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The Importance of Considering Both Depth of Penetration and Crater Volume in Forwards-Ballistic Penetrative Experiments

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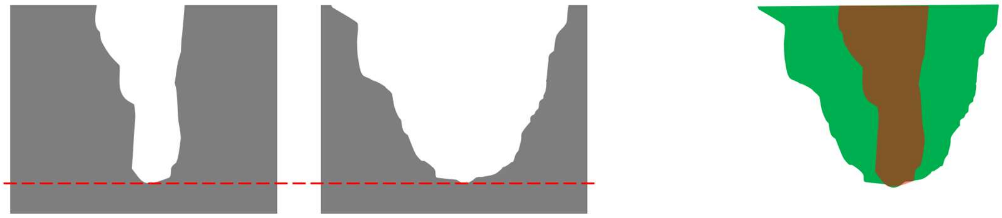
Abstract. The most common method of analysing armour performance is the Depth of Penetration (DoP). However, this one-dimensional measurement does not provide insight into the method of penetration or energy absorbed by the target; the crater could be particularly narrow or very wide and yield the same DoP. Analysis of the crater through Crater Volume (CV) provides a more detailed metric to be used alongside DoP to visualise the crater, indicating whether energy was dispersed over a large area. CV provides a wider insight into how a material resisted penetration events, giving evidence of potential defeat mechanisms. Digital reconstruction of the craters using X-ray radiographs or Computed Tomography (CT) scanning can also provide a useful tool for computational models to be compared against. The simple calculation of CV through X-ray radiography and image processing has been demonstrated to be accurate to within ±6% of the CT scanned CV. Success in utilising this analytical tool was demonstrated through comparison of three armour configurations. A consistent difference in the ratio of DoP:CV was seen between steel targets, ceramic-steel targets and ceramic-air-steel targets, indicating variation in the defeat mechanism between the three target configurations.

INTRODUCTION

When designing an armour system, seeking ways to improve the penetrative resistance without increasing the armour mass is a constant challenge. Forward ballistic experiments are amongst the most popular practical techniques for assessing material response to high-velocity impacts, making them a useful tool for armour developers. One such method to provide quantitative values for accurate analysis in penetration events uses a semi-infinite block of a material placed behind an armour design. A projectile is then fired towards the target at a velocity designed to overmatch the armour, ensuring penetration into the semi-infinite block. The Depth of Penetration (DoP) in this semi-infinite block is then measured. Shallower penetrations indicate that the armour has performed better than deeper penetrations, and this metric can be used to calculate important characteristics such as mass effectiveness, E_m [1]. However, this one-dimensional metric is limited; two craters with the same DoP could be considerably different in shape. This is visualised in Fig. 1.

A superior quantitative analysis can be carried out if the Crater Volume (CV) is measured alongside DoP. Dikshit [2] stated that CV indicates the type of damage caused by a projectile as well as the penetrative resistance of the armour. Their results showed that the same armour configuration and test setup with varying impact velocities of ≈400 m/s and ≈650 m/s created craters with similar DoPs, although the CVs were considerably different in these targets due to the different material failure mechanism at the higher strain rate. This result may not have been well understood without this measurement of CV. CV is also important in the validation of models [3], where measuring DoP alone may result in inaccurate models being considered ‘validated’. Despite this, CV is not commonly advertised as an evaluation tool in sources that summarise ballistic testing [1], [4].



(a) (b)

FIGURE 1. (a) A comparison of two craters with the same DoP but varying CV (b) The craters from Fig. 1(a) overlayed

