SAND2020-4243C

Investigating Typical Additive Manufacturing Defect Geometries using Physical Vapor Deposition Explosives as a Model System

Caitlin O'Grady[1,2, a)] Michael P. Marquez[1], Stephen Rupper[1], Jon Vasiliauskas[1], Robert Knepper[1], Steven F. Son[2], and Alexander S. Tappan[1, b)]

[1]*Sandia National Laboratories, PO Box 5800, MS 1454, Albuquerque, NM, 87185-1454 USA*
[2]*Purdue University, 610 Purdue Mall, West Lafayette, IN, 47907 USA*

[a)]Corresponding author: *cogrady@sandia.gov*
[b)]*astappa@sandia.gov*

Abstract. Additive Manufacturing (AM) techniques are increasingly being utilized for energetic material processes and research. Energetic material samples fabricated using these techniques can develop artifacts or defects during the manufacturing process. In this work, we use Physical Vapor Deposition (PVD) of explosive samples as a model system to investigate the effects of typical AM artifact or defect geometries on detonation propagation. PVD techniques allow for precise control of geometry to simulate typical AM artifacts or defects embedded into explosive samples. This experiment specifically investigates triangular and diamond-shaped artifacts that can result during direct-ink-writing (Robocasting). Samples were prepared with different sizes of voids embedded into the films. An ultra-high-speed framing camera and streak camera were used to view the samples under dynamic shock loading. It was determined that both geometry and size of the defects have a significant impact on the detonation front.

INTRODUCTION

Additive manufacturing (AM) and rapid prototyping have been utilized by industrial applications for more than a decade [1]. AM refers to many different techniques that construct parts in a layer-wise fashion, including 3D printing, additive and freeform fabrication, and rapid prototyping and manufacturing [2]. AM techniques can potentially provide a method of developing custom, complex geometries that produce less waste and use less material compared to other fabrication methods [2]. Using less material means that AM processes have the potential to be safer for use with energetic materials. These are some reasons that AM techniques have begun to be used in the energetics community.

Given the recent interest in AM processes for energetic materials, any common manufacturing defects or artifacts in the material are of interest. For AM work with high explosive (HE) materials, these defects or artifacts could change the detonation performance and safety of the HE. We know that hot spots govern the initiation of energetic materials, but do not fully understand what governs the mechanisms that create these hot spots. To utilize HE materials safely, it is important to understand the processes behind what causes them to initiate. Several reported accident scenarios have occurred due to inhomogeneities in the HE resulting in localized hot spots reacting, leading to detonations [3]. Accidental initiations have occurred at all stages of energetics handling, including storing HE, building and conducting experiments, moving HE, and processing HE [4, 5]. This paper will explore a few common artifacts that result from the specific AM process of direct ink writing (DIW) technique, also called Robocasting, using pentaerythritol tetranitrate (PETN) thin films made via physical vapor deposition (PVD) techniques as a model system. The purpose of these experiments is to model typical AM artifacts as triangular shaped voids in PETN thin films prepared by physical vapor deposition (PVD) processes and investigate the effects of these voids during detonation.

Common AM artifacts and defects

With AM processes there can be a significant amount of variability between parts that were designed to be identical. These variations are usually due to defects or artifacts that result from the deposition process. Specifically, for Robocasting of HE materials, there have been several common types of defect or artifacts that we have observed. These artifacts or defects include voids between deposited layers (slots), diamond-shaped voids, triangular-shaped voids, cracks in the material, agglomerates of HE material, and circular-shaped voids. AM techniques have several defect types that are not found in other methods of fabrications, including step edges that cause surface defects, defects

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between layers, and defects caused by thermal shock [6-9]. Some examples of typical artifacts can be seen below in Figure 1.

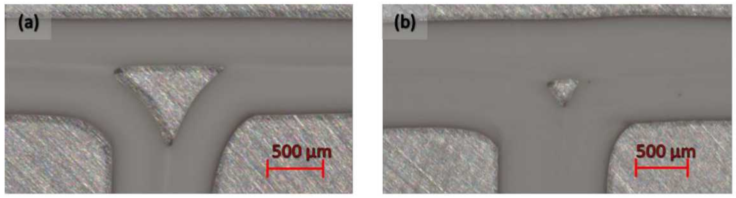

FIGURE 1. Optical micrographs of material deposited by Robocasting that show common AM artifacts, including (a) Large triangle void, and (b) Small triangle void.

