Further testing and development of simulation models for UT inspections of armor

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FURTHER TESTING AND DEVELOPMENT OF SIMULATION MODELS FOR UT INSPECTIONS OF ARMOR

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ABSTRACT. In previous work we introduced an approach for simulating ultrasonic pulse/echo immersion inspections of multi-layer armor panels. Model inputs include the thickness, density, velocity and attenuation of each armor layer, the focal properties of the transducer, and a measured calibration signal. The basic model output is a response-versus-time waveform (ultrasonic A-scan) which includes echoes from all interfaces including those arising from reverberations within layers. Such A-scans can be predicted both for unflawed panels and panels containing a large disbond at any given interface. In this paper we continue our testing of the simulation software, applying it now to an armor panel consisting of SiC ceramic tiles fully embedded in a titanium-alloy matrix. An interesting specimen of such armor became available in which some tile/metal interfaces appear to be well bonded, while others have disbonded areas of various sizes. We compare measured and predicted A-scans for UT inspections, and also demonstrate an extension of the model to predict ultrasonic C-scans over regions containing a small, isolated disbond.

Keywords: Armor Inspection, Ultrasonic Inspection Simulation, Ultrasonic Modeling, Titanium, SiC

PACS: 43.35.Zc, 43.20.Bi, 43.20.Gp.

INTRODUCTION AND BACKGROUND

In last year’s QNDE proceedings we discussed an approach for simulating normal-incident ultrasonic pulse/echo immersion inspections of multi-layer armor panels [1]. The model output is a predicted ultrasonic A-scan display which includes echoes from all interfaces including those arising from reverberations within layers. We demonstrated that such A-scans could be easily predicted for both well-bonded panels and panels containing a large disbond at any given interface. In addition, the simulator was successfully tested against experimental results for a 5-layer composite armor panel containing fiberglass, graphite/epoxy, rubber and ceramic layers [1, 2]. In the present work we continue simulator testing, this time applying it to metal-ceramic armor consisting of silicon carbide (SiC) ceramic tiles fully embedded in a titanium-alloy matrix. An interesting specimen of such armor was made available to us for which some tile/metal interfaces appear to be well bonded while others contain disbonded areas of various sizes. Here we report on ultrasonic inspections of this armor specimen using various planar and focused transducers, and we compare measured and predicted UT A-scans in damaged and undamaged regions. We also demonstrate a new capability of the simulator to predict ultrasonic pulse/echo C-scan images for two-dimensional scans of a transducer over an interface region containing a small isolated disbond.
SIMULATION APPROACHES

The basic inspection problem addressed by the simulator is illustrated in Figure 1. Given a transducer (with known diameter and focal length) and a suitable calibration signal (typically the back-wall response from a low-attenuation reference block), we want to predict the full time-domain waveform seen during the panel inspection for all sound arrival times less than some maximum, $t_{max}$. This is to be done for both an unflawed panel and one having a disbond at a given interface. The disbond may be “large” or “small”. Here a “large” disbond means one that is always larger in area than diameter of any sound pulse incident on it, and “small” covers all other cases. The modeling approach for treating unflawed panels and those containing “large” disbands was described in detail earlier [1] and will not be repeated here. In short, we consider all possible sonic paths, each of which has a well-defined travel time. Some sonic paths will be a simple such as a direct back-wall echo from one interface (see Figure 2a). Others will be more complicated, involving reverberations within layers (see Figure 2a). We compute the response for each possible sound path in turn and then superimpose these in time to arrive at the predicted A-scan. The calculations for the “no disbond” and “large disbond” cases are essentially identical, the only change being the modification of the reflection and transmission coefficients at the disbonded interface [1].

In all calculations, we must account for the finite cross-sectional area of the sound pulse. We do that by combining reciprocity, the Multi-Gaussian paraxial beam model and the Kirchhoff approximation [1, 3]. For the “no disbond” or “large disbond” cases, the effect of the finite beam size is treated by including a diffraction correction factor [1]. In computing that factor (at each frequency in the band width of the sonic pulse) we effectively propagate the sound pulse back to the transducer and perform an integration of the product of the incident and returning sonic displacement fields over a plane immediately in front of the transducer. Such integrals can be done analytically when the Multi-Gaussian beam model is used [3]. By contrast, for the “small disbond” case we integrate the product of the incident and reflected