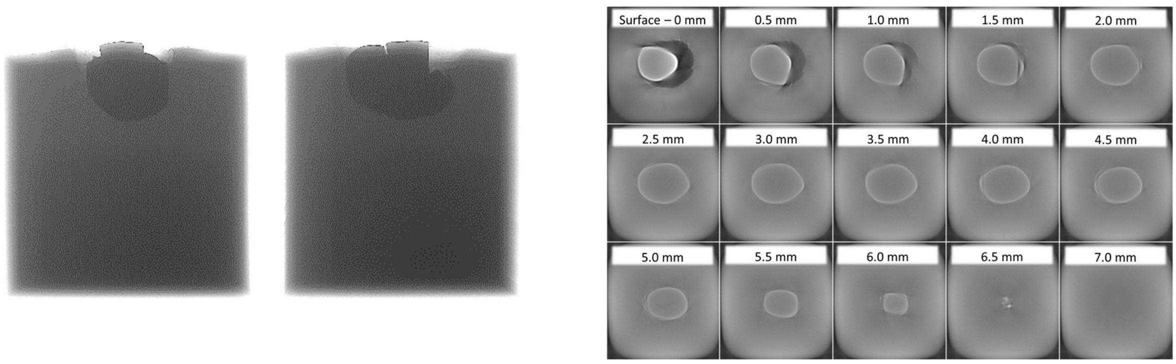
Experimental work in the research and development sector frequently involves novel materials with complex manufacturing methods, often limiting the number of experiments that can be carried out due to costs. Coupling this with the expense and complexity of ballistic range/gas gun experimentation can lead to alarmingly small sample sizes in ballistic experimentation (often as few as three shots). Gathering additional data in experimental work through CV measurements allows for more insightful conclusions to be drawn from these minimal datasets. Establishing a simple and time-efficient data collection method helps to encourage other researchers to adopt CV as a standard measurement.

This work introduces various methodologies that can be used to determine the CV in targets that have been subjected to high velocity impacts, accounting for the different resources that may be available. These methods attempt to account for all potential sizes, shapes and complexities of impact craters, functioning even if there is embedded material within a crater. The accuracy is evaluated alongside the practicality of each method, allowing the best CV measurement method to be selected in any circumstance and encouraging the use of this metric in future ballistic testing. The latter part of this work aims to demonstrate the importance of DoP vs CV, showing that different ratios between these parameters is a likely indication of different failure mechanism(s) occurring in the armour material(s).

METHODOLOGIES

The limited work that does measure the CV achieves this by filling the crater with plasticine or a liquid fill [2], [3] or using 3D laser confocal microscopy [5]. Laser surface scanning can also provide detailed 3D models of the penetration site that could also be used to measure the CV. However, these techniques are difficult to use if the crater has embedded material within it. Other X-ray based techniques can be used to overcome this embedded material limitation, on condition that the embedded and target materials are different. X-ray radiography was used by Lynch *et al.* [3] to visualise craters, later using the digitised images and assuming symmetry to determine the CV. However, this assumption based on a one-dimensional image has the potential to yield considerable errors as one cannot visualise the full crater; this is demonstrated in Fig 2(a), where the crater shape is shown to be different in perpendicular X-ray radiographs. This paper considers seemingly unreported, yet superior, methods of CV calculation and crater visualisation, notably through perpendicular X-ray radiography and Computed Tomography (CT) scanning.

All initial CV analysis was carried out on the same target post-shot. This target consisted of four 25 mm thick steel blocks (creating a semi-inifite 100 mm block) with a 10 mm thick alumina tile adhered to the surface using EA3421



(a) (b)

FIGURE 2. (a) perpendicular X-ray radiographs of the same crater (b) CT scanned cross-sections of the crater in Fig. 2(a)

epoxy. The impactor was a 70 mm long, ⌀4 mm W-Ni-Fe long-rod penetrator, recorded with a high-speed camera to have impacted the target at 693 ±8 m/s. A region of 25x25 mm was then cut around the impact crater in the steel block.

The crater had a DoP of 6.9 ±0.1 mm, determined by CT scanning the block using a Nikon XT H225 micro-CT scanner with a 1 mm copper filter at 200 kV and 155 µA. Image stacks were outputted in the X, Y and Z planes with intervals of 100 µm. Examples of images in the Z-axis (i.e. the direction of penetrator motion) are shown in Fig. 2(b). The crater area in each individual layer at and below the original surface of the block in the Z-axis was then measured using ImageJ [6]. The CV was then calculated by inputting the measured crater area of each layer as a circle into a SolidWorks Computer Aided Design (CAD) drawing, using the "loft" function and measuring the overall part volume.

