ID 1389

NDE OF COMPOSITES USING THE ULTRASONIC METHOD OF SIMULTANEOUS VELOCITY, THICKNESS AND PROFILE SCAN

David K. Hsu and Dong Fei

Center for Nondestructive Evaluation, Iowa State University, Ames, Iowa 50011-3042, USA

SUMMARY: This paper applies the simultaneous velocity and thickness scan technique to image small changes in velocity and thickness simultaneously and extends this technique to map out the surface elevation contours and cross-sectional profiles of a sample. Special considerations for achieving accurate and reliable velocity, thickness and profile images are discussed in detail. This technique for nondestructive evaluation and materials characterization is demonstrated on two industrially relevant materials: (1) composite laminates containing foreign objects and anomalies and (2) plasma sprayed thermal barrier coatings.

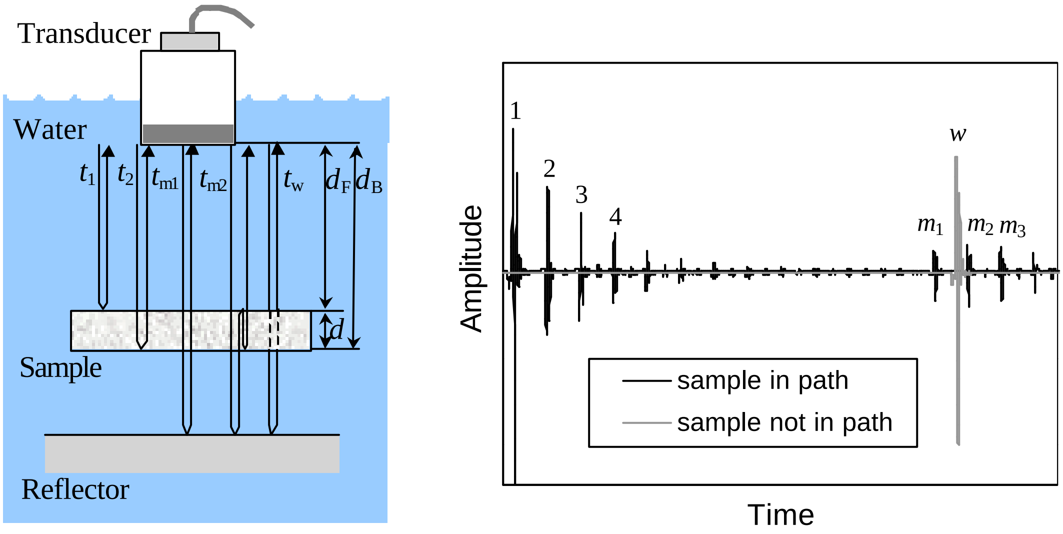
KEYWORDS: ultrasonic velocity measurement; thickness gauging and profiling; ultrasonic imaging.

INTRODUCTION

Ultrasonic velocity has been used extensively in nondestructive evaluation (NDE) to characterize material properties. For a plate of uniform and known thickness, the usual ultrasonic scan based on the time-of-flight (TOF) of ultrasonic pulses can provide a spatial image ("C-scan") of the velocity. However, there are numerous cases where the thickness of the sample is non-uniform or cannot be accurately measured, then it is necessary to separate the contribution of the velocity and the thickness of the sample in the TOF image and determine the spatial variation of the velocity and the thickness simultaneously. Such a capability can serve as a useful NDE tool for cases where a component in service has suffered changes in both thickness and material property. It can also be applied to cases where the velocity is only known approximately and the precise spatial variation of the thickness or the surface profile of the component are the information sought after in the NDE test.

The Simultaneous Velocity and Thickness (SVT) method has been developed over the last 15 years or so by a number of researchers for various NDE [1-3] and medical ultrasonic [4] applications. The SVT scan can be done in immersion using a transmission setup or a pulse-echo setup with the aid of a reflector behind the sample. Automated scans of the SVT method have been reported for both plate [5] and cylindrical [6] geometry; the technique can also be implemented using squirters [3] outside an immersion tank. In most cases the velocity was deduced from the TOF data acquired using peak detection, but Fourier transform and the phase of the signal have also been used [2]. Recently the SVT method has been expanded to include dispersion effects and to provide the ultrasonic attenuation [7]. Applications of the SVT scan method to industrial materials and components have been reported as well [6, 8].

In this paper, the pulse-echo mode of the SVT scan technique was implemented using a SONIX ultrasonic immersion scan system to map out small changes in ultrasonic velocity and sample thickness. This technique was also extended to generate the surface elevation contours and cross-sectional profiles. Special cares were exercised in order to achieve high accuracy and precision. Such a Simultaneous Velocity, Thickness and Profile (SVTP) imaging technique was first demonstrated using an aluminum test sample with machined surface contours and constant material properties. The SVTP technique was then applied to detect small changes in velocity, thickness and profiles of two industrially relevant materials:



(a) (b)

Fig.1 The pulse-echo measurement configuration (a) and typical received waveforms (b) for simultaneous determination of ultrasonic velocity, sample thickness and surface contours.

