TOWARDS UNDERSTANDING THE DETONATION PROPERTIES OF ADDITIVELY MANUFACTURED RDX: DRY POWDER PRINTED

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1. ABSTRACT

Research into additive manufacturing (AM) has been steadily expanding over the past five decades. Where once only polymeric materials could be reliably printed, AM has been adapted to print with a range of materials such as biological, metallic, ceramic and even foodstuffs. The advantages of manufacturing in an additive manner include; a) a layer-by-layer approach allows the creation of architecturally complex structures, b) a reduction in weight, c) lessening of waste and d) the ability to create parts that that are otherwise difficult or too costly to produce.

1,3,5-Trinitro-1,3,5-triazinane (RDX) is regularly used in explosive systems. Its detonation properties when conventionally manufactured are widely researched and broadly understood. However, recent advances in additive manufacturing technologies have led to greater interest in utilising RDX in this manner. There is growing evidence that emerging formulations and printing methods are changing the detonation properties of RDX composites, the critical diameter among them.[1]

This study reports on beginning to understand the detonation properties of additively manufactured RDX via a dry powder printing method.

2. BACKGROUND

Research into additive manufacturing, a layer-by-layer process that allows researchers and hobbyists to build complex structures through computer aided design, has been expanding steadily over the past five decades. Now, energetic materials used for defence applications like thermites, nanothermites, CL-20 and RDX are just some of the energetic materials that have been successfully 3D-printed.[2–5] The most common methods used in these studies are extrusion methods some mimicking Fused Deposition Modelling (FDM) many using Direct Ink Jet Writing (DIW) to print energetic materials.[6] A novel method of additive manufacture, Dry Powder Deposition (DPD) has been developed at Cranfield University and has been used to print thermites[7] (Al/Fe_2O_3, Al/CuO, Al/Ag_2O, Zn/CuO, $Al/CaSO_4$) and RDX. In both cases the combustion properties of both types of materials, whether as a pyrotechnic or a propellant were the initial point of interest. This has now been further expanded to examine using DPD to generate explosive systems and a shaped RDX charge was successfully printed via DPD and detonated.[8]

Whilst the additive manufacture of energetic materials offers manufacturers a route to increase safety and reduce waste it also allows researchers and engineers to access more complex architectures, not available through conventional manufacture. This provides an

exciting and vast research space, the base of which relies on an understanding of new materials including their repeatability, critical diameter, detonation velocity to name a few characteristics. Something that became apparent during the successful proof of concept work described previously. This work describes with the testing of five printed RDX cuboids that have been detonated on mild steel and their detonation velocity recorded using a custom set-up exploiting the detonation electric effect.[9]

3. METHODS

To determine the repeatability of the detonation velocity, five cuboids, 50 x 10 x 6 mm were printed at a layer height of 0.2 mm. Cuboids A-C were printed at the same time using a print file that produces four cuboids at once, Figure 1. Cuboids D and E were printed using a print file that produces two cuboids at once. The RDX powder (Type 2 Class 1) was bound with a solution of cellulose acetyl butyrate (CAB, 12,000 MW, 4 wt%) and polyethylene glycol (PEG, 1 wt%) in a mixture of acetone and water (9:1 by volume).

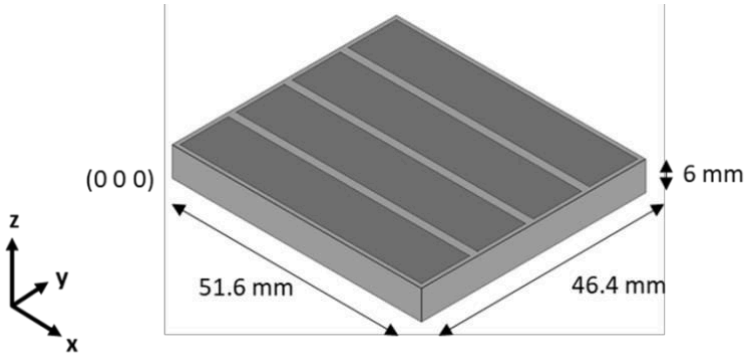


Figure 1. *Schematic of the completed print of four cuboids at once. Dark grey shows the bound parts, light grey shows supporting material.*

Once printed cuboid samples were placed in a desiccator overnight to remove any remaining water. The cuboids were removed from the print bed cleaned with a paint brush, Figure 2, measured with callipers; the mass recorded, then placed into static shield bags for storage.