The block was X-ray radiographed at perpendicular angles using the same conditions as above. An average of 32 images with exposure times of 1,000 ms resulted in the 1,000 x 1,000 pixel images in Fig. 2(a). Using ImageJ, it was possible to identify the original surface and base of the material in each image within ±50 µm of their true values; the distance between these points could be used to set the scale. A line could then be measured between two points at the edges of the crater at the original surface. This was repeated at 0.5 mm depth intervals until the penetration was no longer observed, measuring the width of the crater at 0.5 mm stages. By repeating this on both perpendicular images the crater area at regular depth intervals could be calculated by assuming the crater was an oval. The volume was then calculated using the methods outlined in Table 1. The time consumed using each manual image analysis methodology is indicated by the number of measurements in italics; more measurements or CAD work indicates greater time spent.

Automated measurements were considered, although the aim of this work was to demonstrate that CV measurements can be taken without requiring understanding of coding or other complex techniques. Furthermore, different materials and equipment may produce images that are not compatible with certain automated parameters/thresholds, so are best developed to suit each individual case as required.

The ratio of DoP:CV was then assessed in shots against three different target configurations using a single stage gas gun. In each shot, a 70 mm long, ⌀4 mm W-Ni-Fe long-rod penetrator was fired at different targets, outlined in Table 2. Targets included: 10 mm alumina tiles adhered to the steel blocks (as above); steel without any alumina tiles; and 10 mm alumina tiles with a 3 mm air gap between the alumina and steel. The DoP was assessed through X-ray radiographs and ImageJ. The CV calculations were measured with the "0.5 mm Z-axis reading" technique in Table 1.

TABLE 1. A comparison of the various methodologies used for determining CV in the crater seen in Fig 2(a)

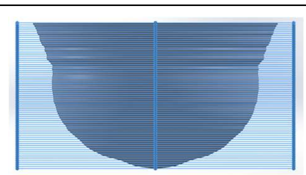
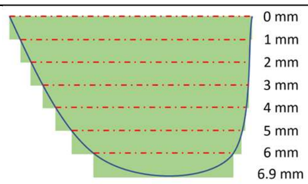
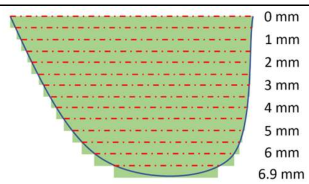
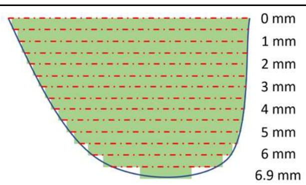
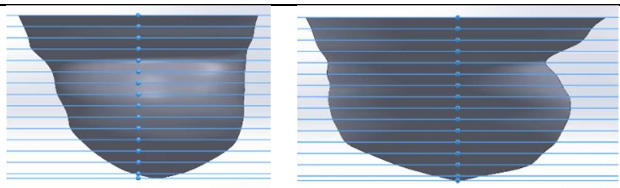
<table>
<tr><td>CV calculation method</td><td>CT scan & CAD circle loft
71 measurements + CAD</td><td>1 mm Z-axis readings
7 measurements</td><td>0.5 mm Z-axis readings
15 measurements</td></tr>
<tr><td>Descriptive image</td><td></td><td>
</td><td>
</td></tr>
<tr><td>Volume (mm³)</td><td>468 ±11</td><td>495 ±14</td><td>472 ±14</td></tr>
<tr><td>% error</td><td>DATUM</td><td>+5.8%</td><td>+0.8%</td></tr>
<tr><td>CV calculation method</td><td>Avg. width between each 0.5 mm Z-axis readings
15 measurements</td><td colspan="2">0.5 mm Z-axis readings offset from a midpoint & CAD loft
15 measurements + CAD</td></tr>
<tr><td>Descriptive image</td><td>
</td><td colspan="2"></td></tr>
<tr><td>Volume (mm³)</td><td>443 ±14</td><td colspan="2">446 ±14</td></tr>
<tr><td>% error</td><td>-5.2%</td><td colspan="2">-4.7%</td></tr>
</table>