(1) carbon epoxy composite laminates containing foreign objects and anomalies and (2) plasma sprayed thermal barrier coatings.

MEASUREMENT METHOD

Basic Principle

In this work the simultaneous velocity and thickness determination is accomplished in a pulse-echo setup with the aid of a reflector plate. As shown in Fig. 1 (a), when the transducer is positioned at a given location over the reflector plate and operates in the pulse-echo mode, two *RF* waveforms are of interest, as shown in Fig. 1 (b), respectively when the sample is in the ultrasonic path (solid curve) and when the sample is not in the path (gray curve). Without the sample in the path, the transducer receives an echo from the reflector, which is labeled *w* in Fig. 1 (b). When the sample is in the path, the transducer receives multiple echoes due to reverberation in the sample and multiple echoes bounced off the reflector plate, also with reverberation in the sample. As shown in the solid curve in Fig. 1 (b), the first set of echoes, labeled 1, 2, 3, …, are directly from the sample, and the second set, labeled m_1, m_2, m_3, …, are from the reflector. It has been shown in reference [3] that by measuring t_1, t_2, t_{m1}, and t_w, respectively the TOF for echoes 1, 2, m_1 and w, the longitudinal wave group velocity, v, and the thickness, d, at the local position of the sample can be determined simultaneously according to the following two equations:

$$v = v_w\left(\frac{t_w - t_{m1}}{t_2 - t_1} + 1\right), \tag{1}$$

$$d = (v_w/2)\left[(t_w - t_{m1}) + (t_2 - t_1)\right], \tag{2}$$

where v_w is the sound velocity in water at the temperature of the experiment, which can be found from a number of references in the literature [9], or be predetermined. Note that the four times-of-flight are gouped into *differences* of time; this is advantangeous as any uncertainties in the zero of time due to the unknown triggerring instant and the signal delay in the electronic measurement system will be subtracted out.

The TOF of the front surface echo can be used to determine the distance between the transducer and the front surface of the sample, d_F, as follows,

$$d_F = \frac{1}{2} v_w t_1 . \qquad (3)$$

Because the sample thickness d has already been obtained from the SVT measurement (Eq. (2)), the distance between the transducer and the sample' s back surface, d_B, can also be easily deduced using the relationship:

$$d_B = d_F + d . \qquad (4)$$

In the SVTP imaging, the transducer is scanned over the sample surface, all the locally measured thicknesses and longitudinal wave velocities respectively form the velocity image and the thickness image. The locally measured distances between the transducer and the front and back surfaces of the sample respectively give the front and back surface contours. Such a SVTP imaging method can be conveniently implemented in a commerical ultrasonic scan systems in three steps. First, we place the sample and make a "sample scan" (TOF scan with the sample in the ultrasonic path) to get the TOF images for echoes 1, 2 and m_1. Then we remove the sample and make a "reference scan" (TOF scan without the sample in between the transducer and the reflector) to get the TOF image for echo w. Finally, we read the output TOF image files from the above two steps, convert the image data back to times of flight for each echo based on the gate setting, and calculate the images of velocity, thickness, and surface contours using Eqs. (1), (2), (3), and (4). The cross-sectional profile images of the sample are further generated from the surface contour images.

Experimental Considerations

Although the above measurement principle and procedure are quite straightforward, special attention must be given to the following items in order to efficiently achieve accurate and reliable images of the velocity, thickness and sample profiles.

Gate settings. It is of obvious importance that in a SVTP measurement all the measured TOFs, including t_1, t_2, and t_{m1} in the "sample scan" and t_w in the "reference scan", must have a common zero-time reference. A simple way to ensure this is not to use any follower gate. Gate length is also an important parameter. A gate should be long enough to cover the possible TOF variation of the selected echo during the scan. A gate, however, should not interfere with the neighboring gates and should not be too long. An excessively long gate degrades the time resolution of the TOF measurement.

Peak detector settings. There are a number of TOF timing methods applicable to the SVT measurement in a commercial ultrasonic scan system [6]. In this work, the peak method, either "positive" peak, "negative" peak or "absolute" peak, has been used for its simplicity. When the "positive" peak detection is chosen, the TOF of the largest positive peak in the gate is recorded; similarly for the "negative" setting. The "absolute" setting records the TOF of the peak whose absolute amplitude is the largest in the gate. One must therefore be careful about the polarity of the peak detection setting to ensure that the TOF of the correct peak is recorded and used in the velocity, thickness and profile calculation. When the sample material has low attenuation and dispersion and the sample has no dramatically irregular cross-sectional shapes, each echo should have a well-defined peak of the proper polarity. The "absolute" peak detection would be the best choice for such a situation because it would always locate the dominant peak of the correct polarity within the gate and no special attention is needed for the pulse polarity. However, if the sample material is highly attenuative and dispersive, the echo waveform may have comparable positive and negative peaks due to the pulse distortion. If the "absolute" peak detection were used, the peak chosen for the TOF measurement may switch back and forth between the positive and negative peaks, depending on the noise and other non-ideal factors. Such switching can cause considerable noise in the resulting velocity, thickness and profile images. Therefore, in cases where the waveform is noisy but the anticipated peak polarity is known, it is important that the correct peak polarity be selected and that the "absolute" peak detection should be avoided.

