A COMPARISON OF NDE METHODS FOR INSPECTION OF COMPOSITE CERAMIC ARMOR

W. A. Ellingson and E.R. Koehl

Argonne National Laboratory

Argonne, Illinois USA

T.J. Meitzler

US Army, TARDEC

Warren, MI

J. S. Steckenrider

Illinois College
Jacksonville, IL

L. P. Franks
US Army, TARDEC

Warren, MI

ABSTRACT

As part of a US Army supported project to establish appropriate NDE modalities for inspecting layered ceramic-composite armor, a series of 84 40 cm (16-inch) square by 50 mm (2-inch) thick, multi-layered ceramic composite armor specimens has been prepared. Some of these have had "designed defects" located in the interior—some do not. All samples are to be ballistically impacted and are to be inspected before and after ballistic testing. The question to be answered is—which NDE modality might best be used to quantify ballistically-induced damage. NDE modalities under present study include: 1)-immersion phased array ultrasonics, 2)- through-transmission, direct-digital x-ray imaging, 3)-non-contact scanning microwaves, 4)-air-coupled ultrasound and 5)-immersion, through-transmission and pulse-echo single-transducer ultrasound. At this time, all 84 samples have been inspected prior to ballistic testing. This paper will discuss these NDE techniques, issues that have been uncovered and will present results obtained.

INTRODUCTION

Effectiveness of multi-layer composite-ceramic armor appliqués, that are to be mounted on military vehicles, can be degraded by defects within the ceramic from production and/or by damage resulting from handling or impact from ballistic threat projectiles. Detection of defects during production is necessary to assure reliable and cost-effective armor production and detection of usage-induced damage is necessary to determine the integrity of in-theatre armor so that appropriate and timely replacement can be made. Recently, a special project was undertaken by the US Army to assess several nondestructive evaluation technologies for detection of ballistically-induced damage. The NDE methods under evaluation include: 1)-immersion phased array ultrasonics, 2)- through-transmission, direct-digital x-ray imaging, 3)-non-contact scanning microwaves, 4)-air-coupled ultrasound and 5)-immersion, through-transmission and pulse-echo single-transducer ultrasound. In

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
08 JAN 2010	**N/A**	**-**

4. TITLE AND SUBTITLE	
A Comparison of NDE Methods for Inspection of Composite Ceramic Armor	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
J. S. Steckenrider; W. A. Ellingson; E.R. Koehl; T.J. Meitzler; L. P. Franks	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Illinois College Jacksonville, IL, USA Argonne National Laboratory Argonne, Illinois USA US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER **20481RC**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) **TACOM/TARDEC**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **20480RC**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at 34th International Conference and Exposition on Advanced Ceramics and Composites (ICACC), 24-29 January 2010, Daytona Beach, FL, USA, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**10**	

order to evaluate these NDE methods, a set of 84 specially made ceramic composite samples was produced. Table I shows the list of samples along with schematic diagrams of the various designs.

Table I List and schematic diagrams of NDE Effects of Defects samples

Run Designation	Panel Designation	Description	Panel Qty	Flaw Size	Flaw Position	Center/Triple Pt
A	A1-A4	Baseline - Center	8	No flaws		
B	B1-B4	Baseline - TP	8	No flaws		
C	C1-C4	Graphite to Rubber	8	½" square		
D	D1-D4	Graphite to Rubber	8	1½" square		
E	E1-E4	Graphite to Rubber	8	2½" square		
F	F1-F4	Graphite to Rubber	8	½" square		
G	G1-G4	Graphite to Rubber	8	1½" square		
H	H1-H4	Graphite to Rubber	8	2½" square		
J	J1-J4	Rubber to S2	8	½" square		
K	K1-K4	Rubber to S2	8	1½" square		
L	L1-L4	Rubber to S2	8	2½" square		
M	M1-M4	Rubber to S2	8	½" square		
N	N1-N4	Rubber to S2	8	1½" square		
O	O1-O4	Rubber to S2	8	2½" square		

To be noted is that the inserted "defects" are placed either above the layer immediately behind the ceramic insert or placed below the elastomer layer following the ceramic insert. In addition, the sizes of the defects inserted varied from 12 mm square (1/2-inch) to 62 mm square (2 ½-inches). Fabrication of the armor test panels further utilized two different ceramic materials. A slightly higher density and different composition material was used in the immediate vicinity of the inserted defects, see gray region in schematics of Table I, and a lower density ceramic material was then used for all surrounding tile (the yellow regions in the schematics of Table I).

