the piezoelectric sensor.

The digital oscilloscope used here is the TDS 1012C-EDU Digital Storage Oscilloscope by Tektronix (Figure 33). It has two channels, color TFT display, 100 MHz bandwidth, and 1.0 GS/s sample rate. It also has a USB port for data export and storage.
As shown above, Channel 2 of the oscilloscope is connected to the charge amplifier as it was found to yield slightly less electronic noise than Channel 1. On the display screen, the Channel 2 RMS and Frequency are measured. On the plot area of the screen, each vertical small division represents 20 V; each horizontal small division represents 250 µs. On the operation area, Trig Manu is set so that only signals that pass certain criterion (here the drop ball instigated signals) will be captured on the screen. Trigger level is set to be negative voltage value on falling slope. The Save pushbutton can save a picture of the displayed signal or the waveform data.

The piezoelectric sensor used here is the R30 General Purpose Acoustic Emission Sensor, manufactured by Physical Acoustics Corporation. The sensor is inserted in a UHMWP casing and laid on a sponge over the HDPE platform (Figure 34); the sponge here is used to eliminate the vibration of the sensor - specimen system on the more rigid
platform. It is a resonant type sensor designed to be low cost, high sensitivity, medium size and medium temperature range, which can be used in most AE applications. It has a varied response with peak sensitivity at about 300 kHz. Some specifications of the sensor are shown in Table 9 and its calibration is shown in Figure 35, which is based on ASTM E976.

![R30 sensor](image1.png)  
![Sensor in casing](image2.png)

Figure 34. (a) R30 sensor; (b) Sensor in casing.

Table 9. Specifications of R30 sensor [41].

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Sensitivity V/(m/s); [V/µbar]</td>
<td>58; [-62] dB</td>
</tr>
<tr>
<td>Operating Frequency Range</td>
<td>150 to 400 kHz</td>
</tr>
<tr>
<td>Resonant Freq. V/(m/s); [V/µbar]</td>
<td>300; [330] kHz</td>
</tr>
<tr>
<td>Directionality</td>
<td>±1.5 dB</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-65°C (149 ºF) to 175°C (347 ºF)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>19 mm (0.75 in) DIA by 22.4 mm (0.88 in) height</td>
</tr>
<tr>
<td>Weight</td>
<td>29 g</td>
</tr>
<tr>
<td>Case Material</td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Face Material</td>
<td>Ceramic</td>
</tr>
</tbody>
</table>
A Castaloy-R clamp by Thermo Fisher Scientific Inc. is clamped on the horizontal stainless steel rod. The ball drop height and position can be adjusted by moving the horizontal rod and the clamp. The ball drop is done by slightly rotating the screw. As shown in Figure 36, a small circle is marked in the center of the type 17-4 PH stainless steel disk as the ball drop target. The position of the clamp is adjusted, and the rotating of the screw is controlled as consistent as possible, so that the ball will fall within the small circle each time to ensure the consistency of the test. Since the steel ball used here is relatively small, it is noticed that the turning of the screw largely affects the
consistency of the ball drop, as a “strong” release can cause the ball to swirl and fly away. To ensure a smooth and consistent release each time, the screw is just lightly pushed against the ball to prevent it from falling down, and petroleum jelly is applied to the threads of the screw to make sure of a smooth release. The petroleum jelly used is by Vi-Jon Laboratories, Inc. Petroleum jelly, which is not water based, will not cause steel to corrode.

Figure 36. Clamp on the rod with steel ball ready for launch.

The steel balls used here to generate acoustic signals are Chrome Steel Bearing Balls from Tool Supply Inc. (Figure 37). They have a composition of Fe/1.3-1.6Cr/0.98-1.05C/0.25-0.45Mn/0.15-0.35Si/<0.02P/<0.008S wt. % and hardness HRC 60-67 [42].
The diameters available are 12.7 mm (0.5 in), 9.53 mm (0.375 in), 7.95 mm (0.313 in), 6.35 mm (0.25 in), 4.76 mm (0.188 in) and 3.18 mm (0.125 in). However, for the best results of the drop ball test, only sizes 4.76 mm (0.188 in) and 3.18 mm (0.125 in) balls were used.

![Chrome steel ball assortment.](image)

Figure 37. Chrome steel ball assortment.