Effects of geometric setup. There are a number of non-ideal conditions in the geometric SVTP scan setup that can cause measurement errors to an unacceptable degree; it is therefore important that we pay attention to the effects of those conditions in order to achieve high-precision images. For example, the locus of the transducer in a scan forms the scan surface. Ideally such a surface should be a plane, but in reality it can have a non-planar profile, due to static factors such as the drooping of the scan bridge, and dynamic factors such as the vibration of the search tube. The scan surface profile directly affects the results of the front and back surface contours of the sample because both of them use the scan surface as a reference. The scan surface profile will not affect the velocity and thickness results as long as the scan surfaces in the "sample scan" and the "reference scan" are the same. If not, the measured thickness image will be affected and the velocity image will also be affected accordingly. A flat, stable, and reproducible scan system is important in achieving high precision velocity, thickness and profile images. Another example is the reflector surface. The reflecting surface should also be parallel to the scan plane and remains the same in the "sample scan" and "reference scan". In practice a frequently encountered problem is that the position and angle of the reflector could be slightly disturbed due to the placement and removal of the sample. Such disturbances directly affect the velocity, thickness and profile results. Therefore, in measurements where highly accurate results are required and the sample is heavy, it is important to make sure that the disturbance of the reflector due to sample placement and its loading effect is kept at a very minimum. Other factors include the transducer and sample orientations. The transducer should be normal to the scan surface and the sample should be placed such that it is essentially parallel to the scan surface despite the small variations in both front and back surface contours.

Sound velocity in water. From Eqs. (1), (2), (3), and (4) we can see that the calculated velocity, thickness and surface contours are proportional to the sound velocity in water. An inaccurate value of the sound velocity in water would therefore directly affect the calculated results. For example, the sound velocity in distilled water is 1482.2 m/s and 1493.9 m/s, respectively at 20.0 °C and 24.0 °C [9]. The percent difference between these two velocities is about 0.8%. The difference caused by a temperature variation of one-tenth of one degree Celsius in this temperature range is about 0.02%. When accurate absolute values of velocity, thickness and surface contours are required, it is important to measure the water temperature in experiment to one-tenth of a degree Celsius and use the corresponding sound velocity in water.

An alternative way of choosing echoes. From the term $t_2 - t_1$ in Eqs. (1) and (2) one can see that only the time *difference* between two consecutive echoes from the sample is required. In principle, such a time difference can be measured using any pair of consecutive echoes in the first and second sets shown in Fig. 1 (b). Particularly, if the purpose of the measurement is only to get the velocity and thickness images, it is advantageous to use echoes m_1 and m_2 instead of echoes 1 and 2 for the following reasons. First, we now only need to acquire, store and process three TOFs, t_{m1}, t_{m2} and t_w, instead of four TOFs that are required in Eqs. (1) and (2). Second, m_1 and m_2 are of the same polarity, while echoes 1 and 2 have opposite polarity. Third, the TOFs of echoes m_1 and m_2 are not sensitive to the distance between the transducer and the sample, which makes the sample level adjustment (or the concentric alignment in a circular turn-table scan) is much less critical and is therefore easier to achieve. Finally, the amplitudes of echoes m_1 and m_2 are usually much smaller than those of echoes 1 and 2. It is often difficult to have adequate gain for echo m_1 without saturating echoes 1 and 2. By using only echoes m_1 and m_2, this dynamic range problem can be avoided. However, it should be also noted that echoes m_1 and m_2 may not be suitable for measurements on samples with high attenuation and dispersion. Because the waves for echoes 2 and m_1 have propagated through the sample only twice while echo m_2 four times, echo m_2 has usually suffered more severe pulse distortion than echoes 2 and m_1. Also, when the sample material is attenuative and dispersive, echo m_2 may not have a dominant peak with a well-defined polarity while echoes 2 and m_1 may still maintain a dominant peak with a well-defined polarity. In that case, echoes 1, 2, and m_1 would still be the better choice for getting low-noise velocity and thickness images.

