9.50  **NDT characterization of Boron Carbide for ballistic applications**

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Boron carbide is widely used to provide ballistic protection in many challenging service environments. This work was undertaken to determine a suitable process for NDT characterization of Boron Carbide. The project involves the introduction of deliberate flaws within the Boron Carbide during processing. An extensive experimental programme of work has been undertaken to establish the best NDT technique for the defect detection and material characterization of Boron Carbide tiles. A number of different techniques such as ultrasonic immersion testing, digital X-ray testing and microwave testing have been employed to establish the capabilities and limitations of each of the techniques. Ultrasonic immersion characterization of the material was found to be able to detect both subtle material density variation and flaws within the material. The detection capabilities and resolution of the technique was found to be dependent upon the focus depth of the ultrasonic beam. The data obtained from the ultrasonic characterization will be correlated with ballistic performance.
NDT characterisation of boron carbide for ballistic applications

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Abstract

Boron Carbide (B₄C) is widely used to provide ballistic protection in many challenging service environments. This work was undertaken to determine a suitable process for Non Destructive Testing (NDT) characterization of Boron Carbide. The project involves the introduction of deliberate flaws within the Boron Carbide tiles during manufacturing. An extensive experimental NDT program has been undertaken to determine the best method to detect defects into the ceramic tiles as well as to determine density variations that can be used for quality monitoring purposes. Ultrasonic characterization of the material was found to be able to detect both density variation and defects within the material. The defect resolution of the technique was found to be dependent upon the focus depth of the ultrasonic beam. The data obtained from the ultrasonic characterization was compared with other NDT techniques such as radiographic testing. This paper presents some of the data obtained during the NDT testing to demonstrate the capabilities and limitations of each of the techniques. A number of the supplied tiles were subjected to testing with all the two presented techniques as means of comparison of the different NDT techniques.

1. Introduction

Ceramic materials such as Boron Carbide (B₄C) and Silicon Carbide (SiC) are usually incorporated into armour systems in order to reduce their weight while providing high hardness, high compressive and tensile strength, and good response to elastic stress. However, the presence of critically sized defects and flaws in ceramic armour, such as pores and inclusions, or density variations across the tile area can compromise the ballistic performance and therefore lead to ballistic failure. An extensive NDT work has been carried out and published on SiC by a number of researchers (1)-(7). However, a limited work can be found in the literature for the NDT testing of Boron Carbide ceramic material(8).

This paper presents the extensive NDT testing carried out on the supplied B₄C to determine the quality, as well as to detect defects that have been deliberately introduced into the ceramic tiles. For that purpose, a number of different NDT techniques have
been assessed for their defect detection and sizing capabilities. The aim of this experimental program was to identify the most suitable NDT technique and to use this technique for further development and optimization. Non-destructive testing methods such as ultrasonic immersion C-scan imaging provide a valuable method to examine and assess the bulk of the ceramic material. This technique can be used for both defect detection and density variation detection across the tile area. The ultrasonic immersion technique will be compared with radiographic and microwave testing.

2. Experimental approach

2.1 Ceramic samples

Boron Carbide tiles used in this study were manufactured and supplied by Kennametal Sinter (Newport, UK). The dimensions of the B₄C tiles supplied for NDT testing are 150mm x 150mm with a thickness of 10mm (except Pressing 7). The tiles in this experimental program were identified by number (#1 to #12) corresponding to their vertical position in the furnace during the pressing, i.e. Tile #1 was at the bottom and Tile #12 at the top. Both surfaces of each of the ceramic tiles were machined flat at the required thickness. Table 1 shows the tiles that were provided for testing. The manufacturing of the supplied tiles is ranging from using the standard process parameters to tiles pressed with different manufacturing parameters. Furthermore, a number of tiles had deliberately introduced inclusions that were used to assess the capabilities of the NDT techniques. For the introduction of deliberate defects in the volume of the ceramic tiles wood and graphite particles were used as well as graphite spheres. The size of particles is ranging from 0.2mm-1mm and the quantity used for each of the tiles differs. The aim was to determine the defect detection capabilities of the various techniques. Table 1 gives details for each of the pressing and the condition of each of the tiles that were tested.