The wave guiding target here is a 31.8 mm (1.25 in) DIA, 15 mm (0.591 in) thick disk made from annealed type 17-4 PH stainless steel, from Speedymetals.com. Per the drop ball test, this target is placed above the polymer specimen (Figure 38); a steel ball is dropped on this disk directly instead of on the polymer specimen, thus to eliminate the
effect of surface hardness of the polymer materials. Type 17-4 PH stainless steel is a chromium-nickel-copper precipitation hardening stainless steel featuring high strength, high hardness (up to Rockwell C40-48) and excellent corrosion resistance. It is chosen as the target mainly for its high hardness, in order that the steel ball will leave little to no dent on the disk surface.

Figure 38. Stainless steel target above one of the polymer specimens.

To make the target, first a 15 mm (0.591 in) thick type 17-4 PH stainless steel sample was cut and sanded to desired dimensions. Afterwards, a H900 heat treatment was performed in order to increase its hardness. Hardness testing was performed for the untreated material using a Rockwell Hardness Tester by Wilson Instrument Division (Norwood, MA) shown in Figure 39, where calibration with standard calibration blocks showed a ± 3 error range. Five hardness measurements were taken and are shown in Table 10, where the average value is C31.9.
A condition H900 heat treatment was then performed on the sample. The sample was heated in a Thermcraft (Winston-Salem, NC) Bench Top Box Furnace at the temperature of 482°C (900°F) for 1 hr, and air cooled afterwards. When the sample was taken out of the oven, a layer of oxide was found on the top surface which was sanded off.
after cooling (Figure 40). Finally the cooled sample was sanded on a Buehler Beta Twin Variable Speed Grinder-Polisher machine using tap water lubricated 600 grit SiC to generate a smooth surface (Figure 41). Another hardness testing was done on the treated specimen, and the results are shown in Table 11. Calibration testing performed on a Wilson Instrument Rockwell C44.1 calibration block gave a result of C40. The average hardness of type 17-4 PH stainless steel was found to be C36.4 after heat treatment.

Figure 40. Type 17-4 PH target with oxide on the surface after heat treatment.

Figure 41. Type 17-4 PH target being sanded using 600 grit SiC.
Table 11. Hardness testing results for H900 heat treated type 17-4 PH target.

<table>
<thead>
<tr>
<th>Trial</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rockwell Hardness</td>
<td>C35.5</td>
<td>C36.5</td>
<td>C36.5</td>
<td>C37</td>
<td>C36.5</td>
<td>C36.4</td>
</tr>
</tbody>
</table>

The use of couplant is another factor that largely affects the result of ultrasonic or acoustic emission testing. As explained in the Technical Background section, couplant fills in the air gap between the test specimen and ultrasonic sensor, and facilitates the transmission of the ultrasonic signal, as air almost cannot transmit any waves between these. For this test setup, couplant is applied between the guiding target and test specimen, and also between the specimen and sensor (Figure 42).

Figure 42. Couplant application.
However, different couplant materials have different acoustic impedance property, viscosity and makeup (e.g. water-based, oil-based, etc.), which are all factors that need to be considered when it comes to the selection of couplant for a particular ultrasonic test setup. For this test setup, four different types of couplant were experimented: glycerin, Ultragel II by Sonotech (Roseville, CA), petroleum jelly and B’laster Silicone Spray Lubricant (Figure 43). Their acoustic impedance and percentage of signal transmission with stainless steel (45.4 MRayl) are calculated using Eq. (5) in Chapter III, and shown in Table 12.

Figure 43. (a) Glycerin; (b) Ultragel II; (c) Petroleum jelly; (d) B’laster Silicone Spray Lubricant.
Table 12. Acoustic impedance and signal transmission of different couplants.

<table>
<thead>
<tr>
<th>Couplants</th>
<th>Acoustic Impedance (MRayl) [22-24]</th>
<th>Signal Reflection with Stainless Steel</th>
<th>Signal Transmission with Stainless Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycerine</td>
<td>2.43</td>
<td>80.7%</td>
<td>19.3%</td>
</tr>
<tr>
<td>Ultragel II</td>
<td>1.8</td>
<td>85.3%</td>
<td>14.7%</td>
</tr>
<tr>
<td>Petroleum jelly</td>
<td>1.95</td>
<td>84.2%</td>
<td>15.8%</td>
</tr>
<tr>
<td>Silicone Spray</td>
<td>0.983</td>
<td>91.7%</td>
<td>8.3%</td>
</tr>
<tr>
<td>Lubricant</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When choosing couplant materials, the following factors need to be considered: signal transmission capability, interaction with test specimen along with consistency and ease on application during repeated testing. However, every couplant candidate here has its own disadvantage. For Ultragel II and Petroleum jelly (Vaseline), it was noticed that the amount of couplant applied each time largely affected the test result, as the drop ball test system presented here is very sensitive and delicate. Ultragel II is water-based, which causes the steel pieces to corrode. Glycerin, as shown in Table 12, has better signal transmission compared to other couplants, however, it does not wet the specimen surface (always tends to gather back into one place), and it is so viscous that the steel target cannot rest stably on the test specimen, that a slightly slanted specimen surface will cause the steel target to slide off. Therefore, in the end, the B’laster Silicone Spray Lubricant was selected mainly because it is very consistent in application as it leaves a thin layer on the specimen surface, and it is not so slippery so that the steel target can rest easily on the specimen without sliding off. Silicone-based lubricant has a low signal transmission with metal, however, in this test setup, as the silicone layer is very thin this effect may not be as significant.
Drop Ball Test Suggestions