DESCRIPTION OF THE NDE METHODS

The following section briefly describes the several nondestructive evaluation (NDE) methods being explored in this effort. These NDE methods include: 1)-immersion phased array ultrasonics, 2)-through-transmission, direct-digital x-ray imaging, 3)-non-contact scanning microwaves, 4)-air-coupled ultrasound and 5)-immersion, through-transmission and pulse-echo single-transducer ultrasound.

1. Immersion Phased Array Ultrasonics

Phased array ultrasonic methods[1] have been discussed previously for application to ceramic armor, but all previous work was only on the ceramic material itself. In a layered structure with several different materials, inherent different acoustic velocities will cause refraction of the acoustic wave and the effects on defect detection were unknown. However, previous work on defect detection in armor quality ceramics had clearly demonstrated that a much higher signal to noise ratio (S/N) was obtained for a phased array system as compared to a single-transducer immersion ultrasound system. Shown below in Figure 1 are photographs of the immersion phased-array ultrasound system used in this study. This system can drive a phased array transducer with up to 128 individual elements with control of the sequencing of up to 32 elements at any one time. Thus this is a 32/128 system.

(a) (b)

Figure 1 Photographs of immersion Phased Array Ultrasound equipment

The importance of using phased array technology for inspecting these ceramic composite armor panels is that by selecting the firing sequence of the transducer elements, the depth of the focus can be dynamically changed. This is shown schematically in Figure 2. By focusing at a well defined depth within the sample, the signal to noise ratio of the detected reflected pulse can be significantly increased.

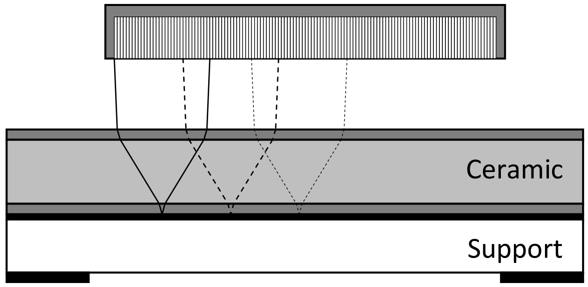


Figure 2 Schematic diagram showing firing sequence of the phased-array transducer with insonification from the "ceramic" side with the focus at the matrix to elastomer interface (horizontal dimensions not to scale). Although inspection insonification from both ballistic impact side (as shown here) and armor mounting side have been conducted, all data presented has been insonified from the ballistic impact side.

While the exact acoustic velocities for each material in the layered structure were unavailable, estimates were used to set the phased array transducer element firing sequence. These data were then used to set the protocol for the phased array testing. Table II presents part of the protocol.

Table II Phased Array Protocol. Using such a protocol, the scan time for each panel was approximately 6 minutes.

•	Transducer, 128-element 10 MHz array with a 0.5 mm pitch and 7 mm width (for a total active area of 64 mm x 7 mm).
•	Conducted with 32 active elements
•	Use an 18 mm water path
•	Scan using a 1 mm (0.04") resolution in the scan direction, 0.5 mm (0.02") resolution in the index direction
•	Set scan speed to 5 mm per second (0.21 inches per second)

2. Through Transmission, Direct-Digital, X-ray Imaging

Two direct digital through-transmission x-ray imaging systems are being used in this work. First, at Argonne, the x-ray imaging work for these test panels is being conducted using a 420 KVp x-ray head coupled to a large area, 17-inch by 17-inch, flat panel detector. This set-up is shown in Figure 3. The flat panel detector has 2048 200 um square pixels.

