A Potential Methodology for Evaluating Ceramic Quality

by Matthew S Burkins, Donald J Little, and Melissa S Love

Reprinted from Proceedings of the 30th International Symposium on Ballistics; 2017 Sep 11–15; Long Beach, CA.

Approved for public release; distribution is unlimited.
NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer’s or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.
A Potential Methodology for Evaluating Ceramic Quality

by Matthew S Burkins, Donald J Little, and Melissa S Love

*Weapons and Materials Research Directorate, ARL*

Reprinted from proceedings of the 30th International Symposium on Ballistics 2017; 2017 Sep 11–15; Long Beach, CA.

Approved for public release; distribution is unlimited.
Metal armor alloys have well-established, stand-alone, ballistic acceptance criteria to demonstrate consistent lot-to-lot performance, thus allowing metals to be qualified prior to cutting and forming into the final armor design. By contrast, ceramics do not have stand-alone quality assurance criteria. ARL undertook a small-scale effort to evaluate an energy-based assessment methodology for bare ceramics developed by TNO in the Netherlands. Bare sintered aluminum oxide tiles and hot-pressed silicon carbide tiles were evaluated using the energy methodology. While this method may have promise, a number of issues must be overcome before this method can be adopted to determine ceramic quality.
A POTENTIAL METHODOLOGY FOR EVALUATING CERAMIC QUALITY

Matthew S. Burkins, Donald J. Little and Melissa S. Love
U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, U.S.A.

Metal armor alloys have well-established, stand-alone, ballistic acceptance criteria to demonstrate consistent lot-to-lot performance, thus allowing metals to be qualified prior to cutting and forming into the final armor design. By contrast, ceramics do not have stand-alone quality assurance criteria. ARL undertook a small-scale effort to evaluate an energy-based assessment methodology for bare ceramics developed by TNO in the Netherlands. Bare sintered aluminum oxide tiles and hot-pressed silicon carbide tiles were evaluated using the energy methodology. While this method may have promise, a number of issues must be overcome before this method can be adopted to determine ceramic quality.

INTRODUCTION

Metal armor alloys have well-established, stand-alone, ballistic acceptance criteria to demonstrate consistent lot-to-lot performance, thus allowing metals to be qualified prior to cutting and forming into the final armor design. By contrast, ceramics do not have stand-alone quality assurance criteria. Ceramic materials must be bonded to a backing material in any practical armor design. When these engineered ceramic targets do not meet performance expectations, the assembly time is lost in addition to the raw materials. Also, fully engineered and assembled targets often do not provide a clear indication of whether the ceramic, the bond, or the backer is at fault for the limited performance.

Erik Carton and Geert Roebroeks at TNO in the Netherlands have pioneered an energy-based assessment methodology for bare ceramics [1]. Their experimental setup is shown in Figure 1. A projectile is fired into a bare ceramic tile and the residual bullet fragments are captured. The velocity of the projectile is measured prior to impact while high speed video provides the velocity of the residual fragments.
Residual mass is determined by measuring the fragments recovered from the catcher. The projectile striking energy ($E_S$) is then compared to the residual energy ($E_R$) using energy loss ($E_{loss}$) as calculated from Equation 1. $E_S$ should be determined just prior to the projectile striking the tile, and $E_R$ is the residual energy of the projectile upon exiting the tile.

$$E_{loss} = \frac{E_S - E_R}{E_S}$$ (1)

ARL conducted a small-scale investigation of this energy methodology to evaluate bare ceramic tiles. Bare sintered aluminum oxide tiles and hot-pressed silicon carbide tiles were evaluated under different conditions as part of this work. Since no international standard exists for this experimental methodology, the initial focus was on factors that affect the consistency of experimental results: type of projectile, method of measurement, method of fragment capture, ceramic thickness variability, etc. While the method may have promise, a number of issues must be overcome before this method can be adopted to regulate ceramic quality.