TABLE 2. Impact and penetration data for the three target configurations

	Target configuration	Impact velocity (m/s)	Depth of Penetration (mm)	Crater Volume (mm^3)
DATUM GROUP	10 mm alumina 1	883 ±9	18.5 ±0.1	1066 ±37
	10 mm alumina 2	818 ±9	11.2 ±0.1	746 ±23
	10 mm alumina 3	693 ±8	6.9 ±0.1	472 ±14
	10 mm alumina 4	539 ±6	3.0 ±0.1	146 ±6
	No alumina 1	734 ±8	9.2 ±0.1	637 ±19
	No alumina 2	752 ±8	9.0 ±0.1	508 ±18
	No alumina 3	717 ±8	9.0 ±0.1	525 ±18
	10 mm alumina with 3 mm stand-off 1	706 ±8	6.6 ±0.1	539 ±14
	10 mm alumina with 3 mm stand-off 2	726 ±8	7.2 ±0.1	531 ±15
	10 mm alumina with 3 mm stand-off 3	726 ±8	8.3 ±0.1	614 ±17

RESULTS

The CT scan of the sample was able to accurately determine the CV using 70 area measurements across the 6.9 mm of penetration and CAD to integrate between each layer. This therefore provided the datum value against which all other methods would be compared in Table 1. All other methods analysed relied on two perpendicular X-ray radiographs and produced results within $\pm$6% of the CV calculated from the CT scan. This indicates that a relatively rapid and accurate assessment of the CV can be achieved with conventional radiographic equipment and does not rely on access to expensive CT equipment or complex software. The ability to recreate crater geometries using CAD provided a useful tool to visualise and qualitatively compare damage within targets.

The error introduced in CV in Table 2 was predominantly due to the potential for human error in the selection of the original surface of the steel. If this were placed above/below the true original surface, all crater area measurements at 0.5 mm intervals below this chosen surface are likely to be consistently higher/lower than their true value, as the crater typically reduces in size as it deepens. This explains the greater error in CV in deeper craters; where there is an increased number of 0.5 mm intervals, there are more crater width/length, crater area and CV calculations that could all be consistently overestimated or underestimated. Selection-based errors were reduced in scaling by taking three measurements and averaging them. The variation between these was found to never be greater than 1%. Selection errors in choosing the start and end points of crater width/length measurements were believed to have a minimal effect on CV, since any overestimated and underestimated values are likely to average out across multiple calculations and trend towards zero. As these errors are small, it is likely that this methodology is acceptably accurate.

This analysis is only based on a single crater shape that was observed in the experiments described above; using these image analysis methods of X-ray radiographs to measure craters with different or complex geometries may not provide the same level of accuracy. To counter this limitation, it is likely that these methods could be adapted, altering the frequency of crater width/length measurements to suit various craters.

Whilst there is potential error in these measurements through human error in the use of ImageJ and the estimations of CV being based on infrequent crater width/length measurements, the accuracy of each method compared to the true volume of the crater is not necessarily essential in all cases. Provided the selected methodology remains consistent, the CV measured for each target in an experimental series could be compared with reasonable confidence.

The above success provided the basis for the further analysis of DoP vs CV to be carried out. As it has been reported that the interlayer/coupling between a ceramic and metal affects the performance of armour configurations [7], it was expected that a different defeat mechanism would be observed between the three target configurations. Considerable variations are observed in both the DoP and CV for relatively similar impact velocities in the same target configurations. Despite this, general trends can still be observed. However, this does show the difficulty in obtaining consistent and reliable data from forwards-ballistic experimental work, emphasising the need to gather all data possible from each shot. The difference in the CV between "No alumina 1" and "No alumina 2/3", despite having very similar DoPs, demonstrates that data may have presented similarly using current conventional DoP measurements, but the CV measurement shows that a potentially different penetration event may have occurred.