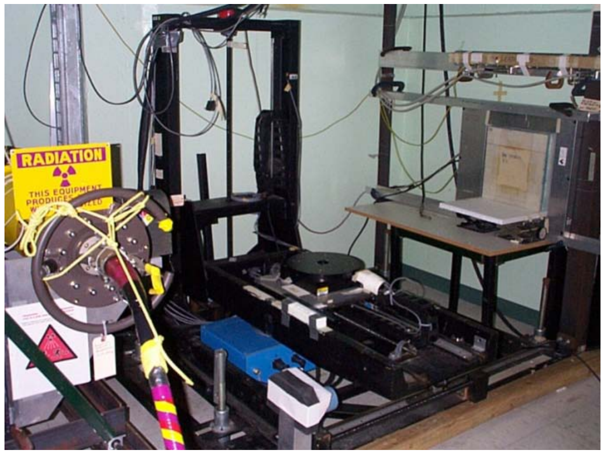


Figure 3: Photograph of X-ray imaging equipment

The second x-ray imaging effort is being conducted by the Center for Nondestructive Evaluation, CNDE, at Iowa State University. In their work they are using a much smaller flat panel, only 13 cm (5.1-inches) square. The CNDE pixels are 127 um square whereas the Argonne pixels are 200 um square. The CNDE effort requires many exposures to cover the entire 42 cm square (17-inch) armor panel while the Argonne image data are acquired in one exposure with little loss in spatial resolution.

Previous work at Argonne[2] on use of x-ray imaging for ceramic materials suggested that detection sensitivity is impacted by the x-ray energy levels employed. Lower x-ray energies are preferred for higher resulting image contrast. In the work at Argonne, two x-ray protocols were used in order to best establish defect detection. The two protocols employed are shown below in Table III.

Table III X-Ray imaging protocols

Standard image acquisition (no saturation)	Low voltage image acquisition
150 kVp, 1.25 mA and 3.00, 1.5 mm spot size	70 kVp, 10.0 mA, 4.5 mm spot size
Tube to sample distance: 234.95 cm	Tube to sample distance: 234.95 cm
Beam filter: 0.127 mm copper	Beam filter: 1.6 mm aluminum
Integration Time: 570 ms	Integration Time: 2.280 Sec
Screen: none	Screen: none
100 frame average	50 frame average

In order to establish the detection sensitivity, the work at Argonne utilized a line pair phantom made of aluminum and carbon rods. Shown below in Figure 4 is a typical through-transmission x-ray image of test panel A5 with the calibration phantom These data were obtained at 150 KVp and at these x-ray energies the higher density center tile is not easily detected.

Figure 4 Calibration x-ray Image. Panel A5. Single center high density tile. 150 KVp data. Line pair phantom, Aluminum and carbon rod Image Quality Indicators visible in upper center tile column.

3. Scanning Microwave Methods

Initially, plans called for exploring the use of the scanning microwave interference technique[3] pattern is created by irradiating the part in microwave energy as illustrated in Figure 5. The probe (transmitter and receiver antenna) is raster-scanned over the part and the signal at the receivers is sampled. The detected different voltage values represent differences in the local dielectric constant. The voltage values for both receivers are saved with the associated X-Y position on the object. The saved voltages are displayed as a function of X-Y position on a computer monitor. The displayed "image" is displayed as a surface; with each X-Y position being shown as a gray scale, a false-color or as a 3D Z value of the part surface.

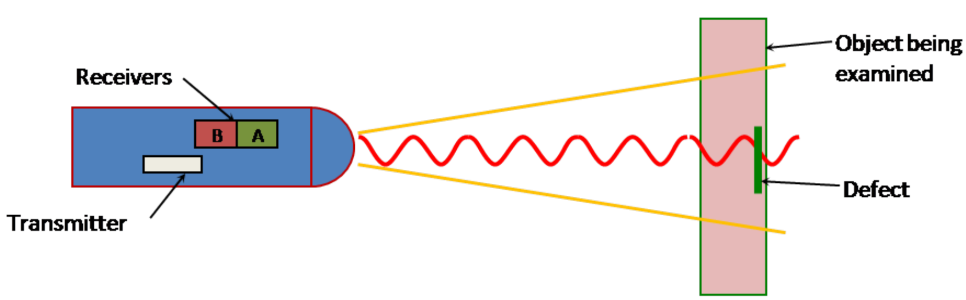


Figure 5 Schematic diagram showing relative position of microwave transmitter and receiver head to the part under examination. One-sided access is shown.

However, the scanning microwave system is best employed when the material is non-electrically conducting. In the case of these layered composite armor samples, certain materials were used that were electrically conducting and thus this NDE method is not applicable. It is to be noted that research is now being conducted to counteract this restriction for armor applications.

