Nondestructive inspection of energetic materials during manufacture

Dr. Wes Cobb (Presenter)
Applied Sonics Inc.
Denver, Colorado, USA
303-471-0290
wcobb@appliedsonics.com

Rajen B. Patel and Sean Swaszek
US Army
Picatinny Arsenal, NJ
973-724-2676, 973-724-2201
rajen.b.patel@us.army.mil, sean.swaszek@us.army.mil

(Submitted to the NDIA IM/EM symposium October 12, 2010, Munich, Germany)

U.S. Army Research, Development and Engineering Command - Armament Research, Development and Engineering Center (RDECOM-ARDEC) is currently developing ultrasonic analyzers that provide quality information during explosives manufacturing. The first instrument is the Multi-Use Ultrasound Analyzer probe. This probes makes use of ultrasound signals to measure a variety of material properties during manufacture including: the particle size of an explosive as it is being slurry coated, the water content of an explosive as it dries, and the settling stability of melt-cast explosives. By measuring these properties, one can gain invaluable information on the manufacturing process and will gain a higher level of control during manufacturing.

The second instrument, the Ultrasound Press Analyzer, monitors the quality of explosive powders as they are pressed into billets for munitions. Inconsistencies in source materials and press operating conditions can lead to defects such as low density, cracks, and poor consolidation. The quality and yield improvements from this technology would benefit any precision warhead system including new pressed explosive formulations such as PAX-3. One available version of this analyzer is small enough to be used for primer caps.

The development of these analyzers is supported by the U.S Army Program Executive Officer for Ammunition (PEO Ammo) and is funded in part through Life-Cycle Pilot Processing (LCPP) initiatives.

Ultrasound Multi-Use Probe Analyzer

Manufacturers of explosives and munitions need to measure the following process parameters to achieve good quality: 1) particle size in a still during coating in real time, 2) settling of melt cast explosive slurry as it is mixed, and 3) water content of an explosive as it is dried. There is demand for a device which combines all of these capabilities into a single device. ARDEC in conjunction with Applied Sonics Inc. are developing ultrasound probes which can measure each of these process parameters in real time.

Many plastic bonded explosives (PBX) are produced using a slurry process where polymer binders slowly bind micron-sized crystals of solid explosives together. The particles then grow to the millimeter sizes suitable for molding powders (see Figure 1). The slurry process starts by mixing a water phase containing the high explosive crystals, and a lacquer phase containing solvent, dissolved polymer, and other additives. The solution is then heated to distill off the solvent. The polymer falls out of solution and "coats" the explosive crystals. To produce PBX explosives at an acceptable cost for munitions, the slurry process must be optimized for yield and product quality.

Figure 1 Photograph of particles after agglomeration.

To control the slurry process, an ultrasound analyzer can be used to measure the particle size of the slurry as it is coated. This principle is based on measuring the sound wave attenuation as the explosive particle is coated and grows (see Figure 2). Since the particle will scatter and attenuate waves more when it is excited at its resonance frequency, one can measure what frequencies attenuate the most, thus finding the resonance frequency. The resonance frequency is dependent on the particle size of the material. Figure 3 illustrates this capability of the ultrasound probes.

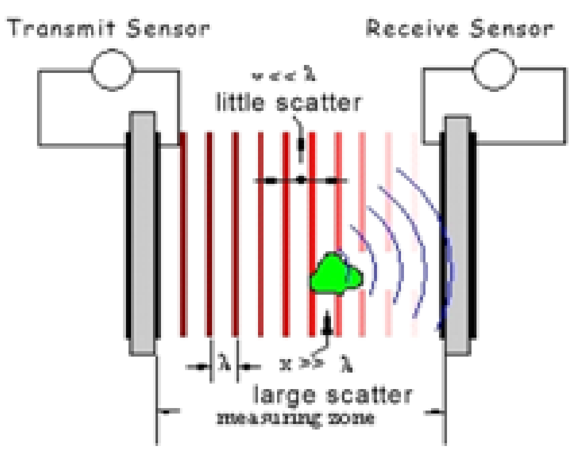

Figure 2 Illustration of ultrasonic attenuation by a particle located between two transducers.