(a) Calibration Block
(b) Given: back-wall response
(c) Multi-Layer Armor Panel
(d) A-scan for Armor Panel

FIGURE 1. Simulator capabilities. Given a normal-incidence reference block setup (a), and an assumed back-wall calibration signal (b) measured at equipment gain setting G1, then for an armored panel inspection (c) the simulator predicts the time-domain response (d) at gain setting G2.
The response at a given frequency is assumed to be proportional to the integral of the product of incident and returning sonic displacement fields. Auld’s reciprocity principle allows considerable freedom in choosing a suitable integration plane. The planes we use for the “large” and “small” disbond cases are illustrated above.

fields over the interface containing the disbond. There the reflection coefficient varies with position and the integration is consequently performed numerically. Currently for “small disbond” cases we are only considering direct echoes from the disbonded interface (like that illustrated in Figure 2b). Our emphasis is on simulating ultrasonic gated-peak C-scans in the vicinity of the small disbond using a time gate centered at the defective interface. Thus we are postponing treatment of cases in which the sound pulse interacts more than once with an interface containing a small disbond.

INSPECTION OF THE METAL-CERAMIC ARMOR SPECIMEN

Figure 3 depicts the metal-ceramic armor specimen studied here and also introduces our nomenclature for identifying the armor layers and interfaces. The two metal layers on either side of a tile are referred to as “metal” and “cap”, respectively, and the two internal interfaces are identified as the “metal/tile” and “cap/tile” interfaces. No pedigree accompanied the specimen, but it was likely fabricated as follows. Beginning with a large block of titanium alloy cavities were machined into the block, ceramic tiles were placed into the cavities, a metal “cap” covering the tiles was welded to the metal block, and the specimen was hipped. The same alloy was evidently used for both the metal block and the cap. The ceramic inserts are believed to be SiC tiles having approximate dimensions of 1.5” x 1.5” x 1.1”. The specimen contains 7 full tiles and two half tiles spaced approximately one-half inch apart. The two largest surfaces are

![Diagram of armor cross-section with nomenclature](image)

Assumed UT properties:

- **Ti alloy:**
  - \( \rho = 4.42 \text{ gm/cc} \)
  - \( v = 0.616 \text{ cm/us} \)
  - \( \alpha = 0.0045 f^{1.2} \) (in N/cm, \( f \) in MHz)

- **SiC tile:**
  - \( \rho = 3.1 \text{ gm/cc} \)
  - \( v = 1.24 \text{ cm/us} \)
  - \( \alpha = 0 = 0 (f < 25 \text{ MHz}) \)

Water at 66.5F:

- \( \rho = 1.00 \text{ gm/cc} \)
- \( v = 0.148 \text{ cm/us} \)
- \( \alpha = 0.00026 f^{2} \)

![Typical inspection setup](image)
not perfectly flat, but rather are slightly concave when viewed from the cap side. In addition the outer cap surface is “waffled”, i.e. slightly sunken above each tile insert.

Ultrasonically, the specimen is quite interesting. As we shall see there are apparently: (1) large disbonds at the cap/tile interface for some tiles; (2) small disbonds at the metal/tile interface for some tiles; (3) substantial interior damage to three tiles as indicated by reflected echoes originating between the metal/tile and cap/tile interfaces; and (4) thin cracks in all tiles as indicated by small variations in reflectivity at both interfaces. Because of these properties the specimen is a good vehicle for demonstrating inspection capabilities and testing simulators.

Density, sound speed and attenuation are required inputs to the simulators. As discussed in Ref. [2], we prefer to begin our study of a new armor design by obtaining samples of each layer’s material and directly measuring the properties that bear on UT inspection. That was not possible here. However, by making UT measurements near the edges of the armor

FIGURE 4. Various gated-peak-amplitude C-scans resulting from ultrasonic pulse/echo inspections of the metal-encapsulated-ceramic armor specimen. In each case the planar or focused transducer was scanned over a 9 inch by 18 inch area using a step size of 0.05 inches. (Original figure is in color.)
specimen (i.e., away from any tiles) we were able to estimate the sound speed and attenuation-vs-frequency curve for the titanium alloy. We then used generic properties for SiC armor tiles, and a generic density for the metal. Our assumed model inputs are listed in Figure 3b. For this metal-ceramic armor, all attenuation values are less than 2 dB/inch at 10 MHz so one can easily perform inspections using 5 and 10-MHz transducers. This is in sharp contrast to the composite armor example where high attenuation values dictated inspections at 2-MHz or below [1, 2].