4. Immersion, Single Transducer, Scanning Ultrasound

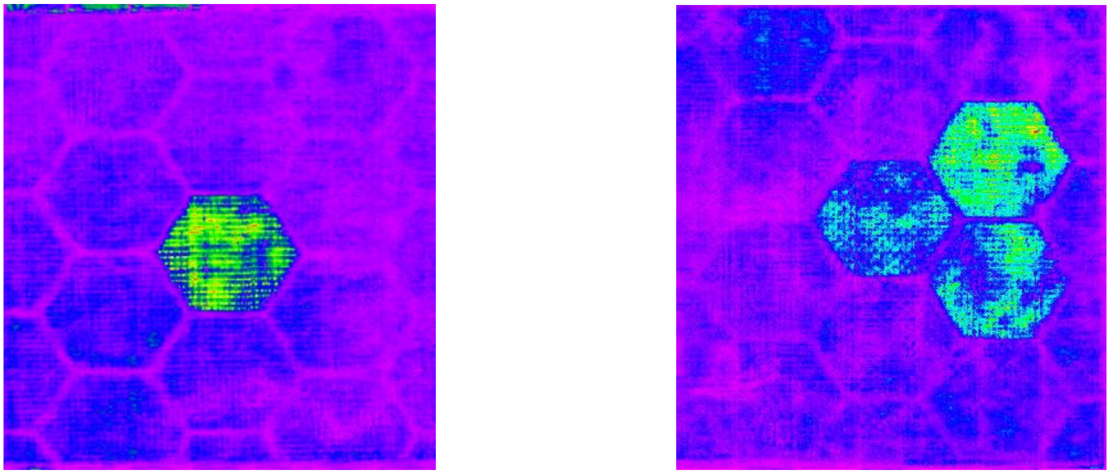
Immersion ultrasound,[4,5] has long been used for defect detection in a wide variety of materials. There are two modes for this technique: through transmission, wherein one transducer, an emitter, is placed on one side of the object, and a second transducer, a receiver, is placed on the opposite side of the specimen under study. Obviously this works best if the specimen under study is a flat plate with nearly parallel sides. The second mode for immersion ultrasound is called pulse-echo. In this case a single transducer is used. Through use of special electronics and digital controls, there is a simple time delay between the transmitted signal and the echo—or received signal. The ultrasonic scanning system is similar to the phased array scanning ultrasound system with the exception that the transducer is not a phased array transducer. In contrast to the phased array, the single transducer cannot be focused at different positions within the object unless the stand-off distance between the transducer and the test part is changed. Thus to scan with the "focus" of a single transducer, one must make several scans and between scans, the stand-off distance has to be changed. This usually results in very long data acquisition times as compare to phased array scans.

5. Air Coupled Ultrasonic methods

Air-coupled ultrasound[6,7] is a relatively new technology. This method eliminates the need for any liquid coupling between the test object and the ultrasonic probe. However, the method is limited to use in the through-transmission mode because of the low acoustic energy insertion. Further, because of issues with fabrication, usually air-coupled transducers are limited to frequencies less than 1 MHz. The limitations imposed by use of low frequencies thus also limit the defect size that can be detected. The authors have explored various air-coupled ultrasonic transducers including both piezo-electric and capacitance. Piezo –electric air-coupled transducers tend to be of high Q and thus offer little subsequent digital spectral analysis. Capacitance-based air-coupled transducers, while offering broad band sound and thus the potential for digital spectral analysis, provide very low acoustic signals and thus offer lower signal to noise ratios. In the work for this project, air-coupled ultrasound methods using through-transmission with piezo-electric transducers are being explored by CNDE.