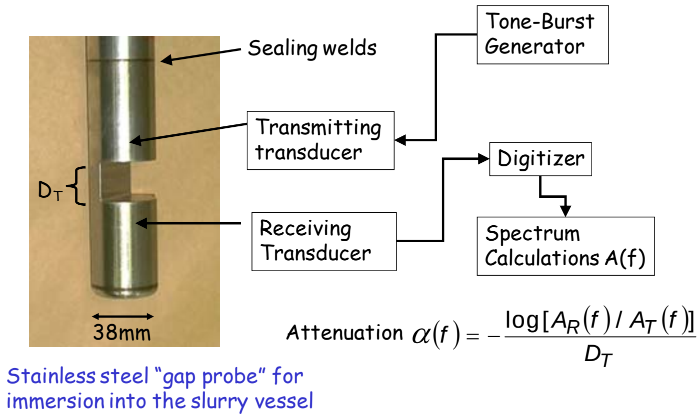

Figure 3 Photograph of the ultrasonic probe and illustration of the attenuation measurement.

Results for ultrasonic attenuation measurements on several slurries are shown in Figure 4. The fitted attenuation curves are plotted for each of the three slurries with particles sizes indicated in the legend. Note that, since these slurries have a large particle size range (not mono-disperse) the attenuation peaks are broad and span many frequency indices. However, as for mono-disperse particles, the attenuation peaks move to lower frequency indices for larger particles in the slurry. This frequency shift can be clearly seen in Figure 5, where the frequency index of peak attenuation is plotted versus the size range of the particles. There is a very consistent drop in the frequency of peak attenuation for larger particles. As indicated by the equation on this figure, this relation appears to closely follow a quadratic form. Note that the inverse of this relation can be used to calibrate the probe and provide mean size measurements from the peak attenuation frequencies.

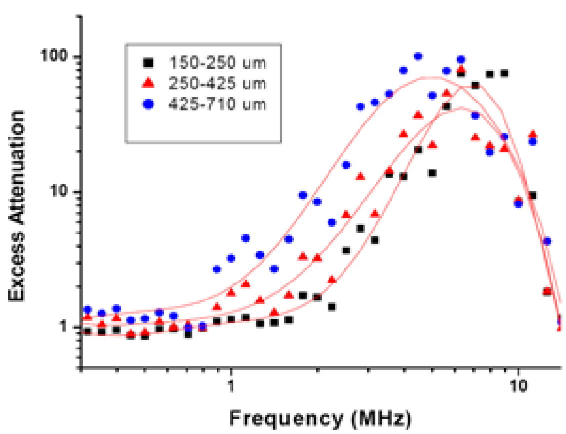

Figure 4 Measured ultrasonic attenuation for three slurries with different particle size ranges

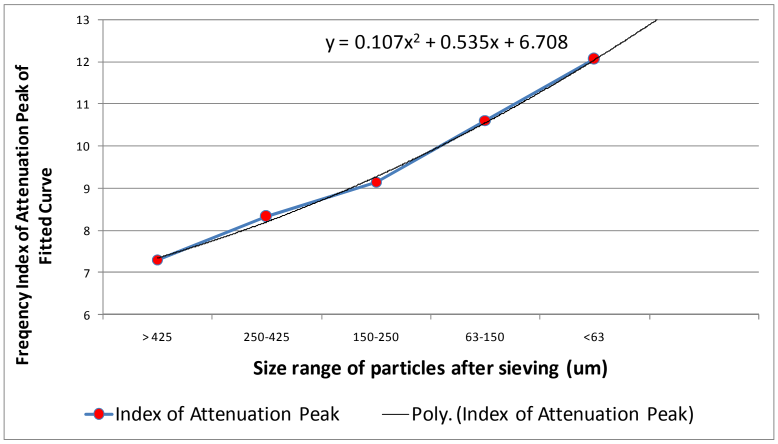

Figure 5 Measured frequency shift of the attenuation peak for changes in mean slurry particle size

The multi-use probe which measures particle size and settling of an explosive can also be used to measure water content of an explosive as it dries. While the ability to measure particle size is based on the ultrasound attenuation, solids concentration measurements are based on ultrasound velocity data.