Table 1. Boron Carbide Tiles Supplied for NDT Testing

<table>
<thead>
<tr>
<th>Pressing</th>
<th>Quantity of plates</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>Standard benchmark pressing</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>Plates 2 = 10mm thickness – Wood inclusions 1mm³ (10cc); Plates 3 = 10mm thickness – Graphite inclusions 1mm³ (5cc);</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>Plate 1 = 9mm thickness – 0.2mm-0.3mm graphite sphere inclusions Plate 5 = 9mm thickness – 0.4mm-0.5mm graphite sphere inclusions Plate 9 = 9mm thickness – 0.7mm-0.8mm graphite sphere inclusions</td>
</tr>
</tbody>
</table>
2.2 Ultrasonic testing experimental set up

In the immersion ultrasonic technique, the tiles were submerged into an X-Y scanning immersion tank. A beam of ultrasound is transmitted into the material, and the reflected energy is recorded and analyzed. The transducer is scanned across the tiles at increments of typically 0.5mm. A 7-axes ultrasonic immersion tank (USL7, Ultrasonic Sciences Limited, Aldershot, UK) used for the testing of the ceramic tiles that can operate at frequencies of up to 25MHz. The experimental set up used to carry out ultrasonic immersion scanning is shown in Figure 1. The focused immersion transducer was positioned at such a distance from the top or bottom surface of the tile as to focus on the material at depths of ¼ and ½ of the sample thickness. Using the experimental set up shown in Figure 1 the full volume of the tile was inspected with increased defect detection and sensitivity capabilities. Three ultrasonic scans were carried out for each of the ceramic tiles to cover the full tile volume at the highest detection sensitivity. Two of the scans were performed from the bottom surface of the tile and the third scan was carried out from the top surface, after the tile had been flipped over. This configuration was used as the types of defects found in ceramic materials are volumetric and are mainly inclusions, porosity and voids.

![Diagram of the ultrasonic immersion testing experimental set up](image)

**Figure 1. Diagram of the ultrasonic immersion testing experimental set up**

The beam width is smaller at the focal point and, therefore, smaller defects can be detected. Also better sensitivity is achieved since the ultrasonic energy is concentrated at that point.

3. Experimental results

3.1 Ultrasonic immersion testing

3.1.1 Pressing 1 ultrasonic results

For calibration and technique development purposes, Tile 1 from pressing 1 was machined with a diamond saw, and slots generated at different depths across the tile. Figure 2a shows a schematic diagram of the calibration tile used during the ultrasonic testing technique development. The slots have depths of 1mm, 2.5mm, 5mm and 7.5mm from the bottom surface. The tile was inspected from the top surface, and the purpose was to assess the penetration capabilities of the ultrasonic wave at various depths and different frequencies. Ultrasonic frequencies ranging from 5MHz to 50MHz (NOTE: Different immersion tank used for frequencies higher than 25MHz) were tested and it was concluded that the most suitable frequency for B₄C material was found to be the
15MHz transducer (Ultrasound Products, WC1003-04) with 76.2mm (3’’) focal length in water. All the slots and their depths in the tile can be clearly seen in the Time of Flight (ToF) data shown in Figure 2b. In ultrasonic immersion testing the ultrasonic transducer is scanned across the area of the tile. This allows the creation of two-dimensional C-scan maps corresponding to the ToF of ultrasound through the material. Images of the changes in ToF over each tile area were collected by gating the top and bottom surface reflected signals and determining the difference between them², or ToF, to obtain the transit time that in turn the software is translating into millimeters (mm) giving the tile thickness. The ultrasonic inspection system is monitoring the top and bottom surface reflected signals as well as the material volume to record the ToF data and the presence of indications in the tile. Using the ToF data in conjunction with the precise thickness of the tile, the longitudinal ultrasonic velocity can be accurately calculated as well as the depth of any indications detected within the tile. It should be noted that all the ultrasonic data presented in this paper was acquired using the 15MHz probe with 76.2mm (3’’) focal length in water.