These typical AM artifacts and defects have been determined to result from several different factors both during and after the deposition process. Generally, AM artifacts result from known causes, but it is difficult to predict their exact size and shape. Conversely, determining the exact cause of AM defects can be difficult as there are many factors that are involved with the deposition process. During deposition there are several factors that can affect the creation of an artifact or defect including: the volumetric flow rate of the material, the table speed at which the sample is built, and the toolpath or direction(s) in which material is deposited. These factors can affect the size or type of artifact/defect in the resulting sample. Our focus in these experiments is to investigate the effects of AM artifacts rather than defects. Figure 1 above shows an example of different artifact sizes as both images (a) and (b) show the same material and toolpath, but at different table speeds. The sample shown in Figure 1 (b) was built at half the table speed as the sample shown in Figure 1 (a). The slower table speed and deposition rate resulted in a smaller triangular-shaped void. The purpose of these experiments is to determine the extent to which size and geometry of these triangular-shaped AM artifacts could create hot spots and affect the shock/detonation front of an HE.

EXPERIMENTAL METHODS

PETN thin films were deposited by vacuum thermal sublimations in a custom deposition chamber [10]. A shadow mask was created to precisely define the 3 mm × 5 mm deposition area on polycarbonate substrates with a triangular shape void on one end of the substrates. The deposition process consists of several pairs of polycarbonate substrates being loaded into custom fixtures with the shadow mask affixed atop them; then the substrates are put into the custom chamber and cooled against a water-cooled copper block. PETN powder is loaded into an effusion cell deposition source and the chamber evacuated to approximately 10^{-6} Torr. The powder sublimes or evaporates once the effusion source is heated to the correct temperature [10]. During the deposition process, the substrates are rotated to ensure uniform material thickness is deposited [10]. Each pair of substrates resulted in a sample with an isosceles triangle-shaped void with either 0.25 mm or 1 mm side lengths and a sample with no void. These preliminary experiments focused on triangular-shaped void samples with 1 mm side lengths.

PVD was chosen for this experiment as it allows for precise dimensions of HE to be deposited with small-scale voids embedded in the PETN during deposition to simulate the geometry of AM artifacts. PVD does not allow for large amounts of material to be deposited easily, but PETN thin films prepared with PVD can detonate at very small scales [11, 12]. The PVD process allows for control over the microstructure of the material as well as the lateral dimensions and thickness of the films in a precise, repeatable way [11]. Unlike other fabrication methods, PVD allows for the chosen void geometries to be embedded in the HE with minimal defects. PETN film thickness was determined from surface profiler (Dektak XT, Bruker) measurements and found to have thicknesses of approximately 165 µm, which is greater than the critical detonation thickness [12]. Two substrates were assembled together to create a triangular-shaped void as shown in Figure 2.

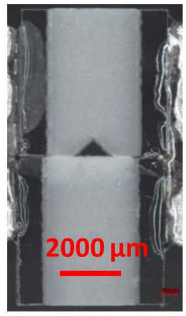

FIGURE 2. Optical microscope images of the assembled substrate setup with a 1 mm triangular-shaped void.

The substrates were epoxied into a modified Thorlabs cage plate, initiation was started at the bottom of the substrate assembly, and detonation propagated upwards. An ultra-high-speed framing camera (SIMX, Specialised Imaging) was used to provide a record of the experiment.

RESULTS AND DISCUSSION

As the effect of common AM artifacts on the detonation front of an explosive has not yet been fully explored, it was difficult to speculate on the nature of hot spot formation and detonation propagation around such geometries. The size of the void was expected to influence possible formation of spall or jetting. The voids were expected to disrupt the detonation front, which becomes split by the interaction with the void and proceeds as separate detonation fronts along the sides of the void. The void collapse was thought to potentially form a hot spot that would aide in the separate detonation fronts recombining or have minimal effect depending on the size and geometry of the void. The experimental data show that a large triangular-shaped void did affect the detonation front of the HE, and the void collapse may have contributed to propagation of the detonation front. Several frames of these dynamic images for the experiment are shown in Figure 3 in sequential order.