The amount of water in an explosive, such as RDX, as it dries is a critical process control parameter. Excessive water can cause decreases in performance and undesired decreases in sensitivity, which would result in faulty ammunition. The ability to measure the amount of water in an explosive during the drying process would allow for improved drying procedures, but also ensure consistency in the drying process, reducing manufacturing variation.

Figure 6 shows the ultrasound probe being used to gauge the amount of water in an explosive as water is removed during drying. The measured ultrasound velocity is plotted against the amount of solids particles in the slurry. Note the consistent, linear relationship between ultrasound velocity and solids percent as indicated by the fitted line. As noted above, the inverse of this relation can be used to calibrate the probe and provide solids content measurement from the velocity readings.

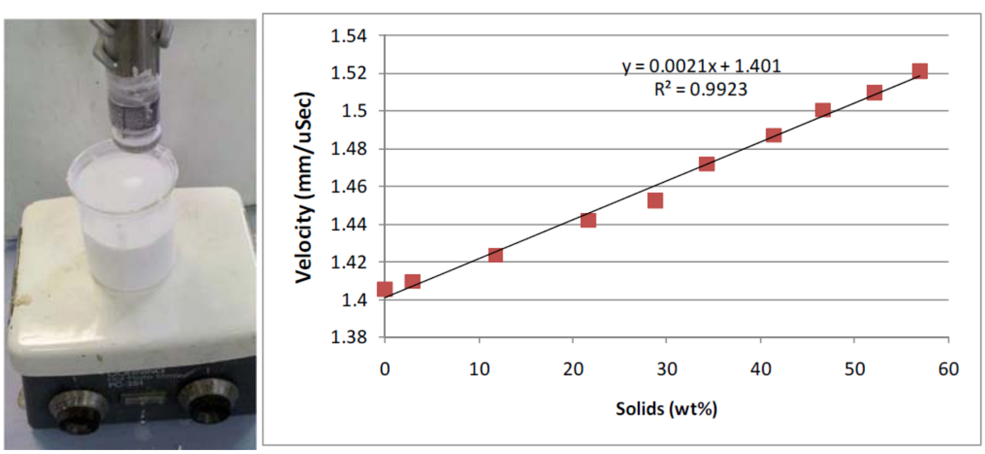

Figure 6 This graph illustrates the relationship between amount of drying of an explosive and ultrasound velocity through the explosive.

ARDEC in conjunction with Applied Sonics Inc. has developed a standalone probe capable of meeting many of the Army's manufacturing needs. We expect these probes to have high commercial viability in addition to being useful to Army manufacturing plants.

Explosives Press Analyzer

Currently, there is no reliable way to measure the density of an explosive as it is press loaded. The method used to measure density is generally water weight, which must be done after processing. This makes detection and remediation of defects extremely difficult, and only allows one to gain information on the end product. The physical changes to the material as it is pressed are lost. Additionally, only an overall density is obtained, since sectional density is impossible to gain without destroying the billet. Another problem with the water method is it is time consuming, meaning water weight densities can be difficult to obtain for all of the pressed billets. Finally, water weight density cannot be used on water soluble materials. Ultrasound technology provides a method to avoid the various problems with water weight density measurements. Ultrasound technology can be used in explosive pressing operations to continuously monitor physical properties as the explosive powder is pressed into a billet for precision charges or warheads.

ARDEC has been working to develop an ultrasound system for a 190 ton press with an 81 mm die. The ultrasound press analyzer integrates the ultrasonic sensors into a die that is compatible with existing press operations. As illustrated in Figure 7, these sensors are embedded within the die (or rams) of the press and do not contact the explosive material. Ultrasonic waves sent through the pressed powder are analyzed to sense changes in the material properties as the powder is compacted. Measurements are taken in real time, allowing an operator to make adjustments during the pressing process based on the feedback from the ultrasound data. The 81mm press analyzer has seven ultrasound sensor pairs running axially in a helical pattern, with one ultrasound pair running from the top punch to the bottom punch. These sensors provide vital ultrasound data used to determine the properties of the pressed material as it is compacted.