RESULTS

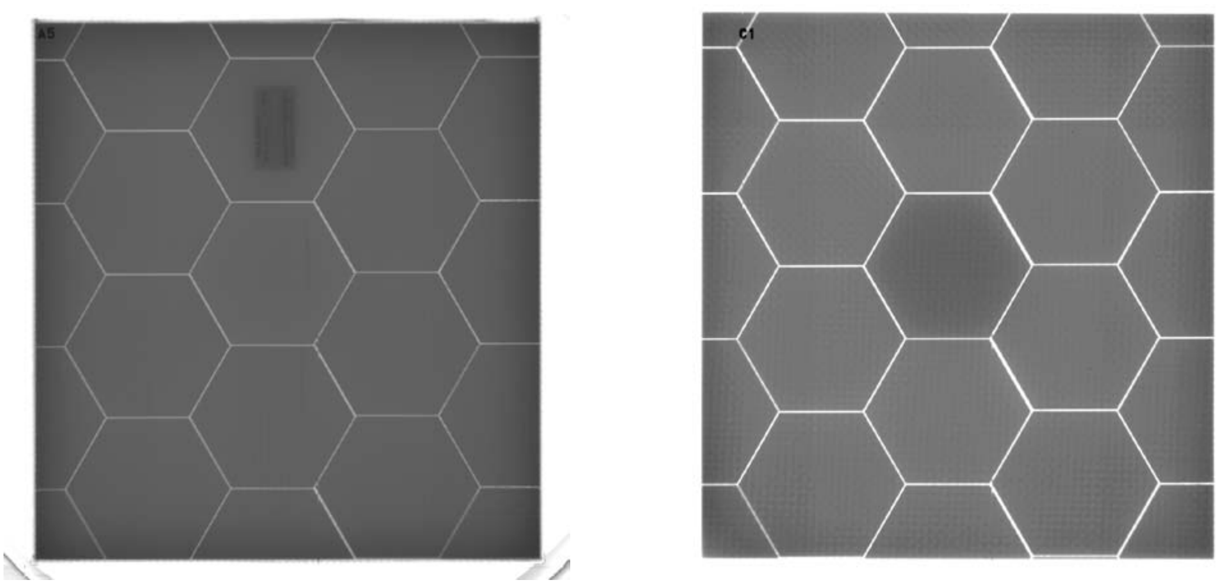
The results below show that the defect detection sensitivity for each NDE method has several dependency factors. In the case of phased array ultrasound, the effects of the different materials in each layer impacts the signal to noise ratio. Thus it is best to insonify from the side of the material where there are fewer interfaces. Shown below in Figure 6 are examples of use of water-immersion phased array ultrasound used to detect higher density ceramic tile in a complete layered ceramic composite armor plate. These plates were about 16-inches square and contained several layers of different materials. On the left it is shown that there is a single higher density tile and on the right it is shown that there are three higher density tiles.



(a) (b)

Figure 6 Phased array ultrasound data used to detect higher density ceramic tile in a complete ceramic composite armor appliqué. a) Single higher density center tile, b) three clustered higher density tile

For x-ray projection direct-digital imaging, there is little if any effect on whether or not the ballistic impact side is towards the x-ray source or towards the x-ray detector. However, there is a significant detection sensitivity difference as a function of incident x-ray energy. Figure 7a below shows a 150KVp projection image of a test panel with a single higher density center tile and Figure 7b shows a similar confirmation test panel imaged at 70 KVp. Note that Figure 7b from the 70 KVp x-ray more readily detects the higher density center tile and is differentiated from the lower density outer tile.



(a) (b)

Figure 7 X-ray image of Panel C1. a)- 150 KVp projection image and b)-70KVp projection data with gray scale adjusted

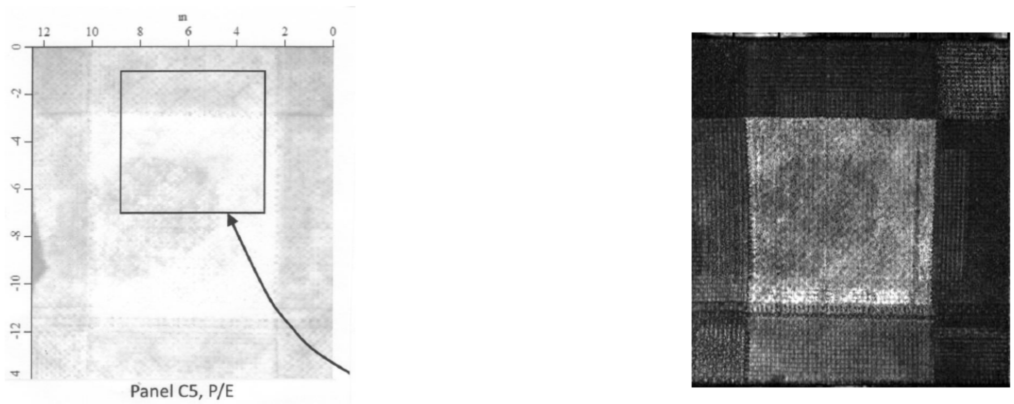
Based on the results of these initial tests, the following observations have been made:

1—Use of low KVp imaging techniques allows better contrast detection between tiles of different materials.