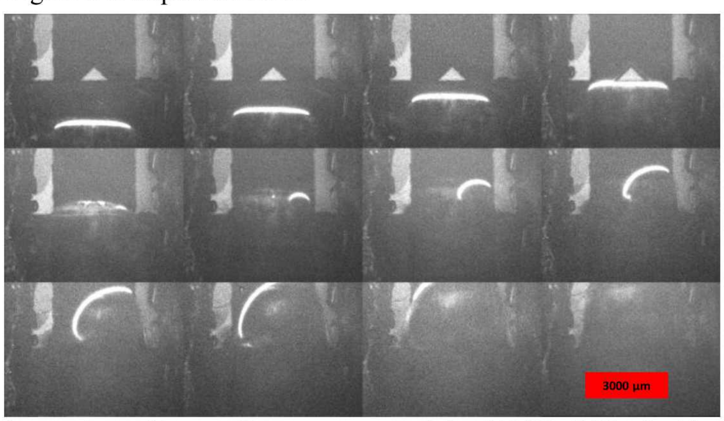

FIGURE 3. Dynamic experimental images. Images were recorded at 14 MHz (1/70 ns) with an exposure of 10 ns.

It was noted that the detonation front was significantly affected by the interface between the two assembled substrates. Characterization of the assembled substrates with an optical microscope revealed that the assembly process for the substrates resulted in a small gap between the HE at the interface of two substrates on the left side of the void (based on the framing camera orientation), and a small crack and gap along the right upper edge of the lower substrate. These additional defects significantly impacted the experimental results. The detonation front was quenched along the left side of the void due to the very small gap between the HE, and the detonation front was partially quenched by the small crack and gap on the right side of the void. These additional defects, small gaps and crack, can be seen in Figure 4 below.

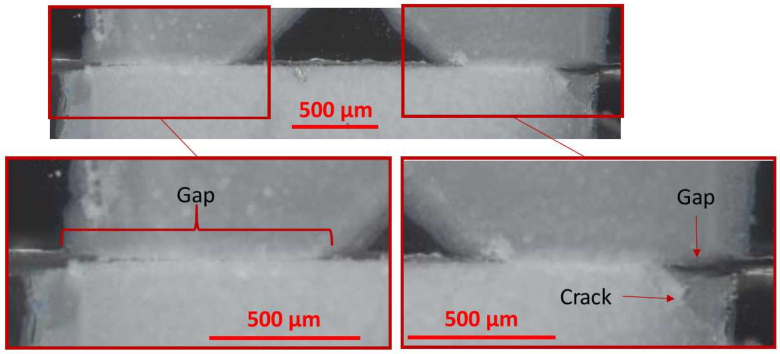

FIGURE 4. Optical microscope image of the assembled substrates showing the interface between the two substrates. It can be noted that there is a very small gap at the interface of the substrates on the left side of the void (based on framing camera view orientation) and a small crack and gap at the interface on the right side of the void.

To better analyze the data, the detonation front was extracted by thresholding the experimental framing camera images and overlaid on top of the optical microscope images that were taken after assembly, but prior to detonation. These images and observations are labeled and can be seen in Figure 5. In addition to the failure of the detonation front due to the small gaps and crack at the interface of the two substrates, several phenomena were observed, including jetting, pre-shock of the material ahead of the detonation front, partial reaction of the material, and interaction of the detonation front with shocked material after passing the void. Initiation started at the bottom and propagated upward with a relatively flat detonation wave. Upon the detonation front reaching the interface between the two substrates, the detonation front failed and became a shock wave on the left side of the void and was partially quenched on the right side of the void. Next, it can be observed that the shock front moved along the edges of the void ahead of the detonation front, which resulted in the material being pre-shocked or compressed and potentially partially reacted. Additionally, as the detonation front on the right-side curves around the void during later frames, some of the material appears to undergo late reaction behind the detonation front, as evidenced by a persistent luminous region behind the detonation front. This late reaction may be due to the interaction of the detonation front with material that has already been shocked. In some cases, material that has been shocked will become compressed, which causes incomplete reaction upon interaction with the detonation front, which may be the cause of the persistent luminous region seen in this experiment. Finally, as the detonation front reaches the material on the left side of the void, the detonation front fails when it interacts with the damaged, compressed, and pre-shocked material.