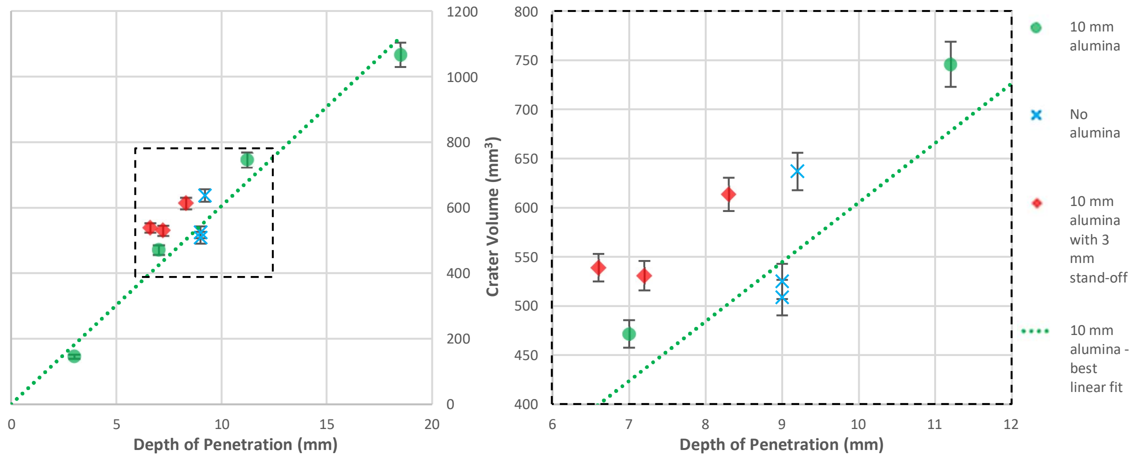


FIGURE 3. DoP vs CV for the target configurations in Table 2. Left: all results. Right: enlargement of selected area.

Figure 3 shows the DoP vs CV compared to the datum target configuration. The "10 mm alumina with 3 mm stand-off" was found to produce a consistently larger-than-expected CV for the given DoPs, as seen by all the data points being considerably above the trendline and a DoP:CV ratio of ≈1:75. The target with no alumina followed a similar pattern as the standard "10 mm alumina armour", with the ratio of DoP:CV remaining at ≈1:60 for both configurations.

The variation in DoP:CV is likely indicative of the different defeat mechanisms in each target configuration. The air gap behind the alumina in the "10 mm alumina with 3 mm stand-off" targets would have reduced the resistance to flexure in the ceramic, resulting in its premature catastrophic failure. Some of this ceramic may then have been driven into the steel surface, overmatching the steel hardness and excavating more of the steel, resulting in a wider crater. The snapped ceramic tile may also have caused the impactor to deflect and impact the steel at an angle, resulting in a wider crater forming. These inferences could not have been drawn without the measurement of CV alongside DoP.

CONCLUSIONS

Previous methods of calculating the CV in forward-ballistic experimentation would not work if a projectile is embedded within a target. However, CV can be calculated with reasonable accuracy and ease using two perpendicular X-ray radiographs, even with embedded projectiles in the crater. An accurate method measured the crater size in each X-ray radiograph at fifteen points, which was not excessively time-consuming. Automating this process would make this tool even more accessible, but would need to be adjusted to suit the radiographs obtained, as these would vary dependent on the equipment used and the materials being imaged. More advanced and accurate techniques are available such as CT scanning or laser surface profiling, although this equipment is less likely to be easily accessible.

Whilst there are limitations with the X-ray radiograph CV techniques, they provide a rapid assessment of crater size and geometry through both quantitative (CV) and qualitative (CAD) means with results accurate to within ±6%. The value of these measurements and being able to visualise the crater provides computational modelers with real-world crater formation data to validate their models against.

The benefits and importance of measuring CV have been demonstrated in previous literature, with these findings reinforced through the variations seen in DoP:CV ratios in different target configurations. With additional CV measurements across various experimental setups available in future literature, patterns in DoP:CV ratios for a variety of armour failure mechanisms could become more easily recognised. This could save time and money in future experimental work, preventing the need for complex materials analysis post-shot to determine the failure mechanism and gathering more data from these expensive experiments.

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