Conventional attenuation measurement usually consists of an ultrasonic source (which may include a pulse generator, function generator, and amplifier [26]), transmitting transducer, and receiving transducer that are separated by a known distance. The received signal is then analyzed with an ultrasonic analyzer and displayed on an oscilloscope [26]. With these types of setups, attenuation is typically evaluated at high frequencies, i.e. MHz range. The drop ball test setup presented here is different from conventional testing methods in the following aspects:

1. It evaluates ultrasonic activities at a much lower frequency range, i.e. up to a few hundred kHz, since this is what the ball drop generates. Most real acoustic emission activities occur in the kHz range.

2. It features a simpler test setup, utilizing only a piezoelectric sensor, charge amplifier, digital oscilloscope, and a simple drop ball mechanism. It does not need the function generator or transmitting transducer.

Besides, the screw release ball drop mechanism is proven to be very controllable and consistent. The ball drop mechanism can be used in other impact testing applications as well.

Nevertheless, ultrasonic or acoustic emission testing is a very meticulous, sensitive and “tricky” type of experimental science. Many factors have to be considered and dealt with properly to ensure the validity and success of the test. In the same way, many small details, if ignored, can cause the test results to be inaccurate. The lessons and tips of performing the presented drop ball test are given as follows.
1. The contact surfaces of the specimen have to be very smooth, flat and parallel. Surface irregularities (e.g., hills and valleys) significantly affect the results. To ensure flat and parallel surfaces, it is preferred to sand the specimen by hand. The smoothness of the surface affects the signal transmission. In this case, all of the specimens were sanded to a 600 grit surface finish.

2. The release of the ball has to be kept consistent each time. Too much pushing and twisting will cause the ball to rotate in the air and fall on target in a different manner. To ensure consistency, before release, the screw is just lightly pushing against the ball to prevent it from falling, and petroleum jelly is applied to the screw threads to make sure of a smooth turning of the screw.

3. The drop ball has to be controlled so that the ball will hit the target on the exact same location every time. An issue is that the frequently hit area of the guiding target ends up with a different surface condition from the rest.

4. As the test system presented here is very sensitive and delicate, the amount of couplant applied and the manner of application greatly affect the results. Silicone spray was chosen here as the couplant material because of its easier-to-control consistency in application. To ensure consistency in every test, the residue couplant on the sensor and specimen surfaces is wiped out, and the silicone spray is reapplied in the same manner and amount.

5. Since the couplant material is slippery and the drop ball test involves an impact load, the testing pieces may slide or slightly change position after several tests. One should always watch out for the sensor and test specimen position change.
6. The influence of the ambient environment on the test system should be eliminated. Here a sponge is placed between the sensor and the platform to prevent the testing system from rocking on the hard platform surface. After each drop of ball, the bouncing up ball is captured by hand so that it will not hit the platform surface. The platform surface has to be flat and laying horizontally.

7. The amplifier range is set so the signal is not saturated. Oscilloscope is also set up to fit the signal, and to eliminate electrical noise as well. Trigger level is set properly according to each specimen to capture the wanted signals.

8. The test specimen size and the input signal strength must match to ensure an effective measurement of signal attenuation. At first, a 9.53 mm (0.375 in) DIA steel ball and 15 mm (0.591 in) thick specimens were used for testing, but yielded very similar RMS results among different specimens. It was conjectured that the input signal was too strong for the specimen; that the attenuated portion was very small compared to the input signal and could not be fully appreciated on the resultant RMS measurement. Later, the 4.76 mm (0.188 in) and 3.18 mm (0.125 in) DIA balls were chosen, the specimens were made to be 50 mm (1.97 in) tall, and the RMS results became much more distinct.
VI Drop Ball Test Results