Our inspection setup is illustrated in Figure 3c. All measurements were made at normal incidence with the armor specimen immersed in water and resting on a turntable. The specific measurements we will discuss here used either 5-MHz planar or 10-MHz spherically-focused transducers. For the focused transducer cases we used different transducers for inspections through the “metal” and “cap” sides of the armor, in each case adjusting the water path to focus at the tile interface closest to the transducer. For a sampling of the inspections, Figure 4 displays gated-peak amplitude C-scans using a narrow time gate centered on an interface echo of interest. In each case the general setup, the transducer used, and the interface of interest are indicated by the small drawing above the C-scan. Notice the three tiles in the right-hand region of the specimen for which reflected amplitude from the cap/tile interface is unexpectedly large, indicting disbonding over wide areas. Small, isolated regions of unexpectedly high reflected amplitude from the metal/tile interface can also be seen. One such disbond denoted as “Defect 1” in Figure 4d will be considered in detail later. For apparently well-bonded tiles, variations in reflected amplitude can be seen which arise from two sources: (1) speckle due to propagation through the metal microstructure; and (2) loss of exact normality at interfaces due to the slight curvature or waffling of the outer surfaces.

Three of the tiles definitely have internal cracks, namely those tiles having large disbonded areas at the cap/tile interface. That is demonstrated in Figure 4f where a time gate is used that spans the interval between the front and back-wall echoes from the tiles (but excludes both interface echoes). There one sees clear evidence of scattering from tile interiors. It is likely that all tiles in this armor specimen are cracked. For the focused-transducer inspections one can boost the signal amplification level (“gain”) and use a gray scale to increase the contrast in C-scan images. That has been done in Figure 5 for direct reflections from the metal/tile and cap/tile interfaces, respectively. Notice the thin dark lines of lower reflected amplitude which have roughly similar appearance on both sides of a given tile. We speculate that these are due to tight tile cracks oriented nearly perpendicular to the plane of the figure.

**FIGURE 5.** High contrast C-scans of a portion of the armor specimen revealing thin regions of reduced reflectivity from the metal/tile interface (left) and cap/tile interface (right).
INSPECTION SIMULATION FOR THE METAL-CERAMIC ARMOR SPECIMEN

Figure 6 compares measured and predicted A-scans for pulse/echo inspections of the armor specimen. For all of the cases shown the measured data was acquired either in a region with no apparent interface disbands or in a region having a very large disbond at the cap/tile interface. For each case shown the inspection setup is indicated and the principal echoes from the various interfaces have been labeled. The time interval displayed extends roughly 20 microseconds beyond the front-wall response. Compared to the pulse/echo A-scans for inspections of the 5-layer composite armor [1], those in Figure 6 tend to have features which are much better resolved in time. This is a consequence of the higher inspection frequencies used.

The results shown in Figure 6 are typical examples chosen from a larger set of comparisons. Although it is not evident on the time scale used in Figure 6, the predicted shapes of the various waveform features (as well as the amplitudes) are in generally good agreement

**FIGURE 6.** Examples of predicted and measured ultrasonic A-scans for inspections of the metal-ceramic armor specimen using a 5-MHz planar transducer. Only “large disbond” or “no disbond” cases are considered.
with experiment. That is illustrated in one instance by the blowups of the predicted and measured tile/cap echoes shown in the upper portion of Figure 6c. We note that no adjustable scaling parameters have been used in the model calculations, as all absolute amplitudes are fixed by the calibration signal and the experimental gain setting. Here, a back-wall response from a one-inch-thick or two-inch thick fused-quartz block served as a calibration signal. Overall we found that model and experiment tended to be in slightly better agreement for the planar-transducer inspections than for the focused-transducer ones, particularly for sound paths which transit a tile thickness. This may be due to the effects of the tight tile cracks. Since we focus at the tile front wall, the beam diverges rapidly within the tile, and hence is more likely to interact significantly with thin tile cracks that run parallel to the sound propagation direction.

