Part 2 of 2 — Development of the BAI Pulse-Echo Sensing Method

New Sensors Help Improve Heat-seal Microleak Detection

By Scott A. Morris, Ph.D., Ayhan Ozguler and William D. O'Brien, Jr., Ph.D.
University of Illinois

FOCUS: In an effort to improve reliable inspection of film-sealed shelf-stable food packages for micro-leaks and product contamination in the seal area, a newly developed nondestructive ultrasonic testing method called the Backscattered Amplitude Integral (BAI) was evaluated. Tubular channel defects (6-15 µm dia.) and simulated food strand inclusions (20-60 µm dia.) were fabricated perpendicular to the seal within the seal region of both all-plastic and foil-containing retortable pouches. Results showed that 17.3 MHz pulse-echo BAI-imaging method reliably detected channel defects (9.5-15 µm) and tendon-inclusion defects in both types of package materials under conditions that would defeat traditional sensing methods. This represents a dramatic increase in resolution over direct imaging methods and provides the basis for development of high-speed on-line sensors as well as applications in other fields.

Editor's Note: This is Part 2 of a two-part series on the development of new on-line dedicated sensors for package seal inspection. It covers the development of a new Backscattered Amplitude Integral (BAI) pulse-echo sensing method. Part 1, which ran in the July issue, provided background information on the evaluation of ultrasound sensing methods.

Introduction

An important requirement for shelf-stable film sealed and flexible food packages is the complete fusion of the opposing seal surfaces to prevent the entrance of microorganisms. The presence of water vapor, air bubbles, product, wrinkles, blisters and delamination in the seal region can cause a seal failure. Lampi et al. (*1976*) observed that occluded particles in the seal area resulted in the decrease in the overall bursting strength of retort pouch seals after six months of storage. Since the loss of strength can result in package loss, detection of occluded materials as well as incomplete seals is necessary.

Destructive inspection methods result in the loss of product, are costly, and do not provide 100 percent on-line inspection. Manual or visual inspection has high personnel costs, suffers from unpredictable variation and an inability to detect surface artifacts smaller than approximately 50 µm. It also offers no capability of seeing through opaque material. Thus, there is need for a reliable, fast and inexpensive nondestructive technique to evaluate the seal integrity of film-sealed shelf-stable packages if they are to economically replace traditional, less material- and energy-efficient rigid cans and jars.

Ultrasonic Techniques

Ultrasonic techniques are common to the field of nondestructive evaluation. Low-power ultrasonic applications do not result in any permanent change in the medium under evaluation; therefore, due to their nondestructive nature, they are used to detect defects (particularly in steel and other metals), obstacles, anatomical structure (medical ultrasound), material properties and flow. When a traveling ultrasonic wave strikes a boundary or buried artifact in a material, part of the energy is transmitted across the boundary, or around or through the artifact, and the balance is reflected and scattered.

Two general ultrasonic techniques that are used for flaw detection are the transmission and pulse-echo (reflection) techniques.

In the transmission technique, separate transmitting and receiving transducers are positioned on the opposing sides of the specimen. The ultrasonic beam passes through the sample under evaluation, and the receiving transducer detects the transmitted beam. When the beam strikes inhomogenities within the sample, its amplitude decreases due to the reflection and scattering (McGonnagle, 1966).

In a recent study, Safvi et al. (*1997*) showed that the Scanning Laser Acoustic Microscope (SLAM) detected 10 µm channel defects in the seal region of both polyethylene films and retortable plastic pouches at an ultrasonic wavelength of approximately 20 µm (f = 100 MHz). This demonstrated that acoustic imaging can be used to image defects in the material, but also exhibited the limitations of resolution of the method since it is not possible to directly image defects smaller than the wavelength of the incident energy. Furthermore, signal penetration decreases with increased frequency, so lower frequency, pulse-echo techniques, which have good penetration, would lack sufficient resolution to directly image the defects, and higher frequency methods would lack penetration depth.

BAI-mode Pulse-echo Imaging

In the ultrasonic pulse-echo technique, an ultrasonic pulse is propagated into the sample, and the reflected pulse (echo) produced by inhomogenities and flaws is generally received by the same transducer (*Szilard, 1987*). Jarman et al. (*1994*) claimed that the pulse-echo technique would not be sufficiently sensitive to detect very fine flaws (such as 1.0 mm^2 meat fiber) in the seal area of thin flexible packaging materials.