An alternative to a reflector plate. Instead of using a large reflector plate and making a reference scan, a small planar reflector large enough to intercept the entire ultrasonic beam may be used. This small reflector is positioned at the desired distance from the transducer, orientated perpendicular to the beam, and "ganged together" with the transducer via a U-shaped yoke. The depth of the yoke should be sufficient to accommodate the sample size and the sample may be mounted horizontally or vertically. During a SVTP scan, both the transducer and the reflector move together to collect data at different scan positions. There are several advantages in this alternative setup. First, the reflector will always remain perpendicular to the beam and the alignment is unaffected by the placement or removal of the sample. Second, because the distance between the transducer and the reflector is fixed, t_w is not a function of scan position. There is therefore no need for a "reference scan"; a single TOF measurement for t_w and a "sample scan" will provide all the times of flight needed for constructing the velocity, thickness and surface profile images. This method can be applied equally well to the scan of flat plates and circular cylinders. An obvious limitation of this setup is that the sample size will be limited by the depth of the U-shaped yoke.

RESULTS AND DISCUSSION

In the following, the extended profiling ability of the SVT imaging technique was first demonstrated using an aluminum sample with surface features and constant material properties. The SVTP imaging technique was then applied to two industrial material systems using samples with spatially varying ultrasonic velocity and/or thickness and profile to demonstrate its value in nondestructive testing and material property characterization. The two materials were: (1) woven carbon epoxy laminates containing various foreign objects and anomalies and (2) plasma sprayed thick thermal barrier coatings that were mixtures of metal (NiCrAlY) and ceramics (Zirconia).

Validation of the Technique

We machined an aluminum test sample with a dimension of 101.6 mm $\times$ 50.9 mm $\times$ 9.50 mm. The sample had designed recess on both the front and back surfaces. As shown in Fig. 2 (a), the sample's front surface had a 12.7-mm wide, 1.35-mm deep rectangular groove and an 18.9-mm diameter, 0.76-mm deep circular indent. The back surface had a 25.4-mm wide, 1.53-mm deep rectangular groove and a 12.6-mm diameter, 1.02-mm deep circular indent. The sample surfaces were not polished.

The SVTP scan was performed with a spherically focussed transducer (Panametrics V311, 10 MHz central frequency, 12.7 mm in diameter, and 101.6 mm in focal length) at a step size of 0.01 inch (2.54 mm) in both x and y directions. The sample was placed in the focal zone. The resulting images for the velocity, thickness, front surface contour and back surface contour are given in Figs. 2 (b), (c), (d) and (e), respectively. A sketch of the top view of the sample contour was superimposed on all the figures as dotted lines for geometrical comparison. As expected, the velocity image (Fig. 2 (b)) shows that the sample had a uniform velocity distribution and the value was consistent with that measured by conventional methods. It should be noted that the corners at the grooves and indents disrupted the ultrasonic beam and