RMS Results of Two Test Sets

Two sets of drop ball tests were performed on various samples, one using a 4.76 mm (0.188 in) DIA steel ball, and another using a 3.18 mm (0.125 in) DIA ball. The specimens tested were of the type 17-4 PH stainless steel target only (no 50 mm specimen), 50 mm (1.97 in) tall type 17-4 PH stainless steel, epoxy, polyester, Teflon®, UHMWP, Type I PVC, Type II PVC, Neoprene rubber and polyurethane rubber. The drop ball test was performed several times on each test specimen from a drop height of 12.0 cm (4.72 in). The RMS voltage value of the signal received by the sensor was recorded, which indicated the average power of the received signal. The higher the RMS value was, the less the impact signal was attenuated, which indicated a poorer attenuation ability of the test material, and vice versa. For each material, five tests were performed with the average and standard deviation obtained. For the test set using the 4.76 mm (0.188 in) DIA ball, the test setup is shown in Table 13; the RMS results are shown in Table 14 and plotted in Figure 44.

Table 13. Test setup of the 4.76 mm (0.188 in) ball test set.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier Transducer Sensitivity</td>
<td>11.0 pC/psi</td>
</tr>
<tr>
<td>Amplifier Range</td>
<td>5 V/psi</td>
</tr>
<tr>
<td>Oscilloscope Display</td>
<td>20 V/div; 250 μs/div</td>
</tr>
<tr>
<td>Ball size</td>
<td>4.76 mm (0.188 in) DIA</td>
</tr>
<tr>
<td>Drop Height</td>
<td>12.0 cm (4.72 in)</td>
</tr>
</tbody>
</table>
Table 14. RMS results for the 4.76 mm (0.188 in) ball test set.

<table>
<thead>
<tr>
<th>Material</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Std. Dev.</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target only</td>
<td>26.6</td>
<td>26.2</td>
<td>26.6</td>
<td>25.8</td>
<td>25.8</td>
<td>0.40</td>
<td>26.2</td>
</tr>
<tr>
<td>Type 17-4 PH stainless steel</td>
<td>9.71</td>
<td>9.46</td>
<td>9.64</td>
<td>9.71</td>
<td>9.43</td>
<td>0.14</td>
<td>9.59</td>
</tr>
<tr>
<td>Epoxy</td>
<td>6.40</td>
<td>6.63</td>
<td>6.71</td>
<td>6.61</td>
<td>6.66</td>
<td>0.12</td>
<td>6.60</td>
</tr>
<tr>
<td>Type II PVC</td>
<td>5.91</td>
<td>5.81</td>
<td>5.76</td>
<td>5.85</td>
<td>5.75</td>
<td>0.07</td>
<td>5.82</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>5.59</td>
<td>5.52</td>
<td>5.67</td>
<td>5.40</td>
<td>5.49</td>
<td>0.10</td>
<td>5.53</td>
</tr>
<tr>
<td>Teflon®</td>
<td>4.93</td>
<td>5.02</td>
<td>5.06</td>
<td>4.92</td>
<td>4.95</td>
<td>0.06</td>
<td>4.98</td>
</tr>
<tr>
<td>Polyester</td>
<td>4.42</td>
<td>4.54</td>
<td>4.40</td>
<td>4.63</td>
<td>4.58</td>
<td>0.10</td>
<td>4.51</td>
</tr>
<tr>
<td>UHMWP</td>
<td>4.06</td>
<td>4.12</td>
<td>4.20</td>
<td>4.07</td>
<td>4.17</td>
<td>0.06</td>
<td>4.12</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>4.03</td>
<td>4.02</td>
<td>4.00</td>
<td>4.03</td>
<td>4.05</td>
<td>0.02</td>
<td>4.03</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>3.85</td>
<td>3.80</td>
<td>3.77</td>
<td>3.84</td>
<td>3.74</td>
<td>0.05</td>
<td>3.80</td>
</tr>
</tbody>
</table>
As reported in Table 14, the type 17-4 PH stainless steel target only (with no 50 mm thick test specimen) had the largest average RMS value of 26.2 V. Since there is no test specimen, it was treated as the minimum attenuation case. The 50 mm (1.97 in) tall type 17-4 PH stainless steel specimen had the next highest average RMS value of 9.59 V, which was to be expected as metals attenuate much less than polymers. The tested polymer materials had average RMS values ranging from 3.80 to 6.60 V. Among these, epoxy had the poorest attenuation characteristics, while neoprene rubber and polyurethane rubber had the best. It might be expected that polyurethane should yield low
RMS values, since it attenuates 27.6 to 100 dB/cm @ 5 MHz, which is the highest reported attenuation amongst all materials tested here; but realize that this is reported at a higher frequency than the present study. Other than the rubbers, UHMWP and polyester also had good attenuation capabilities.