Contradicting this claim, the Backscattered Amplitude Integral (BAI)-mode pulse-echo imaging technique developed at the University of Illinois has demonstrated the capability of reliably detecting channel defects (as small as 10 µm) within the seal region of retortable plastic pouches (total material thickness = 220 µm) using energy that has a wavelength 20-40 times larger than the defect. This represents a substantial breakthrough in ultrasound technology and offers promise for all inspection techniques.

In this technique, which analyzes backscattered energy rather than generating images directly, the BAI value for each scan point is calculated by integrating the envelope of received echo signal and is proportional to the square root of the backscattered energy. As long as the seal region of the package is flawless and its surfaces are smooth and parallel, the BAI value will be virtually constant. However, any discontinuities in that region can cause this value to vary; this variation is visualized by a gray mode BAI-image.

Even though the BAI imaging technique has been quite successful in detecting channel defects as small as 10 µm in diameter in the seal region of plastic laminate pouches—demonstrating resolution far beyond direct imaging methods—its absolute lower detection limit and detection ability for different packaging materials have yet to be discovered, since much higher frequencies may easily be adapted to this technique.

Evaluation, Materials and Methods

Evaluation of the BAI-mode imaging technique was done with two flexible packaging materials (transparent all-plastic and opaque foil-containing retort pouches) and with two types of defects of different sizes to determine the technique's detection limits. The two defect types were channel defects (6-15 µm dia.) and inclusion defects, i.e. tendons (20-60 µm) extracted from mouse tail as simulated material for food particles such as meat fiber that might be captured in a package's seal region.

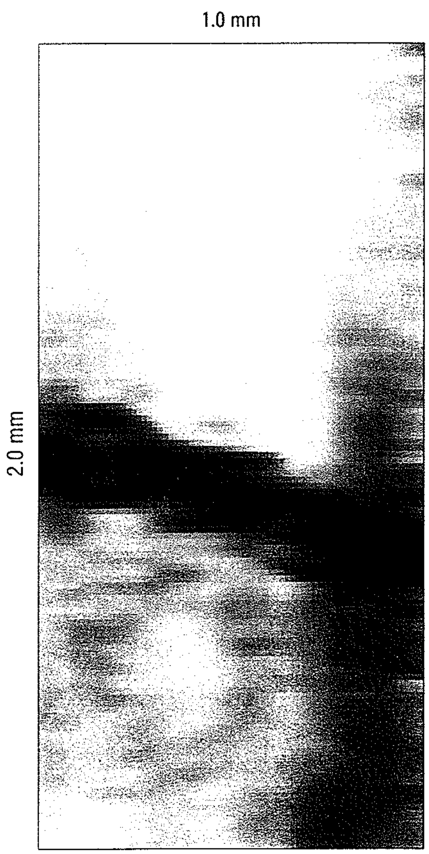
*1. **Sample Preparation***—Two retortable pouch materials—an all-plastic transparent trilaminate (110 µm thick) and an opaque foil-containing composite film (120 µm thick) were used as samples. The heat-sealing layer of both pouches was polypropylene. To fabricate different sized channel defects, i.e. air-filled (Figure 1) and water-filled (Figure 2), tungsten wires (6, 10 and 15 µm dia.) were used. These wires were positioned transverse to the sealing direction, sandwiched between two layers of pouch materials, and then sealed using an automatic band sealer[1]. After sealing, the sample seals were air cooled before removing the wire.

To create water-filled channel defects, the samples were immersed in water, and the wire was then removed, drawing water into the channel. After wire removal, the channel ends were sealed with the band sealer to

[1] Doboy model HS-C42051.

Figure 1

BAI-mode Image of 6 µm Air-filled Channel Defect in Foil Containing Retort Pouch Material



keep the water inside the channel defect.