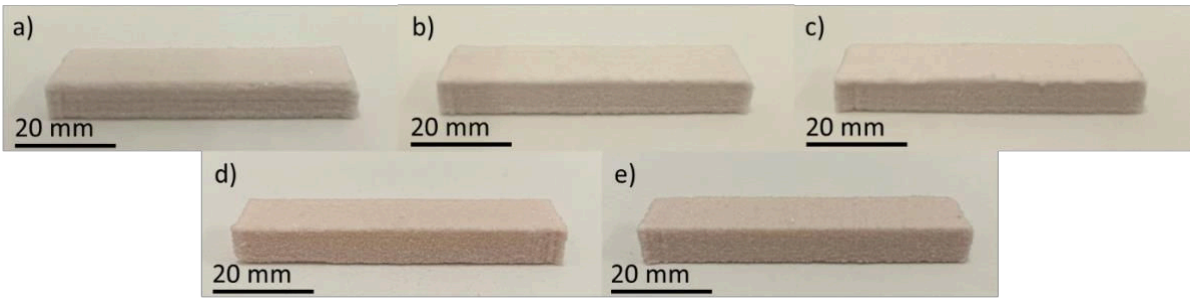


Figure 2. *Sample cuboids A to E used to determine the detonation velocity of dry powder printed RDX.*

Table 1. *Dimensions, masses, and densities for the five cuboids to determine the detonation velocity of dry powder printed RDX.*

Samples	$\bar{x}$ / mm	$\bar{y}$/ mm	$\bar{z}$ / mm	Mass/ g	Density/ g cm^3
A	51.66	10.71	6.82	2.875	0.76
B	51.64	10.87	6.90	3.000	0.78
C	51.71	10.76	6.88	3.029	0.79
D	51.77	10.65	6.71	3.097	0.84
E	51.87	10.63	6.67	3.183	0.87

The cuboid samples were retrieved from storage prior to detonation testing. Cuboids were placed in the of mild steel witness plates, 150 x 110 x 8 mm, and attached using double sided sticky tape. Those that were broken in storage were re-assembled on the witness plates. The detonator was placed at the (0, 0) end of the part except cuboid sample C where the cuboid was rotated 180° in the z and x axis. The ribbon wire was placed inside a plastic holder up against the cuboid, 3 mm above the witness plate, and the plate connected to ground, **Error! Reference source not found.**.

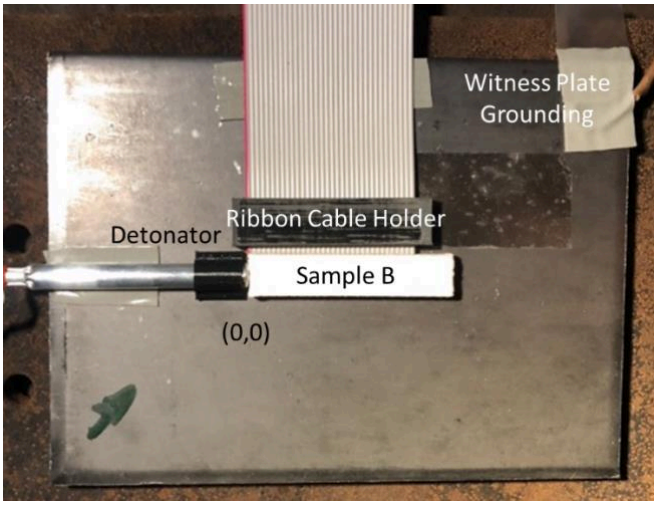


Figure 3. Typical set up for the detonation of printed RDX cuboids, where the witness plate is grounded allowing circuit completion when the detonation wave passes.

Upon detonation a short circuit is detected by an Intronix LogicPort logic analyser 34 channel (LA1034) and the point at which the shockwave passes recorded by Intronix LogicPort software. The first instance of a short is taken as the time at which the shockwave has passed. Each wire in the ribbon cable is 1.27 mm apart and there are 32 active channels. The detonation velocity is determined by plotting the distance against the time a short circuit is detected, then applying a linear robust fit to give the gradient.

4. RESULTS AND DISCUSSION

The density of the printed samples shows that most of the printed part consists of voids, with 40 - 47 % of the volume made up of RDX, Figure 4.

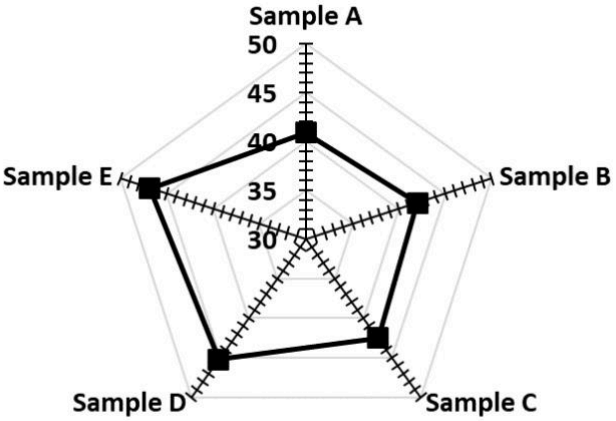


Figure 4. Density of the printed samples as a percentage of the true density of RDX.