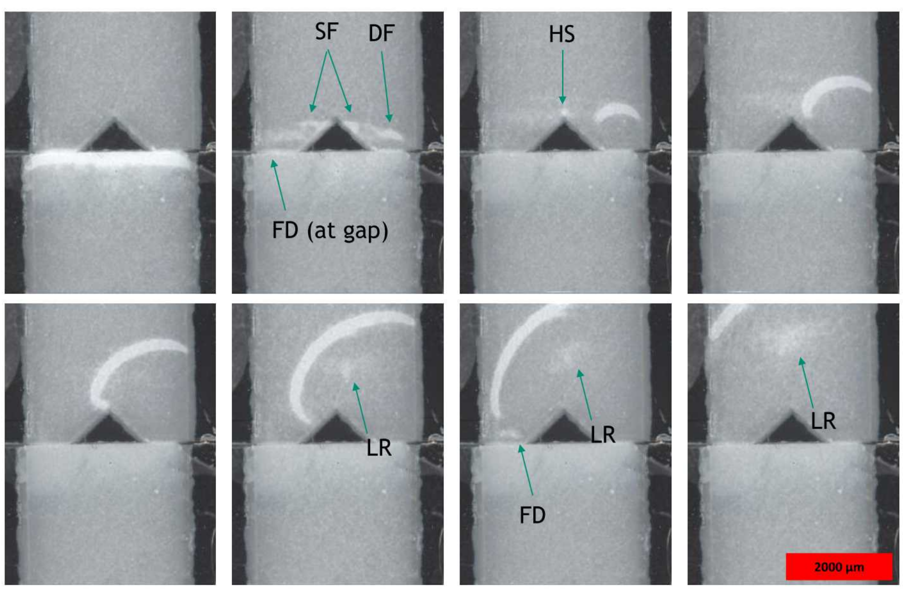

FIGURE 5. Dynamic experimental images from frames 4 through 11 overlaid on an optical microscope image of the substrates prior to detonation, labeled for observed phenomena. Images were recorded at 14 MHz (1/70 ns) with an exposure of 10 ns. SF refers to the shock front, DF refers to the detonation front, FD refers to a failed detonation, LR refers to a late reaction, and HS refers to a hot spot.

There were several important aspects of this experiment worth noting that will be useful for future experiments focused on determining the effects of size and geometry of typical AM artifacts on detonation front of HE. First, very small gaps between samples of HE can cause detonation failure [13]. This proved to be significant for this experiment, as the gap was sufficient to cause the detonation front to fail on the left side of the void. Second, large-scale triangular voids do affect the detonation front of a HE. There were several phenomena that were observed from this experiment that provide evidence for this hypothesis, including formation of a hot spot at the apex of the triangular void, and shock front moving ahead of the detonation front around the edges of the void. Finally, additional experiments on HE with different sizes and geometries of voids are needed in order to further test the effects of typical AM artifacts. Experiments will need to be conducted to determine the effects of both void sizes and void geometries to fully determine the effects of typical AM artifacts. Overall, this experiment proved that the typical AM artifact of a large triangular void will affect the detonation front of an HE, but more experiments are needed.

CONCLUSION

Experiments were performed to determine the effects that typical AM artifacts of triangular-shaped voids will have on the detonation front of an HE. The resulting data showed that a large triangular void will affect the detonation front of an HE. Several different phenomena were observed, including jetting, pre-shock of the material ahead of the detonation front, quenching of the detonation front, partial reaction of the material, and interaction of the detonation front with shocked material after passing the void. Based on the experimental results, both the size and shape of the artifact or defect are expected to affect the detonation/shock front of the HE, but more experimental data are needed.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge Ben Hanks for assistance with manufacturing and Adrian Casias, Billy Cunningham, and Amanda Nicole Dean for assistance with deposition masks. This project was funded in part by Purdue ONR MURI project and the Joint Department of Defense/Department of Energy Munitions Technology Development Program as well as Sandia's Laboratory Directed Research and Development program.

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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