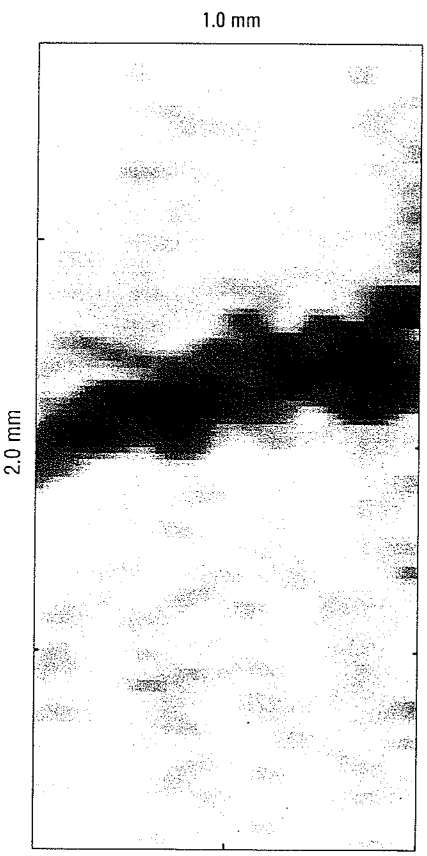
Defects that include food material were simulated by the use of transversely positioned mouse tail tendons since the extraction, characterization and handling of small tail tendon strands was much more reproducible than that of meat fibers. Both ends of the defect region were sealed to protect the interaction of the inclusion material with the degassed water used as an ultrasound conductor during the experiment. Six water-filled and six air-filled channel defect samples (6-15 µm), and three tendon defects (20-60 µm) were fabricated for each packaging material, for a total of 30 samples.

2. Sample Validation—The size of the defects in the seal areas were determined by light transmission microscope images gathered with a computer equipped to capture images in high-quality digital format. Defect sizes from the side view were measured after the samples were frozen to -70°C and cut in the direction transverse to the defects' longitudinal axis with a cyrostatic microtome.

3. Ultrasound Data Acquisition—A block diagram of the ultrasound data acquisition system is shown in Figure 3. A PC-controlled five-axis precision positioning system was used to move the transducer. The sample was submersed in a degassed-water tank, and its surface was positioned normal to the direction of the propagated sound beam. A pulser-receiver operating in pulse/echo mode was used to produce a pulse that excited a 17.3 MHz ultrasonic transducer. The received echo signal was amplified, filtered, digitized and transferred to a workstation for off-line processing. The image data were collected in a rectangular grid pattern by moving the transducer relative to the fixed-position sample.

Figure 2

BAI-mode Image of 6 µm Water-filled Channel Defect in Foil Containing Retort Pouch Material



4. BAI-mode Image Production—The Backscattered Amplitude Integral (BAI) imaging method (*Raum et al., 1998*) was used to evaluate package defects. This signal processing method reduced the three-dimensional data set to a two-dimensional BAI-value matrix. The matrix was then normalized and interpolated to decrease the pixel size and make each pixel approximately square, then the final image matrix was normalized to yield a gray-scale image.

Results

Lateral Size Measurements of Defects— Although the top view image of defects in the transparent all-plastic retort pouch was captured by the light microscope, those in the foil-containing pouch were not detected due to the materials' opacity. The lateral size of channel defects in the all-plastic material's seal area was, at most, 5 percent smaller than the wire diameter. The tendon-containing defects' lateral size in the transparent all-plastic pouches was also measured; however, since this size varied along the tendon's length, the minimum measured size was recorded.

Reliability—The 17.3 MHz BAI-mode imaging technique detected all channel defects ranging from 9.5 to 15.0 µm in diameter regardless of the medium (air-filled or water-filled), whereas a small number (4 out of 24) of the 6 µm diameter channel defects (approximately $\frac{1}{32}$ of the acoustic wavelength) were not reliably detected.

Discussion

BAI values obtained at the normal incidence to the sound propagation direction were smaller in the channel leak and the tendon inclusion than in the undisturbed regions of all-plastic and foil-containing pouches. Therefore, the defect region on the gray-scale BAI-mode image can be shown as contrasting the undisturbed region.

The sizes of all channel defect images on the 17.3 MHz BAI-mode scan were approximately 150-200 µm even though their actual fabricated size was much less, which indicates the BAI imaging technique magnifies the size of defects. This result was consistent within all of the channel defects. Raum and O'Brien (*1997*) measured the lateral resolu-

Continued on page 56

Heat-seal Microleak Detection

Continued from page 54

tion of tungsten wires (25-80 µm) and found that the lateral resolution of wires was about 176 µm for 17.3 MHz transducer. Sizes of the channel defects obtained by BAI-mode imaging (150-200 µm) in this study are consistent with the lateral resolution in these observations. This is an advantageous situation because the image of small defects will be magnified and can easily be inspected.