Figure 6d presents model calculations for a case in which there is no experimental counterpart, namely an inspection through the cap side when a large disbond is present at the metal/tile interface. Notice the increase in amplitude of the metal/tile echo due the disbond and the subsequent drop out of the later arriving metal/water echo. Such calculations demonstrate the usefulness of the simulator for inferring (at a glance) the effect of a large disbond. This can serve as a valuable tool when designing an inspection and choosing time gates for C-scans.

As discussed earlier, the armor specimen evidently contains several small disbonds at the metal/tile interface, one of which was designated as “Defect 1” in Figure 4b,d. Two factors are of chief important when computing the ultrasonic pulse/echo response from such a disbond: (1) the spot size (cross-sectional area) of the interrogating sound pulse at the interface in question; and (2) the difference in sonic reflectivity between the disbonded region and the remainder of the interface. The situation is illustrated in Figure 7 for the inspection of “Defect 1” through the thick metal side. The precise size and shape of this disbond are unknown, but we have made an educated guess of its extent (shown in Figure 7a) to further the discussion. There we display the relative sizes of the assumed disbond and the beam spots for the 5-MHz-planar and 10-MHz-focused inspections of Figure 4b,d. In particular the beam spots shown are full widths at half maximum of the square of the incident pressure at the nominal center frequency of each transducer. Under the approximation we are employing, the computed response from the interface at a given frequency is proportional to integral (over the full beam footprint) of the square of the incident pressure times the local interface reflectivity. In this case we are modeling the disbond as a perfect reflector having a reflection coefficient of R = 1. Away from the disbond the reflectivity depends on the relative impedances (Z) of the two

Assumed Disbond Geometry (within a 1.0” x 1.0” square)  

5-MHz Planar Transducer (1.0” x 1.0” scan area)  

10-MHz Focused Transducer (0.5” x 0.8” scan area)  

FIGURE 7. (a) Assumed geometry of Defect 1. Measured and predicted C-scans for 2D scans of the defect using planar (b) and focused (c) transducers. The dimensional scale and color bar are the same for all images. (Original figure is in color.)
layers, namely \( R = \frac{Z_1-Z_2}{Z_1+Z_2} \). When approaching the metal/tile interface from the metal side, \( R \) is negative since the ceramic tile has the higher impedance. When the beam footprint is partially on and partially off the disbond, the change in sign of the reflectivity usually leads to a partial cancellation within the integral and a lowering of the UT response (although this effect can be modulated by the curvature of the sonic wave fronts).

In Figures 7b and 7c we compare measured and predicted gated-peak-amplitude C-scans for “Defect 1”. Model C-scans, based on the disbond shape in Figure 7a, are predicted by computing the time-domain metal/tile interface echo at each transducer position, and then displaying the rectified peak-amplitude of that echo. For each image in Figure 7 the color bar is chosen such that violet/blue denotes zero amplitude and red denotes the peak amplitude present. A “signal-to-background” ratio (S/B) is also indicated. This is the peak amplitude value within the image divided by the amplitude at locations far removed from the defect. As the S/B value increases, the disbond becomes more noticeable in ultrasonic inspections.

For the focused transducer inspection, the beam spot is smaller than or on the order of the disbond width, and the general size and shape of the disbond are well reflected in the C-scan image. On the other hand, the beam spot is noticeably larger than the disbond for the planar transducer inspection and the C-scan image is a less faithful rendition of the disbond geometry. There, prominent interference minima are seen which are well removed from the disbond boundaries. One sees in Figure 7 that the general appearances of the C-scans and the S/B ratios are reasonably well predicted by the model, although, for the planar transducer, the interference minima are misplaced. This may be due to the breakdown of the Kirchhoff approximation at 5-MHz for such a thin disbond (disbond-width / wave-length \( \sim \) 1.6) or simply to uncertainty in the size, shape and reflectivity of the defect which is modeled here as a perfect reflector.

**SUMMARY**

We have continued our work on the development and testing of models to simulate ultrasonic inspections of multi-layer armor. The metal-encapsulated-ceramic armor specimen used in the present study provides an interesting contrast with the composite-based armor studied earlier [1, 2]. The relatively low ultrasonic attenuation values for the metal-ceramic armor permit straightforward inspection at higher frequencies (5 to 10 MHz), allowing large and small disbonds and tile cracking to be readily detected. Model simulations of pulse/echo inspections of armor regions containing large and small disbonds were found to be in generally good agreement with experiment. We believe that such simulators can serve as useful tools for helping to design and qualify armor inspections.

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