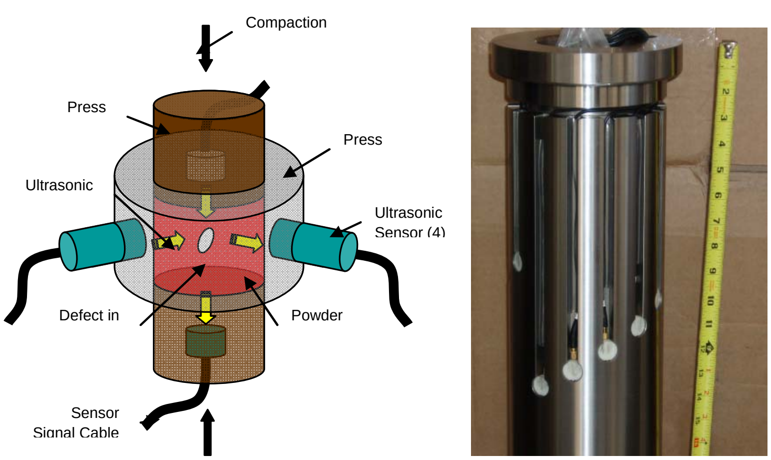

Figure 7 a.) Ultrasound Press Analyzer Concept (left) b.) Ultrasound Instrumented Die (right)

The most important powder characteristic measured with ultrasound is the real-time billet density. For most materials there is a direct linear relation between ultrasound velocity measurements and density. The real time density provides invaluable information to the engineer operating the press. This would allow for much more accurate models than those currently available, quicker optimization of pressing processes, and overall higher billet density.

The relationship between ultrasound velocity and density is shown in Figure 8, where an inert salt powder was examined. By pressing salt billets with varying pressures, a relationship was found between the density of the billet and the speed of sound through the billet. This relationship can be established for virtually any inert or explosive powder, which would allow all of them to be examined using ultrasound technology.

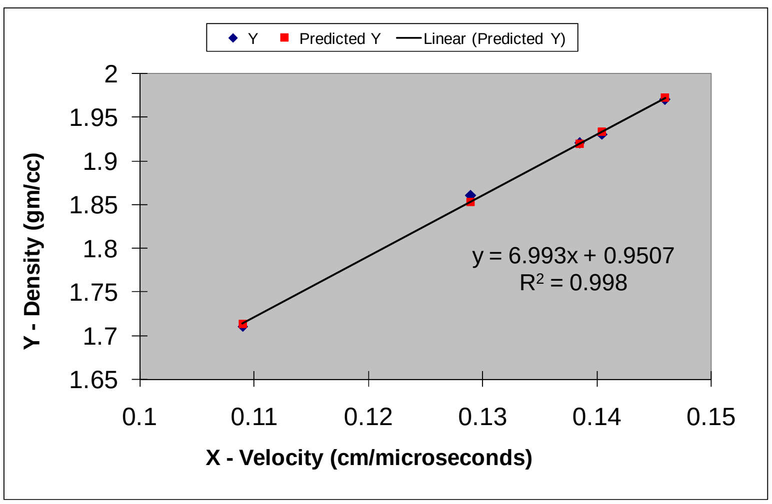

Figure 8 Relationship between Ultrasonic Velocity and Density.

Live tests have been run with PAX-2A, PAX3, and LX-14 explosives to prove-out the Press Analyzer system. To illustrate the changes in the signal amplitude, velocity and ram force during compaction, Figure 9 shows rapid measurements of each parameter during three compression cycles of PAX-2A explosive performed over a ten minute period. For each cycle, the ram force increases rapidly to about 20,000 pounds as the ram moves together and compacts the powder. The rams are then held stationary for about two minutes. At the end of the stationary period, the force is slowly removed, and the ram withdraw slightly within the die liner. The ram force is kept at zero for about one minute and the cycle is repeated.