**RESULTS – PHASE 1**

The ARL experimental setup is shown in Figure 2. CoorsTek AD995 aluminum oxide ceramic tiles [2] from a single lot were used for all experiments. The front of a 90mm x 90mm AD995 ceramic tile was placed against two support bars in order to assure the tile was at zero degrees obliquity with respect to the shot line. As can be seen in Figure 2, the back surface of the tile is completely unrestrained. Projectile striking velocity, vertical pitch, and horizontal yaw were measured via 2 pairs of 150 keV orthogonal flash x-rays [3]. A break screen was used to start the video camera, which captured images of debris behind the tile. A second break screen, placed 305mm behind the tile, was used to initiate 2 channels of 150 keV flash x-rays, permitting observation of the higher density bullet debris that could not be seen within the ceramic debris cloud shown on video. A catcher was placed behind the target (not shown in Figure 2) to capture the bullet debris that exited the ceramic tile. The composition of this catcher was varied using different proportions of plywood and celotex. Celotex was better at catching small fragments but was easily perforated by the larger fragments. Plywood was better at catching larger fragments but the smaller fragments often failed to penetrate the surface.

The 7.62mm APM2, Figure 3, was selected as the experimental penetrator to match TNO’s prior work. This projectile has a hardened steel core within a gilding metal jacket. While the nominal muzzle velocity of this projectile is 841 m/s, experiments were conducted at 830 m/s ± 10 m/s to match the prior work at TNO. Two thicknesses of AD995, 7.62mm and 8.13mm, were tested and the ballistic results are provided in Table I. The AD995 ceramic thickness was measured at the center of the tile where the projectile would impact. Total yaw is the vector sum of measured vertical pitch and horizontal yaw. Residual Mass, Residual Velocity, Residual Energy, and Energy Loss in black text indicate the velocity and the bullet condition (combined core and jacket) were obtained using x-rays. The red text indicates that the energy calculation was performed using the mass for the steel core (excluding jacket) and the video velocity.
Figure 2. Experimental setup for bare ceramic evaluation at ARL.

Figure 3. Cutaway of 7.62mm APM2 projectile.
While two thicknesses of AD995 were tested to look at variability as a function of tile thickness, only the results for the two nominal 8mm thick tiles are plotted in Figure 4 because this thickness matched the TNO work. The TNO data using aluminum oxide [1] are reproduced in blue as a function of lateral tile size. The TNO data were subjected to a second order fit shown by the blue curve. Since TNO had not evaluated 90x90mm tiles, the ARL data had to be compared to the curve rather than to actual data points. Note the scatter of E loss, calculated using equation 1, in the TNO data. The red squares show the ARL data using the mass of the core only and the velocity obtained by video. This matches the conditions that TNO used for calculating energy loss. The black triangles show the same two experiments using the combined recovered mass of core and jacket, as well as the velocity obtained from the x-rays. TNO assumed that the projectile jacket is stripped from the core during the dwell phase and that the velocity of the debris cloud is the same as the velocity of the residual projectile [1]. The assumption that the jacket is removed from the steel core during penetration did not match the experimental results at ARL, as shown in Figure 5, where the steel core has part of the jacket attached. Whether to include the jacket in the residual energy calculations is a fundamental issue that needs to be resolved. On the other hand, the assumption that the video velocity of the cloud is the same as the velocity of the residual projectile appears to be valid. Figure 5 shows one of the more extreme cases where x-ray and video velocities differed by nearly 30m/s; however, for other experiments, the difference was less between the two methods.
RESULTS – PHASE 2

The Phase 1 experiments revealed a number of challenges with the initial implementation of the bare ceramic testing. At both TNO and ARL, the residual energy and E loss values show quite a bit of scatter with the 7.62mm APM2 projectile. The brittleness of the core probably contributes to this problem, in addition to the jacket issues discussed previously. Furthermore, catching the bullet fragments in the celotex/plywood packs proved less than satisfactory. This leads to adopting a water catch tank for the projectile debris, which would allow easy collection of the projectile without causing further damage. Another change was to examine the use of a solid, ductile metal projectile that would avoid the issues with the jacket and the brittle core of the 7.62mm APM2.
The setup for Phase 2 is shown in Figure 6. The same batch of CoorsTek AD995 90mm x 90mm tiles was used for Phases 1 and 2. Break screens were again used to initiate video and x-rays. The distance was 445mm from the front of the tile to the steel deflector plate that protects the catch tank, shown bottom left. The location of the lights and video camera are also shown. The bare back surface of the tile is visible.