Moreover, it also can be seen from Table 14 that the drop ball test is very controllable and reproducible, that it produces very consistent RMS results with standard deviations ranging from just 0.5 - 2.0%. As shown in Figure 31, the drop height, location, and ball size are all adjustable in order to generate desired impact load. The drop ball mechanism may have potential use for other impact test applications, and can possibly serve as a substitute for the commonly used Hsu-Nielsen pencil lead breakage method or breaking of glass capillary tubes for generating acoustic source waves in acoustic emission or ultrasonic testing.

The tan δ and attenuation data of some test materials are recalled in Table 15. RMS vs. tan δ and RMS vs. Attenuation of these materials are plotted in Figure 45 and 46. Note that the attenuation data here is the average value of the materials of the same category, and is measured at 5 MHz, so it can only serve as a reference. However, from the plots, a general tendency is that the average RMS values decrease as tan δ and attenuation increase.
Table 15. Average tan δ, attenuation, and RMS data for some test materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Avg. tan δ [31]</th>
<th>Avg. Attenuation dB/cm @ 5 MHz [33-38]</th>
<th>Avg. RMS (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 17-4 PH stainless steel</td>
<td>0</td>
<td>-</td>
<td>9.59</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0.016</td>
<td>17.5</td>
<td>6.6</td>
</tr>
<tr>
<td>Type II PVC</td>
<td>0.013</td>
<td>-</td>
<td>5.82</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>0.013</td>
<td>11.2</td>
<td>5.53</td>
</tr>
<tr>
<td>Teflon®</td>
<td>0.085</td>
<td>3.9</td>
<td>4.98</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.133</td>
<td>15</td>
<td>4.51</td>
</tr>
<tr>
<td>UHMWP</td>
<td>0.043</td>
<td>8</td>
<td>4.12</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>0.11</td>
<td>-</td>
<td>4.03</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>0.075</td>
<td>63.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Figure 45. RMS vs. tan δ for some test materials [31].
Next, a test set using 3.18 mm (0.125 in) DIA ball was also performed as a comparison. The 3.18 mm (0.125 in) DIA ball generates a much weaker acoustic signal than the 4.76 mm (0.188 in) DIA ball. The test set up is shown in Table 16. The RMS results are shown in Table 17 and plotted in Figure 47.

Table 16. Test setup of the 3.18 mm (0.125 in) ball test set.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier Transducer Sensitivity</td>
<td>11.0 pC/psi</td>
</tr>
<tr>
<td>Amplifier Range</td>
<td>5V/psi</td>
</tr>
<tr>
<td>Oscilloscope Display</td>
<td>20 V/div; 250 µs/div</td>
</tr>
<tr>
<td>Ball size</td>
<td>3.18 mm (0.125 in)</td>
</tr>
<tr>
<td>Drop Height</td>
<td>12.0 cm (4.72 in)</td>
</tr>
</tbody>
</table>

Figure 46. RMS vs. Attenuation for some test materials [33-38].
Table 17. RMS results for the 3.18 mm (0.125 in) ball test set.