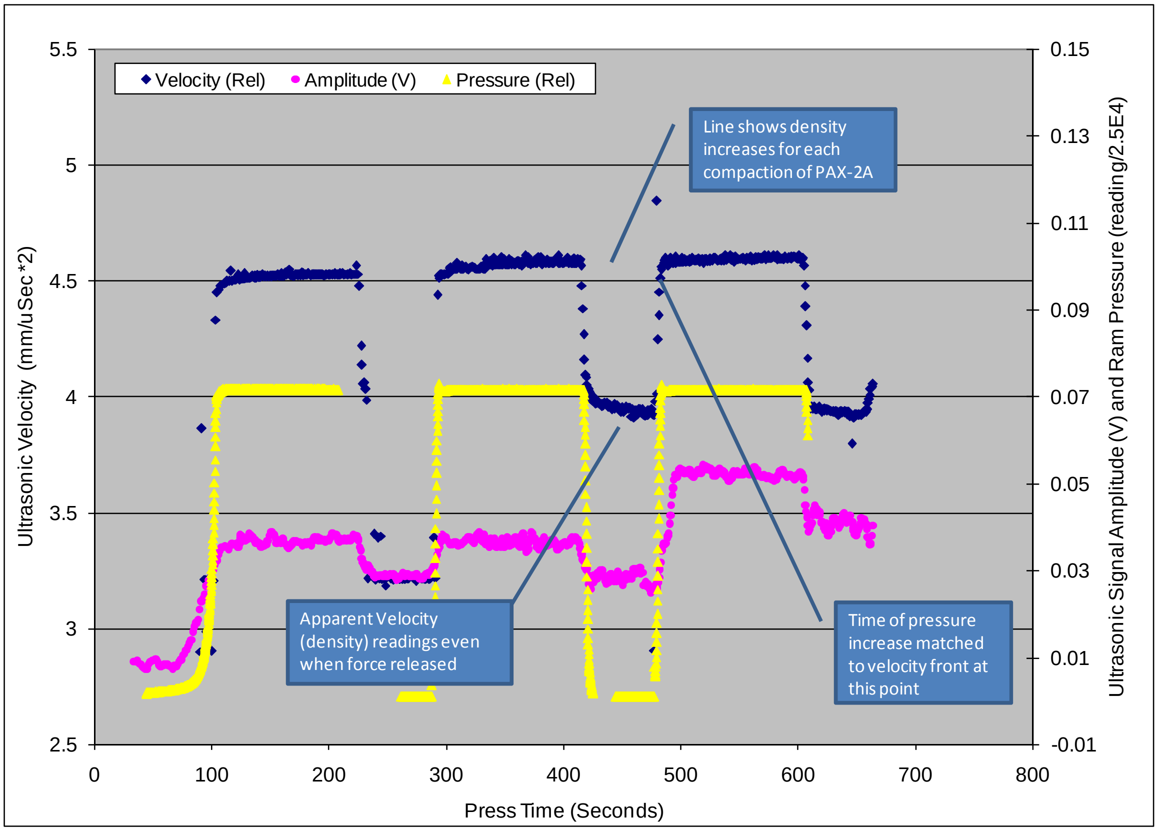

Figure 9 Results of PAX 2A Pressing Using 81mm Ultrasound Die Set.

As shown in Figure 9, the signal amplitude and time-of-flight measurements follow similar patterns for each press cycle. As the ram force increases and compaction proceeds, the velocity increases to at a high value (~2.25 mm/usec). Once the ram is held fixed, the velocity (and density) continues to increases slowly as the force continues to compress the powder. Upon release of the ram force, the velocity quickly decreases as the powdered material expands and density decreases.

Analysis of the amplitude and velocity (density) curves during the compaction cycles provides a wealth of information about the progress and quality of the pressing operation. At the end of each cycle, the amplitude and velocity are characteristic of the degree of compaction of the material at this stage of pressing. For example, for the PAX-2A, the signal amplitudes increase after each press cycle. This is believed to be caused by increased signal coupling of the ultrasonic waves to the walls of the die as well as reduced signal attenuation through the better compacted billet. However, for some pressings the signal amplitude stays constant over the cycles. Understanding of the factors that influence signal amplitude changes during pressing is one of the ongoing research areas for ultrasonic sensing.

Similarly, as the compaction proceeds, the velocity values increase, indicating that the billet is more compacted (higher density) after each press cycle. Comparison of the velocity values, however, show that the last of the three cycles resulted in an increase in compaction relative to the first cycles. Thus, for the PAX-2A additional press cycles are beneficial to final billet quality.   This information can be used to save the time and costs associated with further pressing of the billet.

In addition to information on ultrasound velocity and billet density, the signal amplitude can be an indication of the quality of compaction. For example, if the billet cracked during the compaction, and the crack was located along the path of the ultrasound waves, a significant decrease in received signal amplitude would be measured. To detect a defect in the billet, this signal decrease could be compared to normal, final signal amplitude for a good, un-cracked billet.