![Figure 2. (a) Drawing of the calibration sample (b) Time of Flight scan data from the calibration sample](image)

Furthermore, the ToF data can be used to obtain information regarding density variations across the tiles. Figure 3 shows the ToF data scans for tiles 1 and 2 from pressing 1. Here, the depth range of the ToF data presented in the scan has been changed from 0-11mm to 9.5-11mm. The aim was to detect changes in the material and, by using a shorter depth range; shuttle changes in the interaction of ultrasound with the ceramic material can be more easily seen. The color variations across the tile indicate variations in the density of the material. One of the limitations of the software used to capture the ultrasonic data is the inability to account for velocity changes in the sample due to changes in the material density. Thus, if there is considerable change in the velocity of the material, the software assumes there is a change in the thickness of the sample. As explained previously, the tiles have been ground to a uniform thickness, and any changes in the ToF data is attributed to velocity changes as a result of density changes. The ultrasonic velocity was set up for each of the tiles based on the tile thickness. The ultrasonic velocity for each tile was calculated by positioning the probe at a random point across the tile area, and readjusting the velocity value to get the correct value of the tile thickness. By using this velocity value the whole area of the tile was inspected. If there is a change in the material density, and therefore a change in the ultrasonic velocity, this will translate to color variations in the C-scan data. The color variations in tiles 1 and 2 are predominant indicating velocity changes, and therefore
density changes. The probe was positioned to the different color regions in both tiles, and ultrasonic velocity measurements were taken across each of the regions. Figure 3 shows the measured velocity for each of the tiles across different color regions. It can be seen that tile 1 has two regions that are believed to have different material density. The velocity around the edge of the tile 1 was measured at 11,800 m/s, while the velocity in the center of the tile was 12,200 m/s. However, three density variation regions have been identified in tile 2 with measured velocities of 12,500 m/s, 12,800 m/s and 12,950 m/s. Higher ultrasonic velocities indicate higher material density, while lower velocities indicate lower density.

Figure 3. ToF scan data from pressing 1 of (a) Tile 1 (b) Tile 2

The ToF scan data for the rest of the tiles from pressing 1 shown density uniformity. It was also noticed that each of the tiles exhibits a reduction in density around its edges and corners due to the pressure profile during the manufacturing.

3.1.2 Pressing 4 ultrasonic results

The manufacturing of pressing 4 tiles involved the deliberate introduction of flaws. Wood and graphite inclusions of approximately 1 mm$^3$ were added into the B$_4$C powder before the pressing. Different quantities of inclusions were added to each of the tiles, as detailed in Table I. All the tiles from pressing 4 have a thickness of 10 mm and were produced using the same manufacturing parameters as in pressing 3 (initial pressure ramp applied 100ºC earlier). Focusing at different focal depths from both surfaces, all the B$_4$C tiles were inspected. It should be mentioned that the ultrasonic velocity was measured at 13,850 m/s for all the tiles in pressing 4.

Figures 4 show the ToF data obtained from some of the pressing 4 tiles at different focal depths. It can be seen that the added inclusions in the tiles have been detected using the developed immersion testing. The flaw indications are shown in different colors that denote their depth in the tile. It should also be noted that the flaws are randomly distributed across the area and thickness of the tiles. From Figures 4 it can be seen that additional information can be obtained by focusing the ultrasonic beam at different depths. Indications that cannot be seen in one of the scans are detectable in a different scan. As an example, indications detected in Figure 4c ToF scan (shown in the blue circles) cannot be seen in the ToF scan in Figure 4b. This is also the case for the rest of the pressing 4 tiles inspected. This proves that the detection capability of the immersion testing is improved by focusing the beam at different depths across the tile thickness.
Figure 4. ToF data from Pressing 4 of tile 2 (a) Focus at 2.5mm from top surface (b) Focus at 2.5mm from bottom surface (c) Focus at 5mm from bottom surface

Figure 5 presents the amplitude data scan from two of pressing 4 tiles. The amplitude data from tiles 2 and 3 from pressing 4 is presented in order to demonstrate the sensitivity of the amplitude scan to the presence of inclusions in the ceramic tiles. The amplitude data presented shows the intensity of the signal reflected from the backwall of the tile. In summary, the data presented in the amplitude scan maps is explained by:
- Lighter grey corresponds to higher signal amplitude, i.e. lower attenuation.
- Darker grey corresponds to lower signal amplitude, i.e. higher attenuation.

In Figure 5a variations on the reflected signal amplitude were noted on the scan by red circles. Tile 2 from pressing 4 has 5cc of wood inclusions and because of the density difference between the wood and the ceramic material there are subtle differences in the material attenuation that has an effect to the beam propagation and consequently to the intensity of the reflected signal. Figure 5b presents the amplitude scan of tile 3 that has 5cc of graphite inclusions and the attenuation differences because of their higher density nature are more obvious compared to the wood inclusions.