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Std. Dev.</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target only</td>
<td>17.38</td>
<td>16.9</td>
<td>16.78</td>
<td>17.1</td>
<td>17.2</td>
<td>0.24</td>
<td>17.1</td>
</tr>
<tr>
<td>Type 17-4 PH stainless steel</td>
<td>7.00</td>
<td>7.25</td>
<td>7.18</td>
<td>7.30</td>
<td>7.06</td>
<td>0.13</td>
<td>7.16</td>
</tr>
<tr>
<td>Epoxy</td>
<td>2.98</td>
<td>2.89</td>
<td>2.83</td>
<td>2.87</td>
<td>2.85</td>
<td>0.06</td>
<td>2.88</td>
</tr>
<tr>
<td>Type II PVC</td>
<td>2.05</td>
<td>2.07</td>
<td>2.15</td>
<td>2.17</td>
<td>2.19</td>
<td>0.06</td>
<td>2.13</td>
</tr>
<tr>
<td>Teflon®</td>
<td>2.12</td>
<td>2.14</td>
<td>2.09</td>
<td>2.08</td>
<td>2.17</td>
<td>0.04</td>
<td>2.12</td>
</tr>
<tr>
<td>Type I PVC</td>
<td>2.03</td>
<td>2.05</td>
<td>2.11</td>
<td>2.12</td>
<td>2.03</td>
<td>0.04</td>
<td>2.07</td>
</tr>
<tr>
<td>UHMWP</td>
<td>1.86</td>
<td>1.72</td>
<td>1.86</td>
<td>1.84</td>
<td>1.85</td>
<td>0.06</td>
<td>1.83</td>
</tr>
<tr>
<td>Neoprene rubber</td>
<td>1.80</td>
<td>1.84</td>
<td>1.73</td>
<td>1.83</td>
<td>1.79</td>
<td>0.04</td>
<td>1.80</td>
</tr>
<tr>
<td>Polyester</td>
<td>1.62</td>
<td>1.54</td>
<td>1.52</td>
<td>1.59</td>
<td>1.61</td>
<td>0.04</td>
<td>1.58</td>
</tr>
<tr>
<td>Polyurethane rubber</td>
<td>1.49</td>
<td>1.46</td>
<td>1.49</td>
<td>1.52</td>
<td>1.48</td>
<td>0.02</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Figure 47. RMS results for various test specimens.
The RMS results of 3.18 mm (0.125 in) DIA drop ball show a similar pattern with that of the 4.76 mm (0.188 in) DIA drop ball. However, as seen in Table 17, the best attenuating materials here become polyester and polyurethane rubber, with the poorest still being epoxy. Also the RMS result of type 17-4 PH stainless steel specimen is more distinct compared with the other polymer specimens. Again from Table 17 it can be seen that the drop ball test is very reproducible.

The RMS vs. $\tan \delta$ and RMS vs. Attenuation (dB/cm @ 5 MHz) for some test materials are plotted in Figures 48 and 49. Again, a tendency can be seen that RMS results decrease as $\tan \delta$ and attenuation increase.

![RMS vs. $\tan \delta$](image)

Figure 48. RMS vs. $\tan \delta$ for some test materials [31].
Figure 49. RMS vs. Attenuation for some test materials [33-38].

Wave Signals of Two Test Sets

The oscilloscope has a USB port that can export and store data, so the waveform signal for each drop ball test can be retrieved. Among the five tests performed on each specimen, one was randomly chosen and its waveform signal saved. Here the signals of each test specimen for both the 4.76 mm (0.188 in) ball and 3.18 mm (0.125 in) ball test are given, shown next to one another. Figures 50 to 59 show the signals for all of the specimens tested.
Figure 50. Wave signals for target only (here the amplifier range is set to be 10 V/psi for this case since the signal was too strong, so the RMS values obtained here should be doubled before they can be compared with other specimens with amplifier range setting of 5 V/psi).
Figure 51. Wave signals for type 17-4 PH stainless steel.
Figure 52. Wave signals for epoxy.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball

Figure 53. Wave signals for polyester.
(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball

Figure 54. Wave signals for Teflon®.
Figure 55. Wave signals for UHMWP.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
Figure 56. Wave signals for Type I PVC.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
Figure 57. Wave signals for Type II PVC.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
Figure 58. Wave signals for Neoprene rubber.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
Figure 59. Wave signals for polyurethane rubber.

(a) 4.76 mm (0.188 in) drop ball

(b) 3.18 mm (0.125 in) drop ball
The wave signals presented in the Figures above indicate that different materials respond in very different ways. For example, type 17-4 PH stainless steel supports discernible resonances, while polyurethane rubber on the other hand, damp out quickly but gently. This is rather interesting and worthy of more detailed investigation realizing that the complexity of geometry, material properties, coupling, instrumentation, and their effect on recorded signals is exceedingly complex.

When a FFT (Fast Fourier Transform) is performed on the wave signals shown above, it can be seen that the signals consist of various frequencies. The time domain waveforms of the target only and Teflon® along with their corresponding FFT frequency spectrums are shown in Figures 60 and 61. For target only case, FFT shows various frequencies up to a few hundred kHz, among which the dominating frequency is about 75 kHz. For Teflon®, the major frequency components are below about 100 kHz.