The ultrasound equipment is not limited by size, as shown with other work performed at ARDEC. The primer press is an extremely small press used on high sensitivitiy energetics. An ultrasound system was developed to assist ARDEC in understanding the physics of pressing primers (see Figure 10). This tool is currently being used to investigate the differences between ARDEC's lead azide and lead azide procured commercially. The dimensions of the primer are far smaller than the larger press projects, on the order of millimeters, increasing the difficulty of designing and developing the sensors. However, ARDEC has successfully used the sensors to monitor the pressing of primers.

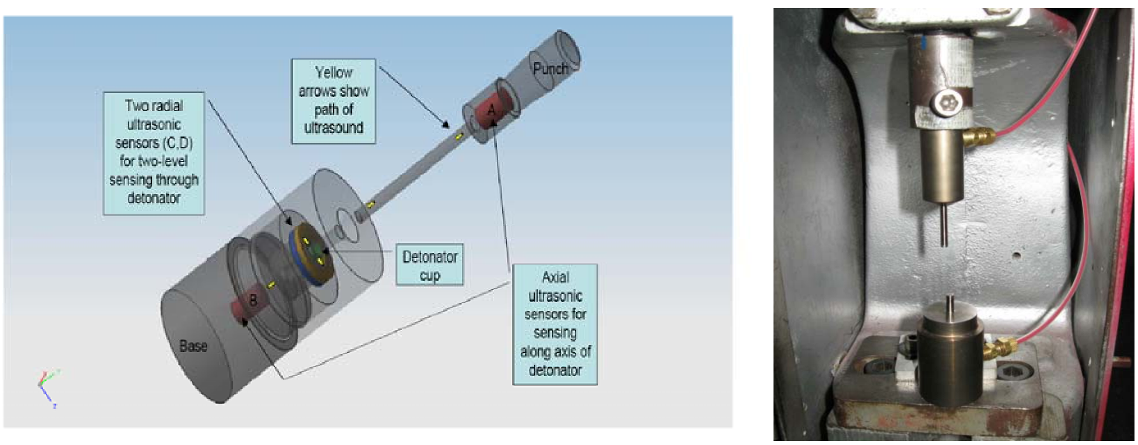

Figure 10 Primer press which was instrumented using ultrasound technology.

Conclusion

Ultrasound technology has found numerous uses in a variety of explosive manufacturing processes. In the 190 ton press, the primer press, and the particle processing facilities, ultrasound technology will eventually be fully integrated to provide a new wealth of data for both scientific investigation and process control. This will provide immediate benefits by providing an increase in the quality of manufactured products, and in the future will produce new insights into how to best optimize the manufacturing process. Due to its low cost, high flexibility, and its ability to provide tremendous amounts of information in real time, ultrasound technology can be used in many types of explosive manufacturing.

References:

1. Patel, R. B. Swaszek, S. Cobb, W. “Development of Quality Control Analyzers for Explosives Manufacturing,” Defense Manufacturing Conferences, Nov 30-Dec 3, Orlando, Florida, 2009
2. Patel, R. B. SBIR Solicitation 2009, “Multi-Use Probes for Quality Assurance of Explosives Manufacturing.”
3. Reddingius, B., Cobb, W., and Travers, B, “Explosives Press Analyzer,” Defense Manufacturing Conference, December 3-6, Nashville, TN, 2006
4. Betts, P. and Cobb, W., “Development of an Ultrasonic TNT Slurry Analyzer,” Defense Manufacturing Conference, December 2-5, Dallas, TX, 2002
5. Geiss, D. A., Jr., Reddingius, B.(RDECOM-ARDEC) and Cobb, W. (DRI), “Development of a Slurry-Mix Explosive Analyzer,” Defense Manufacturing Conference 2004, Las Vegas, NV, December 1, 2004
6. Geiss, Donald A., Jr.(RDECOM-ARDEC), “Application of Six Sigma Principles in the Process Development and Production Scale Up of PAX-2A at Holston Army Ammunition Plant”, NDIA Defense Manufacturing Conference 2002, Dallas, TX, December 4, 2002.