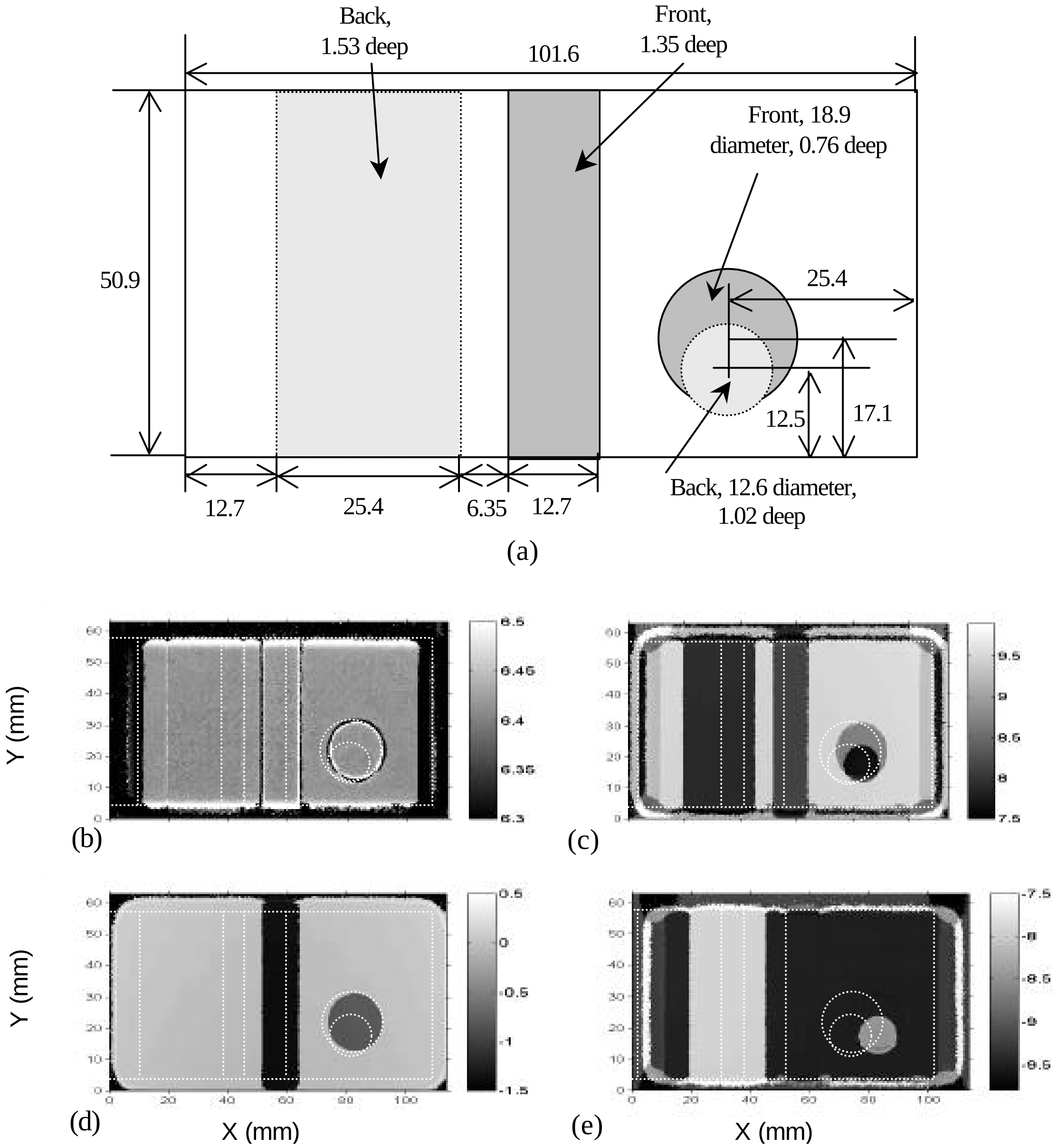


Fig. 2 The aluminum test sample and its SVTP imaging results. (a) dimensions of the sample, (b) velocity image in mm/*m*s, (c) thickness image in mm, (d) front surface contour in mm, and (e) back surface contour in mm. Dotted lines indicate the scaled top view of the sample.

led to edge effects; also the data were invalid at the two ends over the support rollers. The thickness image given in Fig. 2 (c) shows clearly that the sample had five distinctly different thickness regions. However, based on the thickness image alone, one would not be able to determine whether such thickness variations were due to the displacement of the front surface or the back surface, or both. The resulting front surface contour image, as shown in Fig. 2 (d), shows that the sample's front surface had a rectangular groove and a circular indent. The resulting back surface contour image (Fig. 2 (e)) indicates that the back surface had a wider rectangular groove and a smaller circular indent. In both images, the location and size of the surface contour features matched well with the sample geometry (indicated by the dotted lines). On the back surface contour image we can faintly see the edges of the rectangular groove and circular indent on the front surface due to the edge effects.

Application to Composite Laminates Containing Foreign Objects and Anomalies

Composite laminates containing different types of artificially embedded foreign objects and anomalies have also been used as samples to test the utility of the SVTP imaging technique in flaw detection. The first laminate sample was a 4-mm-thick woven carbon/epoxy laminate. A 38.1-mm diameter circular nylon bag was embedded in the laminate. Figures 3 (a) and (b) are the SVTP velocity and thickness images, respectively; (c) and (d) are respectively the conventional BSE TOF and amplitude images, for comparison. The velocity image in Fig. 3 (a) clearly showed the presence of the circular foreign object as a region of slightly lower velocity, which is a result of the stiffness reduction caused by the embedded nylon bag. The thickness image, Fig. 3 (b), shows a diffused region of slightly increased thickness but did not clearly show a well-defined circular area. This was because of the "draping effect" of the plies around the edge of the embedded defect. In contrast, the conventional BSE amplitude and TOF images showed different information. The TOF image in Fig. 3 (c) only showed a very faint image of the flaw. The amplitude image in Fig. 3 (d), however, showed a distinct ring of much reduced amplitude along the edge of the embedded nylon bag. This was caused by the scattering and beam disruption due to the resin-rich area and ply draping around the edge of the inclusion.

In the second carbon/epoxy laminate sample, a 38.1-mm diameter hole was punched in the second ply before lay-up. This circular area was then filled with a disk of neat resin to simulate a resin-rich area. The velocity image produced by the SVTP imaging technique (Fig. 4 (a)) shows clearly the reduction of velocity in the defective circular area. The thickness image (Fig. 4 (b)) again shows a diffused bulge due to the embedded resin. The conventional