For Phase 2, a monolithic projectile entirely composed of a ductile metal was adopted. The resulting 7.62mm brass projectile, manufactured from C464 Naval Brass, is shown in Figure 7, along with the alloy composition. The projectile was manufactured to match the outer jacket profile of the APM2. The nominal 11.0 g mass of the brass projectile was higher than the APM2 due to higher density of the brass alloy compared to steel. The nominal impact velocity for the brass projectiles was 850 m/s. The brass alloy did not experience brittle failure and was easy to launch from a rifle. Experimental results are provided in Table II. Residual Velocity, Residual Energy, and Energy Loss were based on the x-ray measurements when the typeface is black. The red typeface indicates the Residual Velocity, Residual Energy, and Energy Loss were based on video measurements. For the nominal 7.62mm thick tiles, the energy loss varied from 70-76% over seven shots using only the x-rays for measuring velocity. The nominal 8.13mm tiles showed an energy loss of 77-78% using x-rays, but this seemingly smaller spread may be due to having fewer shots. Overall, there do not appear to be enough data to make hard conclusions about energy loss variability as a function of tile thickness.

![Figure 6. Experimental setup for Phase 2.](image)
Figure 7. Sketch of 7.62mm brass projectile.

Some additional experiments were performed using bare 90mm x 90mm x 7.62mm and 90mm x 90mm x 8.13mm thick hot-pressed silicon carbide (SiC) tiles produced by CoorsTek. SiC was chosen since it is a well characterized armor ceramic and should provide a different ballistic performance than AD995. The density of the SiC was approximately 3.24 g/cm$^3$ compared to approximately 3.9 g/cm$^3$ for the AD995; therefore, the areal density of bare SiC tiles was about 16% less than AD995. Once again, the nominal impact velocity for the brass projectiles was 850 m/s. The ballistic results for the SiC tiles are provided in Table III where red typeface indicates that Residual Velocity, Residual Energy, and Energy Loss were based on video analysis.

### TABLE II. RESULTS FOR THE 7.62MM BRASS PROJECTILE VS. BARE AD995.

<table>
<thead>
<tr>
<th>Measured AD995 Tile Thickness (mm)</th>
<th>Projectile Mass (g)</th>
<th>Projectile Striking Velocity (m/s)</th>
<th>Total Yaw (deg)</th>
<th>Projectile Striking Energy [E$_S$] (kJ)</th>
<th>Residual Mass (g)</th>
<th>Residual Velocity [X-Ray Video] (m/s)</th>
<th>Residual Energy [E$_R$] (kJ)</th>
<th>Energy Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.645</td>
<td>10.919</td>
<td>843</td>
<td>0.70</td>
<td>3.88</td>
<td>5.443</td>
<td>634</td>
<td>1.09</td>
<td>72</td>
</tr>
<tr>
<td>7.696</td>
<td>10.893</td>
<td>852</td>
<td>0.51</td>
<td>3.95</td>
<td>4.990</td>
<td>643</td>
<td>1.03</td>
<td>74</td>
</tr>
<tr>
<td>7.645</td>
<td>10.906</td>
<td>854</td>
<td>0.48</td>
<td>3.98</td>
<td>5.035</td>
<td>643</td>
<td>1.04</td>
<td>74</td>
</tr>
<tr>
<td>7.722</td>
<td>10.885</td>
<td>852</td>
<td>0.42</td>
<td>3.95</td>
<td>4.819</td>
<td>632</td>
<td>0.96</td>
<td>76</td>
</tr>
<tr>
<td>7.569</td>
<td>11.123</td>
<td>836</td>
<td>0.42</td>
<td>3.89</td>
<td>5.146</td>
<td>643</td>
<td>1.06</td>
<td>73</td>
</tr>
<tr>
<td>7.620</td>
<td>11.121</td>
<td>847</td>
<td>0.12</td>
<td>3.99</td>
<td>5.761</td>
<td>649</td>
<td>1.21</td>
<td>70</td>
</tr>
<tr>
<td>7.569</td>
<td>11.129</td>
<td>843</td>
<td>0.07</td>
<td>3.95</td>
<td>5.446</td>
<td>644</td>
<td>1.13</td>
<td>71</td>
</tr>
<tr>
<td>8.128</td>
<td>10.893</td>
<td>856</td>
<td>1.28</td>
<td>3.99</td>
<td>4.867</td>
<td>608</td>
<td>0.90</td>
<td>77</td>
</tr>
<tr>
<td>8.204</td>
<td>10.893</td>
<td>859</td>
<td>0.32</td>
<td>4.02</td>
<td>4.384</td>
<td>633</td>
<td>0.88</td>
<td>78</td>
</tr>
<tr>
<td>8.204</td>
<td>10.897</td>
<td>866</td>
<td>1.69</td>
<td>4.09</td>
<td>4.892</td>
<td>616</td>
<td>0.93</td>
<td>77</td>
</tr>
</tbody>
</table>