Acknowledgement

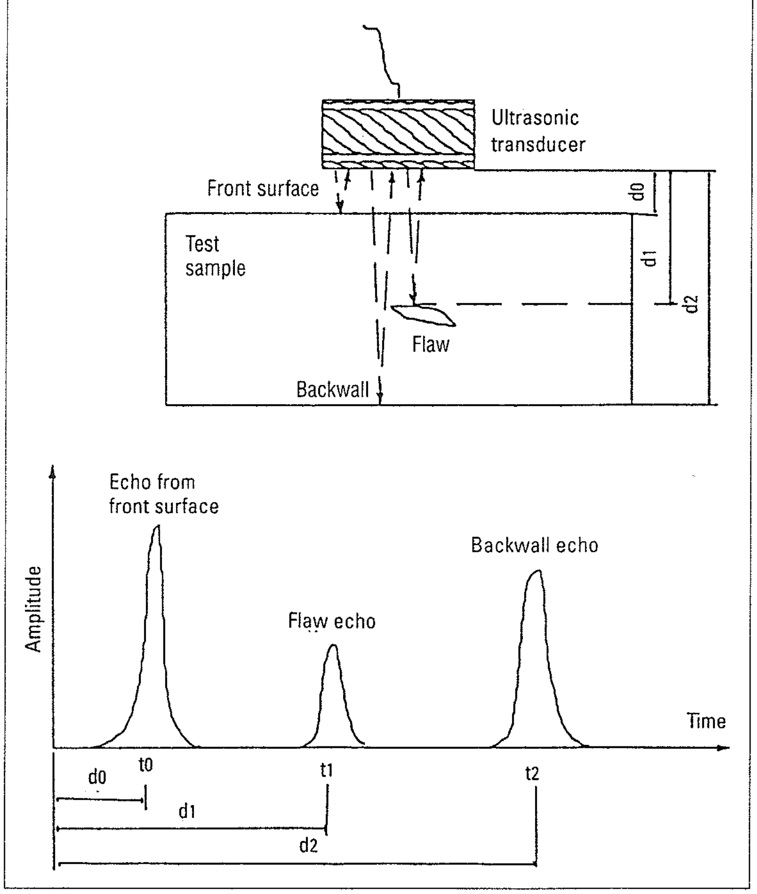
This work was supported in part by the Value-Added Research Opportunities Program, Agricultural Experiment Station, University of Illinois. The authors would like to acknowledge the professional assistance with the sample validation by James F. Zachary, DVM, Ph.D., Department of Veterinary Pathobiology, University of Illinois.

Conclusion

For the highly competitive food industry to implement new types of energy- and cost-efficient flexible and rigid heat-sealed packages for shelf-stable food, a nondestructive 100 percent in-line package seal integrity inspection method that is fast, robust and reliable is needed to ensure safety and to enable economic production, by accommodating the inspection bottleneck imposed by 9CFR§381.301(d). The work reported in this study and its predecessor (*PT&E, July 1998, p. 42*) demonstrates that high-frequency ultrasound imaging can provide the proper sensing method for the construction of such a real-time, non-destructive package seal-integrity inspection device.

Figure 3

Diagram of Pulse-echo Transducer Operation



Alternative nondestructive inspection techniques such as X-ray and MRI techniques do not sense air voids, which might cause microbial penetration through the packaged foods, even though these two techniques have high-resolution capabilities (1.0 µm for X-ray and 30.0 µm for MRI) for electron dense materials. Furthermore, pressure differential testing is a nondestructive technique to determine the leakage, i.e., air voids, within the seal area, however any other inclusions such as food product within the seal area might result in the restriction of gas flow and the failure of a pressure differential test or gas "sniffer" device, while providing a growth pathway for pathogens.

This study showed that unlike other nondestructive techniques, the high-frequency pulse-echo BAI-mode imaging technique is an effective way to visualize and evaluate both air-filled defects and occluded strands of material in the seal area of flexible packaging materials.