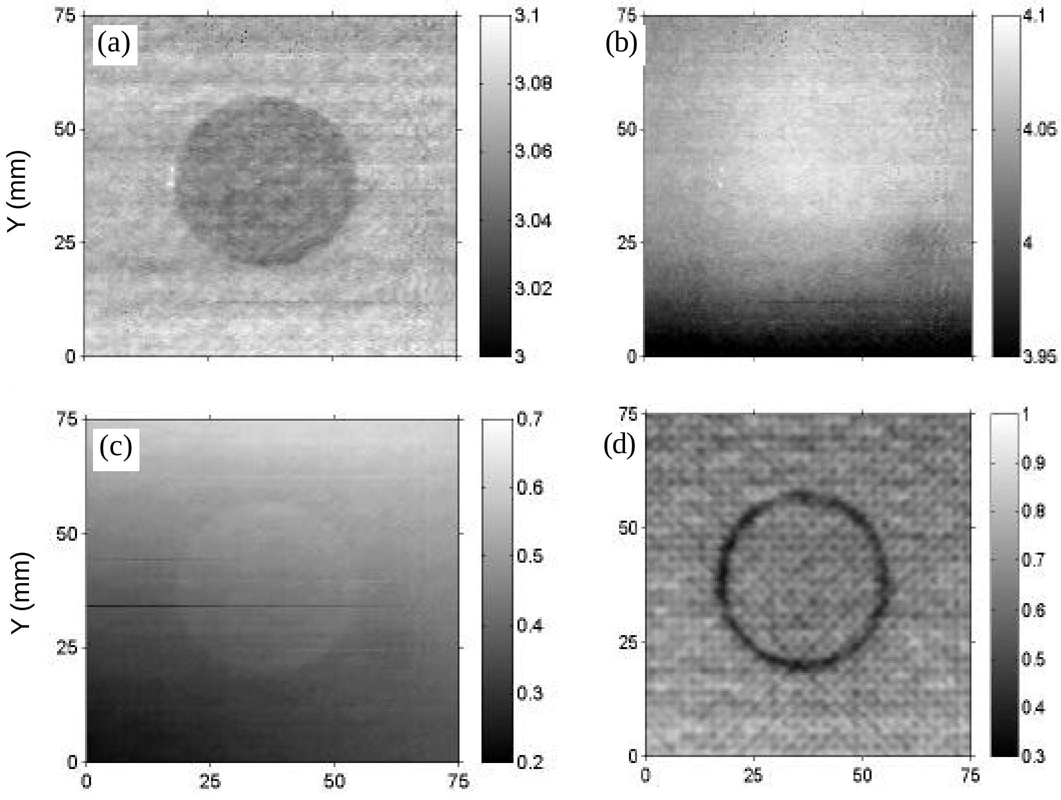


Fig. 3 A comparison of the conventional C-scan images and the SVTP images on a composite laminate with an embedded nylon bag: (a) velocity image in mm/*m*s, (b) thickness image in mm, (c) BSE TOF image in *m*s, and (d) BSE amplitude image in full screen height.

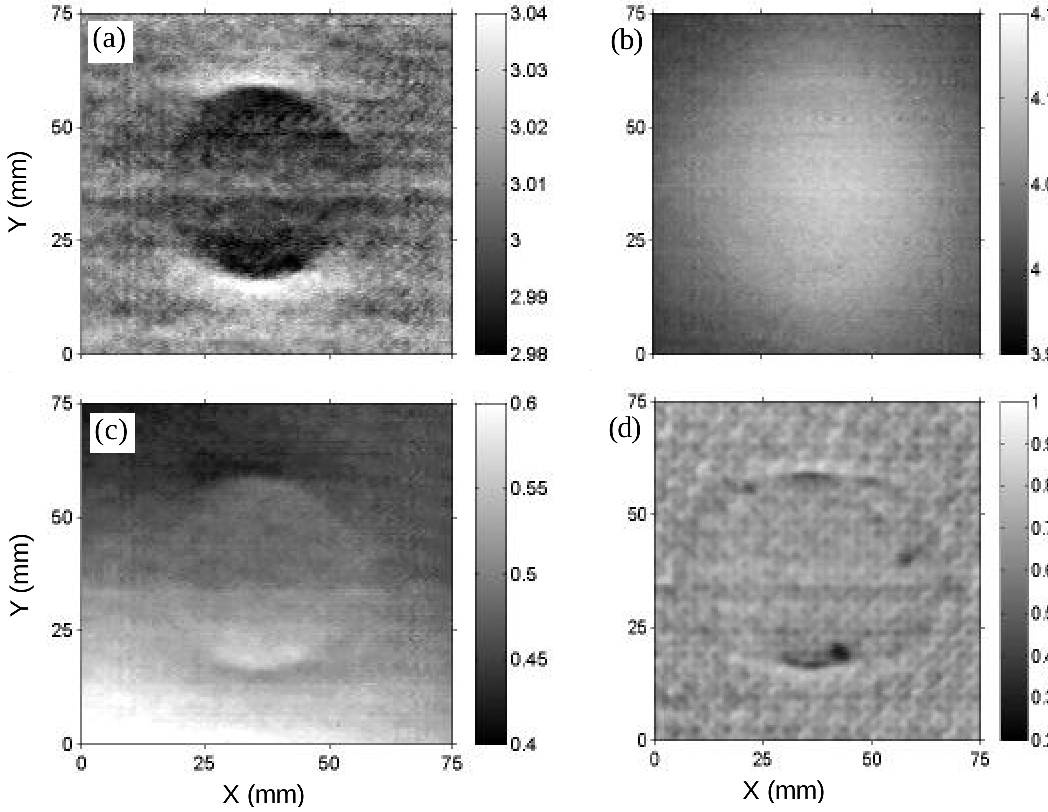


Fig. 4 A comparison of the conventional C-scan images and the SVTP images on a composite laminate with a simulated resin-rich area: (a) velocity image in mm/*m*s, (b) thickness image in mm, (c) BSE TOF image in *m*s, and (d) BSE amplitude image in full screen height.