Figure 5. Amplitude data from Pressing 4 of (a) Tile 2 (b) Tile 3

ToF data for tile 2 from pressing 4 was presented in Figures 4 and although a number of inclusions deliberately introduced into the tiles were identified the amplitude scan was proven to be more sensitive to the density variations caused by the wood (Tile 2) and graphite (Tile 3) inclusions. The amplitude data was especially useful to detect surface or near surface inclusions introduced into the tile. However, the amplitude data can detect the presence of inclusions or voids into the tiles but cannot determine their depth.

3.1.3 Pressing 7 ultrasonic results

Pressing 7 tiles have graphite sphere inclusions supplied by Superior Graphite. The size of the spheres is ranging from 0.2mm to 0.8mm. Table 1 gives the details for each of the Pressing 7 tiles. Figure 6 shows the results from Tile 1 where 0.2-0.3mm graphite sphere inclusions have been introduced into the tile. Figure 6 shows the ToF data at focus depths of 4.5mm and 2.25mm as well as the amplitude scan data. It can be seen
when the beam was focused at 4.5mm in the ceramic material a number of small inclusions have been detected across the tile area. The black area indicates that no ultrasound has been propagated and reflected at the backwall of the tile. This is believed to be caused due to the concentration of graphite inclusions in a small area of the tile that increased the material attenuation and therefore prevented the propagation of ultrasound into the material.

Figure 6. Tile 1 from pressing 7 (a) ToF data at focus depth of 4.5mm (b) ToF data at focus depth of 2.25mm (c) amplitude data

Similarly, tile 5 from pressing 7 has 0.4–0.5mm graphite spherical inclusions and was inspected ultrasonically. However it seems that that the graphite particles have not been properly distributed across the tile area but they appear as clusters. Figure 7 shows that in this case the ToF data cannot detect the graphite inclusions but variations in the amplitude data across the tile area indicates material attenuation differences, which in turn reveals the presence of higher density foreign bodies, i.e. graphite spheres.

Figure 7. Tile 5 from pressing 7 (a) ToF data at focus depth of 4.5mm (b) ToF data at focus depth of 2.25mm (c) amplitude data

Tile 9 from pressing 7 has 0.7–0.8mm graphite spherical inclusions and was inspected ultrasonically. Figure 8 shows that in this case the ToF data has detect a number of the graphite inclusions but also variations in the amplitude data across the tile area indicates the presence of more graphite inclusions in the ceramic material.
3.2 X-Ray radiographic testing

One of the techniques assessed for the defect and density variation detection capabilities is digital X-ray radiographic testing. All the tiles that have been previously tested with ultrasonic immersion testing and presented in this paper were chosen for radiographic testing. The tiles were placed into the 225kV X-ray 5μm microfocus bay (X-Tek). The set up used to obtain the radiographic results is shown in Figure 9. The parameters used to obtain the radiographic images were optimized for defect detection. The X-ray energy used to penetrate and radiograph the B₄C tiles was 50kV.

Initially tiles 2 and 5 from pressing 1 were chosen to assess the sensitivity of X-ray testing to material density variations at the tiles. Tile 2 was previously tested with immersion testing and density variations were detected across the tile area (see Figure 3b). Tile 5 was also tested with the ultrasonic immersion technique and it was found that the material density is consistent across the tile area. Therefore, using these tiles the sensitivity and capability of the X-ray radiographic technique will be assessed. Figure 10 shows the radiographic images obtained from both B₄C ceramic armour tiles. As seen in Figure 10, both images are the same, and density variations found on tile 2 with ultrasonic testing cannot be seen across this tile. In addition, density differences between the two tiles are not noticeable at the radiographs. Note that the darker region at the bottom of the images does not correspond to material feature but is due to the polystyrene used to support the tiles during the radiographic testing.
Figure 10. Radiographic images from Pressing 1 of (a) Tile 2 (b) Tile 5

Figure 11 shows the radiographic images of tiles 2 and 3 from pressing 4. Tiles 2 and 3 had deliberately introduced 5cc of wood and graphite inclusions, respectively. It can be seen that the radiographic testing cannot detect the wood inclusions introduced into tile 2 but can detect some of the graphite inclusions (shown in blue circles in Figure 11b) in tile 3. These results indicate that the ultrasonic data for these tiles (Figures 4 and 5) detected more inclusions compared to the radiographic testing.