The assembly of the detonator holder, ribbon cable holder and the earthing wire was conducted just prior to detonating each sample, around five minutes set-up, and proved a simple but efficient method holding the test pieces in place. The detonation progress from the detonator to 40 mm into the printed cuboid sample was quite regular and is shown in Figure 5. Samples A - E all show a detonation velocity 6.5 - 6.9 km s^{-1}, Table 2.

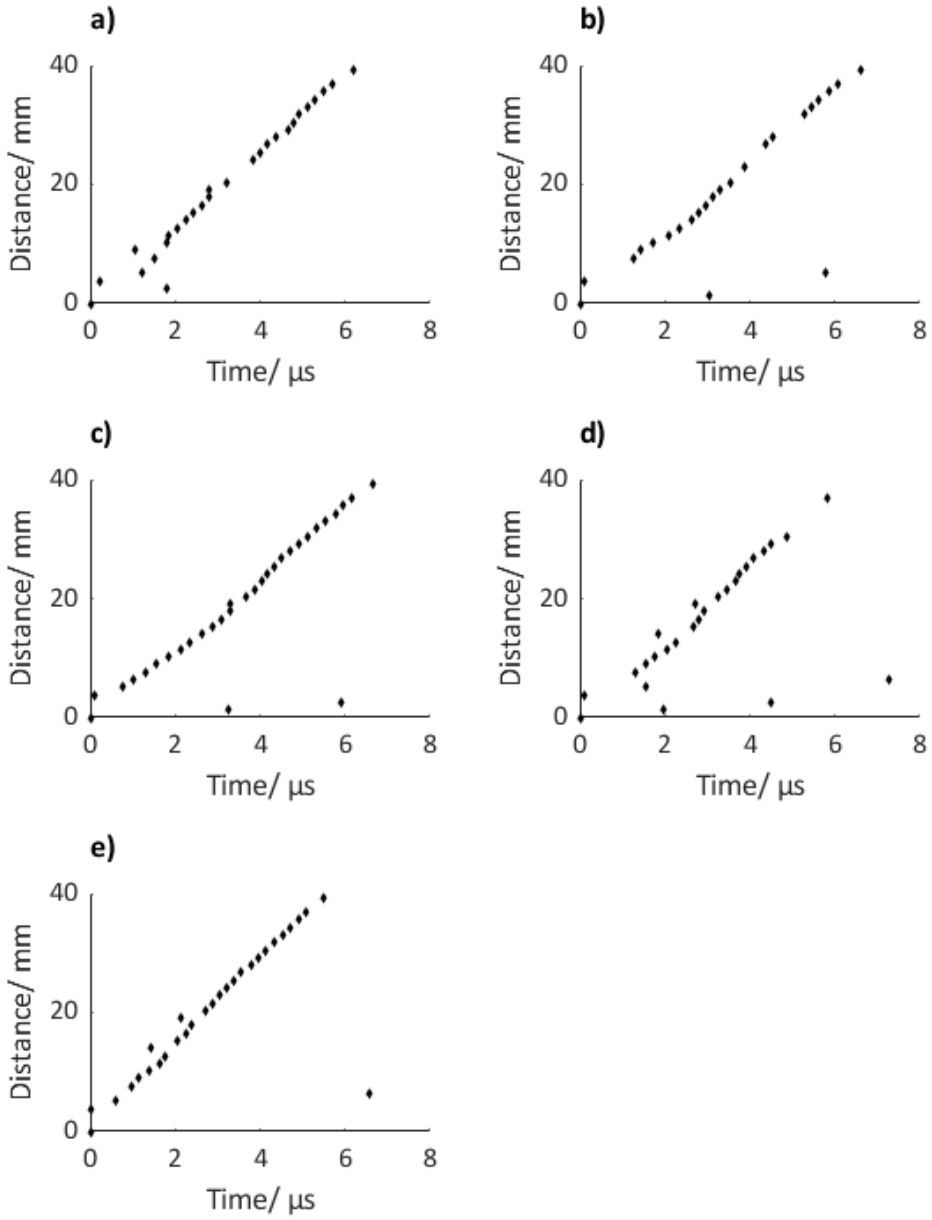


Figure 5. Distance (mm) against time (µs) for the five cuboid samples detonated, a) Sample A, b) Sample B, c) Sample C, d) Sample D, and e) Sample E.