2—Use of simple digital image processing is necessary for better visualization of contrast differences.

3—Initial analysis x-ray image data suggests that while the suggested “delaminations’ are not likely to be detected; the x-ray image data clearly demonstrates the ability for detection of small changes in the gap spacing among the tile.

As a comparison between single transducer ultrasound pulse-echo and phased array ultrasound, Figure 8 below shows test data from armor sample C5. Both data sets were acquired in the same manner—that is insonification from the low elastic modulus side.. The advantage of the phased array is obvious.



(a) (b)

Figure 8 Comparison between a) single transducer ultrasound data and b) phased array ultraound data on same C5 test sample. Both immersion data sets acquired using same insoniofication side

No data were acquired with the scanning microwave system once it was discovered that there was an electrical conductor in the material set.

Data have also been acquired with air-coupled ultrasound. The transducers used in a through-transmission mode were 120KHz focused transducers. Again, the effect of the layers is reduced because as with the x-rays systems, the data are integrated in the through-transmission mode . To date, the detection sensitivity shown by air-coupled ultrasound is far inferior to that from the immersion ultrasound technology, especially the phased array, or direct digital x-ray imaging.

CONCLUSIONS

In conclusion, 84 specially made ceramic composite armor test panels have been produced as part of an Army project to establish which NDE methods might better detect defects in such armor systems. Several forms of ultrasonic testing have been used: Immersion phased array, immersion single focused transducers, air-coupled systems. The advantage of phased array scanning is that it is faster, is able to focus at a depth dynamically and has better detection sensitivity. Two x-ray imaging systems have been explored: both using through-transmission, direct digital systems. One uses a single large-area flat panel amorphous silicon based detector whereas as the other uses a small area, amorphous silicon, flat panel. The use of a single large-area flat panel is preferred because it significantly reduces time for data acquisition, hence cost, with little spatial resolution loss—certainly for the defects of this project. Scanning microwaves were initially explored but are presently unusable if an electrical conducting layer is employed in a layered armor structure. It seems that phased array ultrasound and use of large-area, direct-digital projection x-ray imaging offer the most time and cost effective NDE technologies for evaluating armor appliqués prior to mounting on vehicles or after removal from vehicles.

REFERENCES

[1] J.S. Steckenrider, W.A. Ellingson, and J.M. Wheeler, Ultrasonic Techniques for Evaluation of SiC Armor Tile , *Ceramic Eng. And Sci. Proc*. 26(7) 215-222 (2005)

[2] W. A. Ellingson and M. W. Vannier , Applications of Dual-Energy X-Ray Computed Tomography to Structural Ceramics,in Proc. 37th Ann. Denver Conf. on *Advances in X-Ray Analysis*, , ed. C. S. Barrett, J. V. Gilfrich, R. Jenkins, T. C. Huang, and P. K. Predecki, Plenum Press, NY, 629-640 (1989)

[3] K. Schmidt, J. Little and W. Ellingson, a portable microwave scanning technique for nondestructive testing of multilayered dielectric materials", Proc. 32nd Inter. Conf. & Expos. on Adv. Ceramics and Composites, (2008)

[4] Y. Ikeda., K.Onda, and Y. Mizuta, Nondestructive Evaluation of Porosity in Si3N4 Ceramics by using Ultrasonic method, in *Proc. Of the 4th Symposium on Ultrasonic Testing, JSNDI*,105-108 (1997)

[5] Nondestructive testing handbook, 2nd ed., Vol 7—Ultrasonic Testing, P. McIntire, Ed. Am Soc. For Nondestructive testing (1991)

[6] T. A. K. Pillai, W. A. Ellingson, J. G. Sun, T. E. Easler , and A. Szweda, A Correlation of Air-Coupled Ultrasonic and Thermal Diffusivity Data for CFCC Materials, in *Ceramic Engr. and Sci. Proc.*, Vol. 18, Issue 4 (1997).

[7] W.A. Grandia and C. M. Fortunko, NDE applications of air-coupled ultrasonic transducers, in *Proc. IEEE Ultrasonic symposium*, Vol.1, 697-709(1995)