![Diagram](image)
measurements rather than x-rays. Using only the x-ray velocity data, the thinner tiles showed an energy loss of 71-74% while the thicker tiles showed an energy loss of 73-80%. While this seems to be a reversal of the AD995 results, the number of shots is too few to draw any hard conclusions about energy loss variability with tile thickness.

At this point, all of the brass and steel core bullet data could be used to compare the residual velocities obtained by x-ray and from the high speed video. As can be seen in Figure 8, the ceramic debris cloud velocity as measured by video is within 5% of the residual projectile velocity obtained from x-rays in most cases.

<table>
<thead>
<tr>
<th>Measured SiC Thickness (mm)</th>
<th>Projectile Mass (g)</th>
<th>Projectile Striking Velocity (m/s)</th>
<th>Total Yaw (deg)</th>
<th>Projectile Striking Energy [E_s] (kJ)</th>
<th>Mass [Residual X-Ray] (g)</th>
<th>Mass [Residual Video] (g)</th>
<th>Residual Energy [E_r] (kJ)</th>
<th>Energy Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.671</td>
<td>11.128</td>
<td>833</td>
<td>0.47</td>
<td>3.86</td>
<td>663</td>
<td>667</td>
<td>1.14</td>
<td>71</td>
</tr>
<tr>
<td>7.696</td>
<td>11.122</td>
<td>854</td>
<td>0.38</td>
<td>4.06</td>
<td>677</td>
<td>621</td>
<td>1.07</td>
<td>74</td>
</tr>
<tr>
<td>7.671</td>
<td>11.122</td>
<td>853</td>
<td>0.47</td>
<td>4.05</td>
<td>683</td>
<td>682</td>
<td>1.14</td>
<td>72</td>
</tr>
<tr>
<td>8.230</td>
<td>10.888</td>
<td>865</td>
<td>0.94</td>
<td>4.07</td>
<td>653</td>
<td>622</td>
<td>0.90</td>
<td>78</td>
</tr>
<tr>
<td>8.230</td>
<td>10.888</td>
<td>860</td>
<td>1.23</td>
<td>4.03</td>
<td>651</td>
<td>620</td>
<td>0.90</td>
<td>78</td>
</tr>
<tr>
<td>8.230</td>
<td>10.902</td>
<td>860</td>
<td>1.20</td>
<td>4.03</td>
<td>670</td>
<td>653</td>
<td>1.15</td>
<td>71</td>
</tr>
</tbody>
</table>

Figure 8. Comparison of residual velocity as measured using x-rays and high speed video.
SIMULATIONS