Table 2. *Detonation velocities of five cuboid samples of printed RDX, densities and the goodness of fit through the R^2 are also shown. Detonation velocities have a coefficient of variation of 2.8%.*

Sample	Density/ g cm^{-3}	Velocity/ m s^{-1}	R^2
A	0.76	6.600	0.999
B	0.78	6.541	0.997
C	0.79	6.509	0.996
D	0.84	6.875	0.984
E	0.87	6.893	0.997

Samples A to C were printed as part of a set of four parts, whilst samples D and E were printed in a different print of two parts. There is a difference in density between parts and prints, Figure 4, where the density of parts increases across a print and when the number of parts being printed is decreased. It is likely that this difference is a result of a difference in the time between binder deposition for each part in print. It is also likely that there is a cumulative effect whereby a two-part print will yield more dense parts than a four-part print, Figure 6. There appears to be an inverse correlation between the relative time between binder depositions and the detonation velocity recorded for a four-part print. Though this should be treated with caution. The lower velocities shown by samples B and C when compared to A could also be the result of the part being broken and reassembled on the witness plate. This caution is emphasised by the difference in velocity between D and E made in a two-part print.

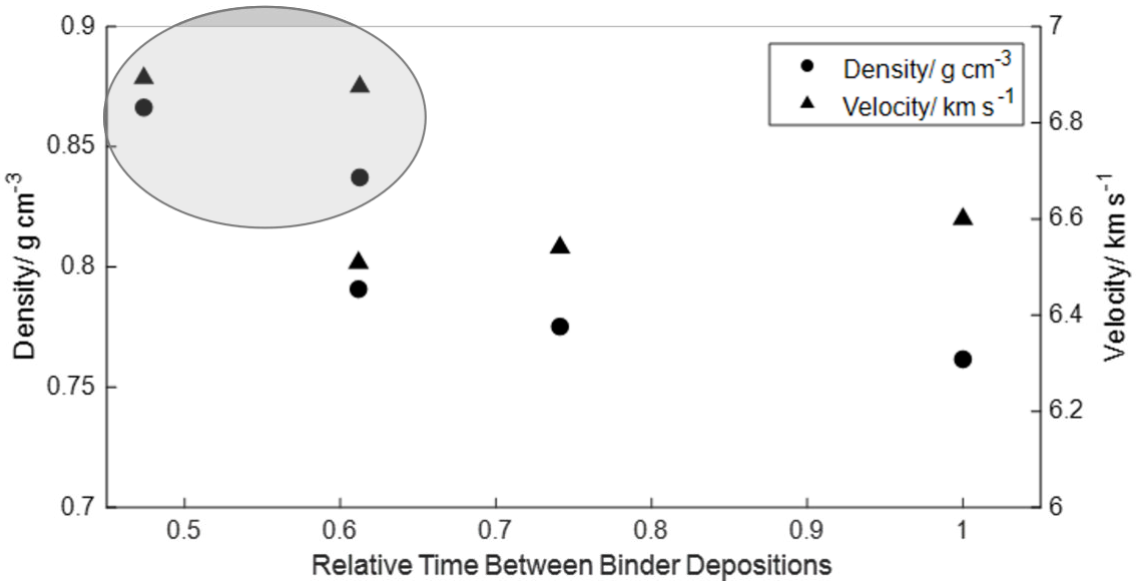


Figure 6. *Density (circle) and velocity (triangle) against the relative time between binder depositions, data points from the two-part print inside the highlighted oval.*

The effect of reassembly of broken parts on the witness plate can be seen most clearly in Figure 7 e). Sample E was broken around 20 mm along the part, the image of imprint on the witness plate shows two different shades of grey, showing where the two parts of the sample were prior to detonation. It may be possible in future work to map this imprint to determine any height difference.