The engineering trade-off of nondestructive evaluation in diagnostic ultrasound is between resolution and depth of penetration. As the ultrasonic frequency is increased, resolution increases and penetration decreases. At the ultrasonic frequency (17.3 MHz) used in this study, the seal area of flexible food packages can be reliably inspected. However, if better resolution is desired, it can be achieved by increasing the ultrasonic frequency while keeping reasonable penetration depth (0.2-0.4 mm) for detection of defects in the seal region of flexible food packages.

Apparent limitations of acoustic imaging methods trials (such as the 6 µm "limit," which is actually the lower limit of reliably produced artificial defects) can readily be remedied by increasing the frequency. The few apparent physical limitations on the method are linked to the types of materials used in the package. Materials such as paper or low-density foams disperse too much acoustic energy to provide a reliable imaging medium, but low-density polyolefin films used in this study perform quite well.

The method discussed is already exceed-

Continued on page 68

Heat-seal Microleak Detection

Continued from page 56

ing the reliability of human inspectors by being able to detect defects that are buried in opaque material or are too small for human inspectors to see. The BAI ultrasound method has demonstrated that it is capable of finding both microleaks that may pose a hazard to the consumer, as well as statistical information about the overall quality of the material and the seal, which raises the possibility of using the BAI data for equipment and control purposes. The actual dedicated scanning equipment will be simpler and less expensive than the experimental equipment. Work currently under way is determining the optimal design parameters for on-line implementation of the ultrasonic scanning method. ❑

For more information about this topic, contact the authors at (217) 333-9330 or email smorris@uiuc.edu. If this article is helpful in improving your packaging operation, **Circle 202** on Reader Service Card.

About the Authors: *Scott A. Morris is Assistant Professor in the Food Science & Human Nutrition and Agricultural Engineering departments at the University of Illinois, Urbana-Champaign, where he has established a packaging teaching and research program. He has a BS and MS in Packaging and a Ph.D. in Agricultural Engineering from Michigan State University.*

Ayhan Ozguler has been a graduate research assistant at the University of Illinois, Urbana-Champaign since 1991. He received his MS in Food Science in 1995 and is currently working on his Ph.D.

William D. O'Brien, Jr., is the Director of the Bioacoustics Research Laboratory at the Beckman Center for Advanced Research at the University of Illinois, Urbana-Champaign and is Professor of Electrical and Computer Engineering and also Bioengineering. He received his BS, MS and Ph.D. from UIUC.

References

C.L. Harper, B.S. Blakistone, J.B. Litchfield and S.A. Morris, "Developments in Food Package Integrity Testing," *Food Technology*, 6(10): 336-340, 1995.

D. Jarman, Farahbakhsh and R. Herzig, "Ultrasonic Inspection of Seal Integrity of Bond Lines in Sealed Containers," U.S. Patent 5,372,042, 1994.

R.A. Lampi, G.L. Schulz, T. Ciavarini and P.T. Burke, "Performance and Integrity of Retort Pouch Seals," *Food Technology*, 30: 38-48, 1976.

W.J. McGonnagle, *Nondestructive Testing*, Gordon and Breach Science Publishers Inc., New York, NY, 1966.

K. Raum and W.D. O'Brien, Jr., "Pulse-echo Field Distribution Measurement Technique for High-frequency Ultrasound Sources," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 44(4): 810-815, 1997.

K. Raum, A. Ozguler, S.A. Morris, and W.D. O'Brien, Jr., "Channel Defect Detection in Food Packages Using Integrated Backscatter Ultrasound Imaging," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 45(1): 30-40, 1998.

A.A. Safvi, H.J. Meerbaum, S.A. Morris, C. Harper and W.D. O'Brien, Jr., "Acoustic Imaging of Defects in Flexible Food Packages," *Journal of Food Protection*, 60(3): 309-314, 1997.

J. Szilard, "Ultrasonics," *Encyclopedia of Physical Science and Technology*, R.A. Meyers (Ed.), vol. 14, Academic Press Inc., Orlando, FL, p. 191-209, 1987.

D. Warrick, "Aseptics: the Problem Revealed," *Food Manufacturing*, 65(10): 63-66, 1990