![Wave signal for target only](a)

![Frequency spectrum for target only](b)

Figure 60. (a) Wave signal for target only; (b) Frequency spectrum for target only.
When a 3.18 mm (0.125 in) DIA ball is dropped onto the piezoelectric sensor directly from 6.0 cm (2.36 in) height, the captured wave signal is shown in Figure 62, which shows sensor resonance and ring-down.
VII Additives in Epoxy

Previous Practice in Filling Additives into Epoxy

Mixing of additives of various kinds into epoxy matrix has been practiced previously to enhance the properties of epoxy. Adding rubber to increase the toughness of epoxy has been widely used [43], and adding alumina has been demonstrated to enhance crack deflection and microcracking of epoxy matrices [44]. Adding tungsten, PZT, or alumina (Al₂O₃) particles of different sizes into epoxy was shown to increase the acoustic impedance and attenuation (evaluated at 3 to 7 MHz frequencies) of epoxy to different degrees [26]. Another study showed that a volume fraction of 7 to 9% of alumina or tungsten particles added to epoxy yields the best attenuation improvement (evaluated at 25 to 64 MHz frequencies) [45]. Liquid amine-terminated butadiene acrylonitrile (ATBN) copolymers, as well as liquid reactive rubber have been incorporated into diglycidyl ether of bisphenol A (DGEBA) epoxy resins to improve toughness [46,47]. U.S. Pat. No. 5,400,296 demonstrated a means of enhancing the attenuation and vibration damping of matrix material by mixing in high acoustic impedance particles, low acoustic impedance particles, or a mix of both high and low acoustic impedance particles, in which case the acoustic energy will be reflected in random directions in the mixtures due to impedance mismatch [48]. It can be concluded from these studies that the type of additive materials, particle size, volume fraction of additive filling, and the interface between the additive and matrix all affect the final properties of the mixture.

Here, improving the attenuation capacity of epoxy through additives is of keen interest. Most of the similar studies in the past evaluate attenuation of the epoxy mixtures
at high frequencies (i.e. MHz). Here, attenuation of epoxy with additives and their performance at lower frequencies (i.e. kHz) is investigated.

**Fabrication of Epoxy with Additives**

Several additive materials were selected: polyester and Neoprene rubber, as they demonstrate a high attenuation capacity shown in the previous Chapter, and they are readily available; alumina, as it has a much larger acoustic impedance (43.1 MRayl) than epoxy (2.81 MRayl) which may cause more energy reflection in the mixture due to impedance mismatch; and PVC powder (vinyl chloride/vinyl acetate copolymer extender resin) manufactured by Vinnolit GmbH & Co. KG (Germany), as it is inexpensive and available. The polyester and rubber powder were obtained by grinding available rod materials as shown in Figure 63. The alumina and PVC powder were purchased and are shown in Figure 64.
Figure 63. (a) Grinding Neoprene rubber powder using Buehler grinding and polishing machine; (b) Collected polyester powder; (c) Collected Neoprene rubber powder.
The fabrication of epoxy with additives was done by first mixing epoxy and hardener at a 3 to 1 ratio by weight, and then stirring in a desired volume fraction of additive powder, as shown in Figure 65. Knowing density for the epoxy and additives allows volume fraction computations. Neoprene rubber and alumina were mixed in at volume fractions of 10% and 5%; PVC and polyester were mixed in at volume fractions of 10%. All fabricated mixture specimens of 50 mm (1.97 in) tall and 31.8 mm (1.25 in) DIA are shown in Figure 66.
Figure 65. (a) Mixing in Neoprene rubber; (b) Mixing in alumina; (c) Mixing in polyester.

Figure 66. All mixture specimens that were fabricated.
RMS Results of Drop Ball Test

Drop ball test was performed on the mixture specimens using a 4.76 mm (0.188 in) DIA chrome steel ball, and the test setup was the same as that shown in Table 13. The RMS results were obtained and are shown in Table 18, where the RMS results for pure epoxy without any additive filling were also recalled. The captured signal waveforms for specimens of 10% volume fraction additive are shown in Figure 67.

Table 18. RMS results for mixture specimens.

<table>
<thead>
<tr>
<th>Additive</th>
<th>RMS (V)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
<th>Test 5</th>
<th>Std. Dev.</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy only</td>
<td>6.4</td>
<td>6.63</td>
<td>6.71</td>
<td>6.61</td>
<td>6.66</td>
<td>0.12</td>
<td>6.60</td>
<td></td>
</tr>
<tr>
<td>5% Alumina</td>
<td>8.75</td>
<td>8.99</td>
<td>9.01</td>
<td>8.91</td>
<td>8.83</td>
<td>0.11</td>
<td>8.90</td>
<td></td>
</tr>
<tr>
<td>10% Polyester</td>
<td>8.37</td>
<td>8.48</td>
<td>8.42</td>
<td>8.48</td>
<td>8.50</td>
<td>0.05</td>
<td>8.45</td>
<td></td>
</tr>
<tr>
<td>10% PVC</td>
<td>7.35</td>
<td>7.37</td>
<td>7.41</td>
<td>7.33</td>
<td>7.25</td>
<td>0.06</td>
<td>7.34</td>
<td></td>
</tr>
<tr>
<td>5% Neoprene</td>
<td>6.9</td>
<td>7.06</td>
<td>7.03</td>
<td>6.95</td>
<td>7.10</td>
<td>0.08</td>
<td>7.01</td>
<td></td>
</tr>
<tr>
<td>10% Neoprene</td>
<td>6.37</td>
<td>6.6</td>
<td>6.63</td>
<td>6.62</td>
<td>6.65</td>
<td>0.12</td>
<td>6.57</td>
<td></td>
</tr>
<tr>
<td>10% Alumina</td>
<td>6.55</td>
<td>6.49</td>
<td>6.48</td>
<td>6.51</td>
<td>6.56</td>
<td>0.04</td>
<td>6.52</td>
<td></td>
</tr>
</tbody>
</table>
(a) Epoxy only