BSE amplitude and TOF images, shown respectively in Figs. 4 (c) and (d), give some indication about the edge of the defective area, but did not clearly show the defective area itself.

Application to Thick Thermal Barrier Coating (TTBC) Samples

The SVTP imaging technique was also applied to measure the small variations in both velocity and physical dimensions of plasma sprayed TTBC samples with different weight composition of metal (NiCrAlY) and ceramic (Zirconia). Here we only show the results on one TTBC sample. This sample had 60% metal and 40% ceramic, and was about 2.3 mm thick and 89 mm in diameter. A 10-MHz spherically focussed transducer (Panametrics V311, 12.7 mm in diameter and 101.6 mm in focal length) was used to obtain high spatial resolution images. As shown in Fig. 5, the velocity image (Fig. 5 (a)) shows that the sample had a relatively higher velocity (around 3.8 mm/*m*s) in the central part and a lower velocity (about 3.4 mm/*m*s) near the edges. The difference was about 10%. The thickness image (Fig. 5 (b)) also shows about a 10% thickness variation in the sample. The front and back surface contour images are shown in Figs. 5 (c) and (d), respectively. The highest point of the front surface of the sample was chosen as the reference point for viewing the surface contour results. From the two surface contours we can see that the pattern in the thickness images was mainly due to the variation in the back surface contour. Three cross-sectional profiles at y = 25, 50 and 75 mm are given in Figs. 6 (a), (b) and (c), respectively. The gray level in the three images indicates the local longitudinal velocity in the thickness direction. Such plots vividly show the variation of both the material property and physical dimension in the sample's cross-sections.

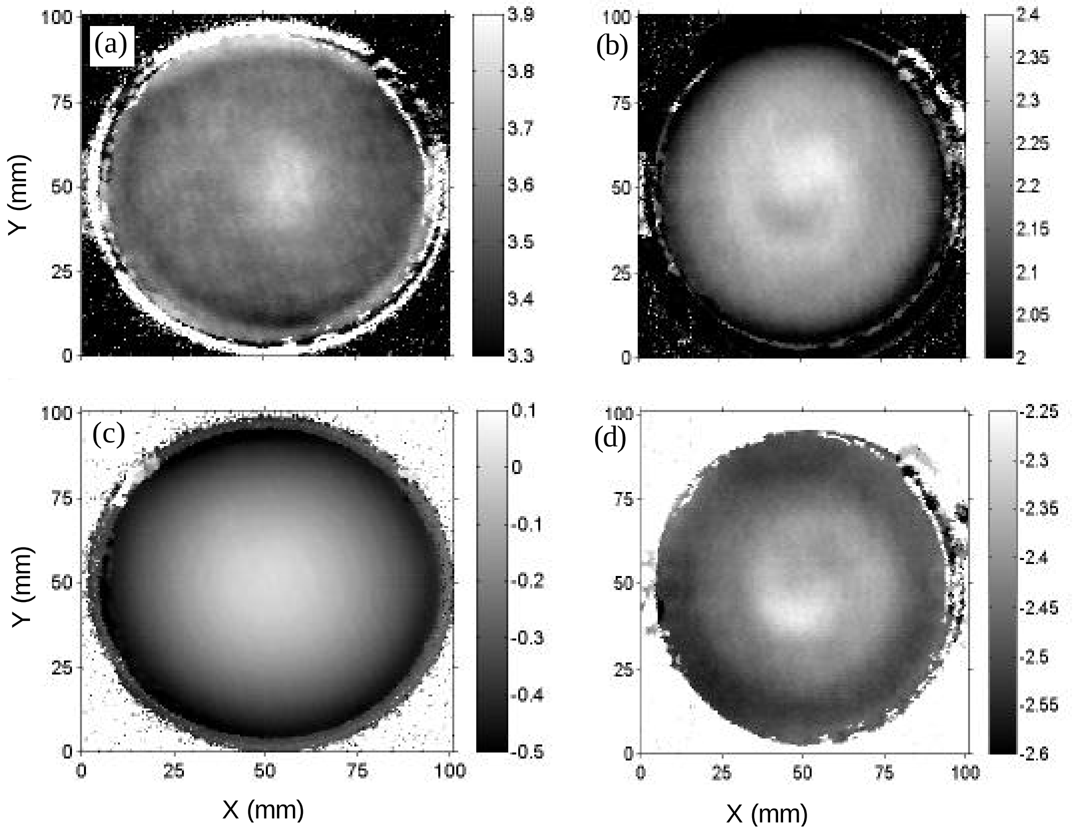


Fig. 5 The SVTP images of the thick thermal barrier coating sample: (a) velocity image in mm/*ms*, (b) thickness image in mm, (c) front surface contour in mm, and (d) back surface contour in mm.