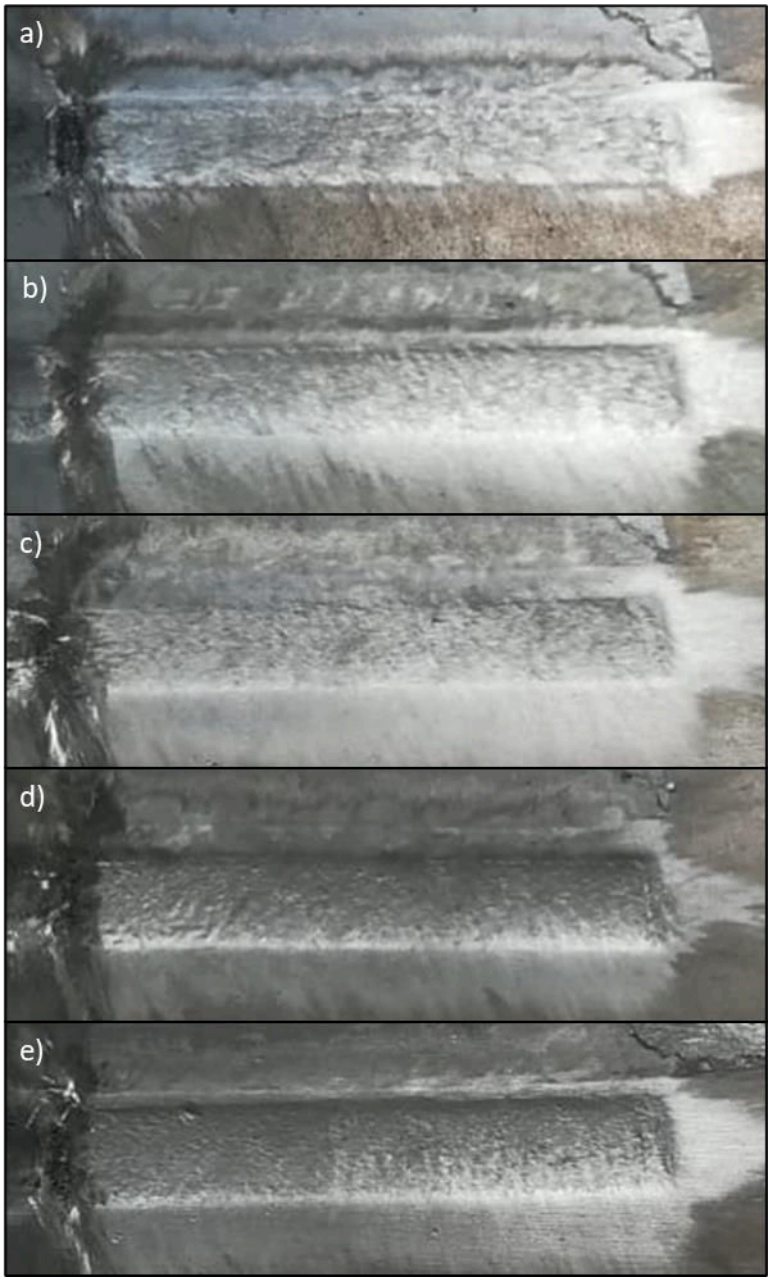


Figure 7. *Mild steel (8 mm thickness) witness plates from the five detonation tests, a) Sample A, b) Sample B, c) Sample C, d) Sample and e) Sample E.*

5. CONCLUSIONS

Five cuboids 50 x 10 x 6 mm of RDX were printed. The density of the printed parts appears to vary dependent on order of print and the total number of parts printed in a single print. They were then successfully detonated showing a detonation velocity of 6.7 ± 0.2 km s^{-1}. The detonation progress appears regular for all samples, including those that were broken during storage. The mild steel plates show interesting imprints from the detonations. Especially those where broken parts were reassembled on the print bed.

6. FUTURE WORK

The work described here is the start of the process in understanding the detonation properties of printed RDX materials. The forthcoming work looks to address some questions

not addressed in this work and to address others raised by this work. The avenues of research are briefly described below. It should be noted that this is not an exhaustive listing of what could be explored.

The printing process appears to have effect on the density and may have an impact on the detonation velocity of parts, as such it would be prudent to investigate these variables further. Through repetition and changing the number of parts printed at any one time.

All parts were printed with the same infill specifications, it is quite likely that a different infill will affect the propagation of the detonation. This is something that may vastly increase the available architectural space for printed energetic and should be explored.

All the witness plates during this piece of testing are mild steel. The shockwave can propagate through the steel and be reflected at the sample. This will likely be supporting the detonation wave in its progress through the part. Thus, identification of magnitude of this effect should be investigated through the repetition of this testing on different witness plates.

The critical diameter of the material was not determined here, it is vital safety and engineering property. As such the determination of the critical diameter for this material should be undertaken. With the nature of the additive manufacture, there is potential to investigate a single print that can be used to determine critical diameter in one shot.

There was only one ribbon wire tracking the detonation wave during this testing. Mechanical anisotropy is a well-known property of additively manufactured materials. There is a strong possibility that there will be detonation anisotropy from the nature of manufacture. Further instrumentation, additional ribbon wires, to track the detonation wave on multiple faces and the addition of other techniques for the determination of detonation properties would be of great interest.

7. ACKNOWLEDGEMENTS

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