(b) 10% alumina
(c) 10% Neoprene rubber

(d) 10% PVC
From the mixture specimens fabricated and the RMS results in Table 18, some observations can be drawn:

1. The RMS results show that 5% volume fraction filling of Neoprene rubber and alumina, and 10% filling of polyester have noticeably reduced the attenuation capacity of epoxy. A conjecture is that chemical structure of epoxy changed and its viscoelastic property is partially lost after filling in additives.

2. However, the 10% filling of Neoprene rubber and alumina in epoxy yields better attenuation capacity compared to that of 5% filling. Adding in larger volume fraction (more than 10%) of Neoprene rubber might improve the attenuation of epoxy due to the high attenuation characteristic of rubber; and larger volume fraction of alumina
might improve the attenuation of epoxy due to the increased energy reflection caused by impedance mismatch.

Based on the observations, a few suggestions for future work can be made:

1. In the future, surface treatment might be performed on the additive particles to avoid reacting with epoxy, or other forms of rubber should be used (e.g. liquid reactive rubber from past practice) as additive.

2. Effect of the volume fraction of additive filling should be further investigated. Adding rubber or alumina at larger volume fraction (more than 10%) may effectively improve the attenuation of epoxy.

3. Additives of bigger particle sizes should be experimented, as the scattering of waves due to inclusions will become more obvious when the dimensions of the inclusions become comparable to the wavelength.
VIII Conclusions and Future Work

Here attenuation measurements were performed on type 17-4 PH stainless steel, epoxy, polyester, Teflon®, UHMWP, Types I and II PVC, Neoprene rubber and polyurethane rubber at frequencies up to a few hundred kHz using a drop ball test. Several conclusions can be drawn from these experiments:

1. In ultrasonic (or acoustic emission) testing, test specimen preparation, test configuration and couplant selection all play a significant role for the validity and reproducibility of the test. For a sensitive testing system, the geometry and surface condition of test specimens is the most affecting variance.

2. Compared to the common acoustic attenuation measurement setup, the setup here which includes a drop ball mechanism, a piezoelectric sensor, charge amplifier, and digital oscilloscope, is simpler and capable of evaluating attenuation at lower frequencies of kHz range.

3. RMS results show that among the tested polymers, epoxy attenuates the least, rubbers the most, while UHMWP and polyester are also excellent attenuating materials. The recorded waveforms substantially differ between materials, indicating that sound waves propagate and are attenuated in very different manners among different materials.

4. The drop ball mechanism presented here is able to generate controllable, consistent, fast and strong acoustic source waves at realistic frequencies. When performed on well prepared test specimens, it can produce waves with less than 1% variation in signal strength. The drop ball mechanism can be used for other impact testing applications,
and can possibly substitute for the commonly used methods such as breaking pencil leads or glass capillary tubes for generating source waves in acoustic emission testing.

5. The effect of mixing in additives of different materials and volume fractions on the attenuation capacity of epoxy resin was also investigated. It is conjectured that the additives can change the chemical property of epoxy resin and reduce its attenuation capacity. However, adding rubber or alumina powder at volume fraction larger than 10% may effectively improve the attenuation of epoxy.

Suggestions for future work are:

1. Mixing in additives of different forms (e.g. liquid reactive rubber), particle sizes, and volume fraction on the effect of improving the attenuation of epoxy should be experimented.

2. More materials should be tested to investigate the correlation between the RMS voltage results of the attenuated waves and the tan δ values of the materials.

3. Improve the test system by using longer, slimmer specimens and non-resonant piezoelectric sensors.
References


25. NDT Resource Center. “Couplant”,