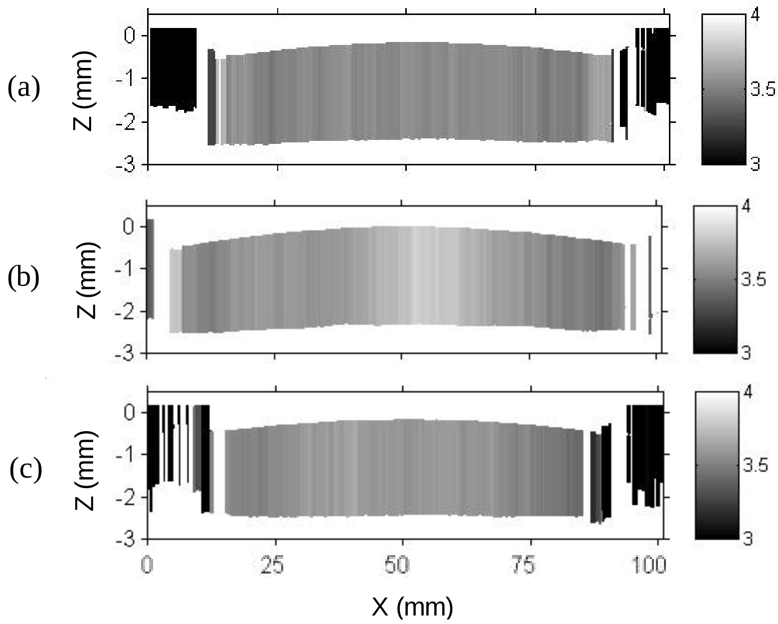


Fig. 6 Three cross-sectional profile images of the thick thermal barrier coating sample, respectively for (a) y = 25 mm, (b) y = 50 mm, and (c) y = 75 mm. The grayscale in each image corresponds to the local velocity in mm/μs.

CONCLUSIONS

This study has extended the simultaneous velocity and thickness imaging technique to produce the sample profiles and has demonstrated that this technique can be easily implemented in a commercial scan system with one transducer and a reflector plate behind the sample. By paying careful attention to the details of the measurement, this technique can be used to produce accurate and reliable images of not only thickness and velocity, but also sample surface contours and cross-sectional profiles. Several application examples have demonstrated that this technique may be a valuable tool for nondestructive testing as well as material property characterization of both metals and composites.

ACKNOWLEDGEMENTS

This work was supported by the NSF Industry-University Cooperative Research Center for Nondestructive Evaluation at Iowa State University. The authors gratefully acknowledge Greig Happoldt of Caterpillar for providing the thermal barrier coating samples. We also thank Dan J. Barnard for useful discussions regarding imaging the surface profiles. One of the authors, Dong Fei, acknowledges the support of a graduate assistantship from the Institute for Physical Research and Technology at Iowa State University.

REFERENCES

1. L. H. Pearson and D. S. Gardiner, in *Proc. of 15th NDE Symposium*, eds. D. W. Moore and G. A. Matzkanin (NTIA center, TX, 1985), p. 234-255.
2. V. Dayal, "An automated simultaneous measurement of thickness and wave velocity by ultrasound", *Expt. Mech.*, **32**(2), 197-202, (1992).
3. D. K. Hsu and M. S. Hughes, "Simultaneous ultrasonic velocity and sample thickness measurement and application in composites", *J. Acoust. Soc. Am.* **92**(2), 669-675, (1992).
4. I. Y. Kuo, B. Hete, and K. K. Shung, "A novel method for the measurement of acoustic speed", *J. Acoust. Soc. Am.* **88**, 1679-1682 (1990).
5. M. S. Hughes and D. K. Hsu, "An automated algorithm for simultaneously producing velocity and thickness images", *Ultrasonics* **32**(1), 31-37, (1994).
6. D. J. Roth and D. A. Farmer, "Scaling up the single transducer thickness-independent ultrasonic imaging method for accurate characterization of microstructural gradients in monolithic and composite tubular structures", NASA Report TM-1998-207924.
7. P. He, "Measurement of acoustic dispersion using both transmitted and reflected pulses", *J. Acoust. Soc. Am.* **107**(2), 801-807, (2000).
8. D. K. Hsu, D. Fei, R. E. Shannon and V. Dayal, "Simultaneous Velocity and Thickness Imaging by Ultrasonic Scan," to appear in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (AIP, 2001).
9. J. R. Lovett, "Comments concerning the determination of absolute sound speeds in distilled and seawater", *J. Acoust. Sco. Am.* **45**, 1051-1052 (1969).