The simplicity of both the brass projectile and the bare ceramic tile provided an opportunity to evaluate and compare the experimental results to ballistic simulations. The goal was to see if the bare ceramic methodology would be helpful in checking the input parameters used in the simulations. The simulations presented here were conducted using EPIC2016 [4], a Lagrangian hydrocode with penetration applications. The brass projectile was constructed and meshed in CUBIT [5] using the median dimensions from Figure 7 and the cartridge brass material available in the EPIC library. Ballistic experiments were conducted with the brass projectile impacting semi-infinite rolled homogenous armor (RHA) steel [6] and 5083 alloy aluminum [7]. These ballistic results were compared to simulation results and show similar penetration and residual penetrator shapes, though details are omitted here due to space constraints.

Figure 9 shows a comparison of the simulation and experimental results for the 7.62mm bare AD995 tile. The simulation was conducted using the nominal projectile velocity of 850m/s and is shown on top with blue text. The experimental results are provided below with black text. The x-ray images are provided, as well as an inset image of the projectile recovered from the water tank. Note that the residual penetrator is close to the leading edge of the debris cloud in the simulation, supporting the previous assumption that the two have the same velocity. The residual penetrator nose is similarly mushroomed in both experiment and simulation. The simulation energy loss is 6% higher than the specific experimental matched case.

Figure 10 shows a comparison of the simulation and experimental results for the 8.13mm bare AD995 tile. The simulation was again conducted using the nominal projectile velocity of 850m/s and is shown on top with blue text. The experimental results are provided below with black text along with the x-ray images and an inset image of the projectile recovered from the water tank. Again, the residual penetrator is close to the leading edge of the debris cloud in the simulation, supporting the previous assumption that the two have the same velocity. The residual penetrator nose is similarly mushroomed in both experiment and simulation. The simulation energy loss is again 6% higher than the specific experimental matched case.

Figure 11 provides a summary of the energy loss versus tile thickness for all of the experiments and the two simulations. The 7.62mm APM2, shown as black triangles, shows large variations in energy loss that led to the switch to a solid brass projectile. The bare ceramic experiments using the brass projectile appeared to provide similar energy loss results for SiC and AD995 tiles at equal thickness. This is disquieting because the two materials have different areal densities, very different costs, and historically exhibited different ballistic performances. While the simulations appeared to capture the experimental trend in this very limited set of cases, they over predicted the energy loss by 6%. More analysis will be required to determine if this relatively small difference is because the cartridge brass material in the model is not representative of the naval brass penetrator material used in the experiments.
Figure 9. Comparison of simulation (top) and experiment (bottom) for bare 7.62mm thick AD995 tile.

Figure 10. Comparison of simulation (top) and experiment (bottom) for bare 8.13mm thick AD995 tile.
The bare ceramic experiments with the 7.62mm APM2, both at TNO and ARL, showed large variations in the energy loss results. Switching to the solid brass 7.62mm projectiles greatly reduced the variation in energy loss results. The assumption that the velocity of the ceramic debris cloud is the same as the projectile velocity appears to be reasonably good based on simulations and experiments. The velocities of the cloud (as measured by high speed video) and the projectile (as measured with x-rays) were within 5% of each other in most cases. The water catch tank provided a more reliable method for catching the residual projectile than the celotex/plywood packs. The simulations appeared to capture the experimental trend in this very limited set of cases but the simulation energy loss was 6% higher than the experimental results. More analysis will be required to determine if this relatively small difference is because the penetrator material in the model is not representative of the penetrator material used in the experiments. The bare ceramic experiments using the brass projectile appeared to have difficulty differentiating between SiC and AD995 tiles at equal thickness. This apparent inability to clearly distinguish between SiC and AD995, two ceramic materials with very different areal densities, costs, and historical performance data, indicates that the bare ceramic energy methodology is not well suited to be used as a quality control measure for ceramics.
ACKNOWLEDGEMENT

The simulation work was supported in part by a grant of computer time from the DOD High Performance Computing Modernization Program at the US Army Research Laboratory.

REFERENCES


5. Sandia National Laboratories. 2015. “Cubit 15.0 user documentation”.