Figure 11. Radiographic images from Pressing 4 of (a) Tile 2 (b) Tile 3

Similarly, Figure 12 presents the radiographic images of tiles 1, 5 and 9 from pressing 7. Ultrasonic testing detected a number of inclusions in all these tiles and it can be observed that inclusions have not been detected or a small number of them detected by radiographic testing. Ultrasonic testing has proven to have increased defect detection and sensitivity capabilities compared to radiographic testing.

Figure 12. Radiographic images from Pressing 7 of (a) Tile 1 (b) Tile 5 (c) Tile 9
4. Discussion

Figure 13 shows the ultrasonic velocities measured from all the ceramic tiles tested. The changes in velocities in pressing 1 tiles indicate changes in density that is dependent upon the vertical position of the tile in the furnace during the pressing. From the ultrasonic results of pressing 1, it is evident that the ultrasonic velocity increases as a function of the vertical position of the tiles in the pressing. Lower ultrasonic velocities were measured in the tiles that were at the bottom in the furnace, while higher velocities exhibited from the tiles that are higher in the furnace during the pressing. The ultrasonic velocities at the centre of the tiles range from 12,200m/s for tile 1 to 13,450m/s for tile 10.

A difference observed in the measured ultrasonic velocities from pressing 3 tiles is the higher velocities exhibited compared with the values obtained from pressing 1 tiles. Even for the tiles placed at the lower part of the furnace higher ultrasonic velocities were obtained. As an example, tile 1 in pressing 1 has a velocity of 12,200m/s compared to tile 1 in pressing 3 with a velocity of 13,600m/s. In general, the velocities measured in the pressing 3 tiles range from 13,600m/s to 13,850m/s. Also, the ultrasonic velocity was uniform across the area of each tile, which indicates the material density uniformity and manufacturing quality of the ceramic armour tiles. Furthermore, the velocity and therefore the density of the tiles were independent of their vertical position in the furnace during the pressing.

![Figure 13. Ultrasonic velocity measurements from the B4C tiles](image)

The differences in the density quality of the pressings 3-7 tiles are attributed to the alteration of the manufacturing parameters during the pressing where the initial pressure ramp was applied 100°C earlier. In order to confirm the correlation between the ultrasonic velocity and the material density a number of tiles were sectioned and their density was measured. Density measurements were taken mainly from the centre of the pressed tiles in order to avoid any edge effects within the tiles.

Figure 14 shows the density measured from the sectioned tiles. As it can be seen from Figure 14, there is a good correlation between the ultrasonic velocity measurements and the measured material density. These results shown that the ultrasonic technique is able to distinguish small density variations of up to 0.01g/cm³, which proves the sensitivity
of the ultrasonic technique to detect subtle material density variations across the ceramic tiles.

![Graph showing correlation between material density and ultrasonic velocity](image)

**Figure 14. Correlation between material density and ultrasonic velocity**

Radiographic testing was proven not to be as sensitive as the ultrasonic testing. Inclusions detected ultrasonically were not detected with the X-ray testing and whenever inclusions were detected with X-ray testing, more inclusions were found from ultrasonic testing by a combination of ToF and amplitude data. Additionally, the radiographic testing does not have very good defect detection capabilities close to the edge of the tiles. Radiographic testing was also proven not to be sensitive to density variations, which is contrary to the capabilities of the ultrasonic testing, where subtle material density changes at the tiles were detected.

5. **Conclusions**

Three different NDT techniques were assessed for their capabilities in detecting defects and density variations in B₄C ceramic armour tiles. Immersion testing was proven to be sensitive to material density variations, which is not the case with X-ray radiography and defect detection. Deliberate defects were introduced into the boron carbide tiles using graphite and wood inclusions of approximately 0.2mm to 1mm in size. Immersion testing proved that these inclusions could be detected. The combination of ToF and amplitude data can provide information about the presence of defects, their size and depth as well as the presence of density variations across the ceramic armour tile. The immersion testing can also provide a measurement of the ultrasonic velocity of the material that is closely linked with the material density. A number of tiles that ultrasonic velocity variations detected were selected for sectioning and measurement of their actual densities. The sectioning and density measurements of the tiles demonstrated a good correlation between the material density and ultrasonic velocity.

Radiographic testing is not sensitive to detect material density variations and under certain circumstances can detect flaws in the material. The flaws detected from the radiographic testing were also detected from the ultrasonic testing but the ultrasonic testing was more sensitive to the detection of flaws embedded into the tile and present at
the surface of the tiles. X-ray radiography testing is suitable for defect detection under specific conditions, such as where the defect is denser than the background material.

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References