PROPERTY-PROCESSING IMPLICATIONS IN ADDITIVE MANUFACTURED MATERIALS FOR MUNITIONS

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ABSTRACT

Additive manufacturing (also referred to as AM) offers many opportunities in the munition design space to tailor bulk properties, such as spatially-variant composition, density, etc., with intent to subsequently affect macro behavior through changes in stress/strain profiles, variable burn rate, fracture progression, and other parameters.

With the introduction of any novel processing and manufacturing technology, new and very different material properties, flaws, and defects are also introduced. Historically this was seen with the introduction of welding in the early 20th century (heat affected zones, inclusions) that drastically changed the science of fracture and fatigue, as well as the introduction of lamellar and fiber-reinforced composites 50 years later that created entirely new fracture, fatigue, creep, and crack-growth phenomenologies. The advent of microelectronics expanded materials science into new realms with layered micro- and nano-metallic films, deposition techniques, and incorporation of metals, semiconductors, and plastics, and introduced even more material failure, flaws, and defect creation.

The Munitions Safety Information Analysis Center (MSIAC, a North Atlantic Treaty Organization multi-national project office) is reviewing the types of materials currently being used in AM, the resultant material properties achieved, and the main issues that will face munitions science in utilizing these AM-created materials. This paper and presentation will provide a summary and introduction to that effort, describing the key issues, a comparison of the materials possible, and assistance for practitioners who plan to employ AM in munitions. Published reports have already illustrated novel pin-cushion shaped flaws in AM metals and plastics that will significantly impact the ease of crack formation and propagation, independent of the material's stress intensity factor (K_{ic}). Additionally, many AM processes appear highly prone to creation of micro- and macro-voids during material build-up dependent on rate of travel/deposition, input heat intensity, etc. This could be particularly deleterious to bulk sensitivity if used to create energetic materials.

1.0 INTRODUCTION

This paper is an overview of an upcoming report on the application of Additive Manufacturing (AM) to the production of munition items, and its impact on material selection, properties, and performance. AM offers many opportunities in the munition design space to tailor bulk properties, such as spatially-variant composition, density, etc., with intent to subsequently affect macro behavior through changes in stress/strain profiles, variable burn rate, fracture progression, and other parameters applicable to the munition design space [1].

A thorough understanding of AM, its definitions, techniques, and evolving standards is beyond the scope of this paper. The Munitions Safety Information Analysis Center (MSIAC, a North Atlantic Treaty Organization multi-national project office) project, of which this paper is a summary introduction, focuses on the application of AM to munitions. Numerous government, industry, and academic research efforts are working to apply AM in the munitions design space, with items as diverse as complex mechanical devices such as fuzes and safe & arm items, structural munition parts, and energetic material components such as boosters, fills, and propellant grains [2][3].

Current work in the aerospace industry to address the qualification and certification of critical parts in airframe and engine applications made with AM [4], closely mirrors the efforts being pursued in the munitions community. The aerospace community is further along the path of discovery and is primarily focused on metal alloy parts. Munitions efforts are looking at various polymer materials and metals, although the propensity of high-solids-loaded polymer matrix composite energetic materials will be a unique challenge to this industry.

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2.0 AM MANUFACTURING TYPES

The ISO-ASTM standard [5] that emerged from ISO technical committee 261 describes AM as a general term "for those technologies that, based on a geometrical representation, creates(sic) physical objects by successive addition of material." This is in contrast to conventional milling, machining, etc. which are *subtractive* methods that remove material. The technology has found use in engineering industry and other technical areas such as medicine, architecture, toys, entertainment, and limited production commercial goods and prototyping.

Numerous terms have been applied to the various devices and systems, sometimes including specific trademarks or application terminology. This can lead to confusing classification, where ostensibly identical techniques are classed or defined separately. Issues like this can seriously hamper communication among the technical practitioners in disparate fields.

52900:2015 defines parameters and terms that are of use in describing, in a consistent and clear manner, the technology surrounding AM. The following seven standard processing types are delineated in [5], which are of great assistance in establishing ground rules for the discussion of AM.

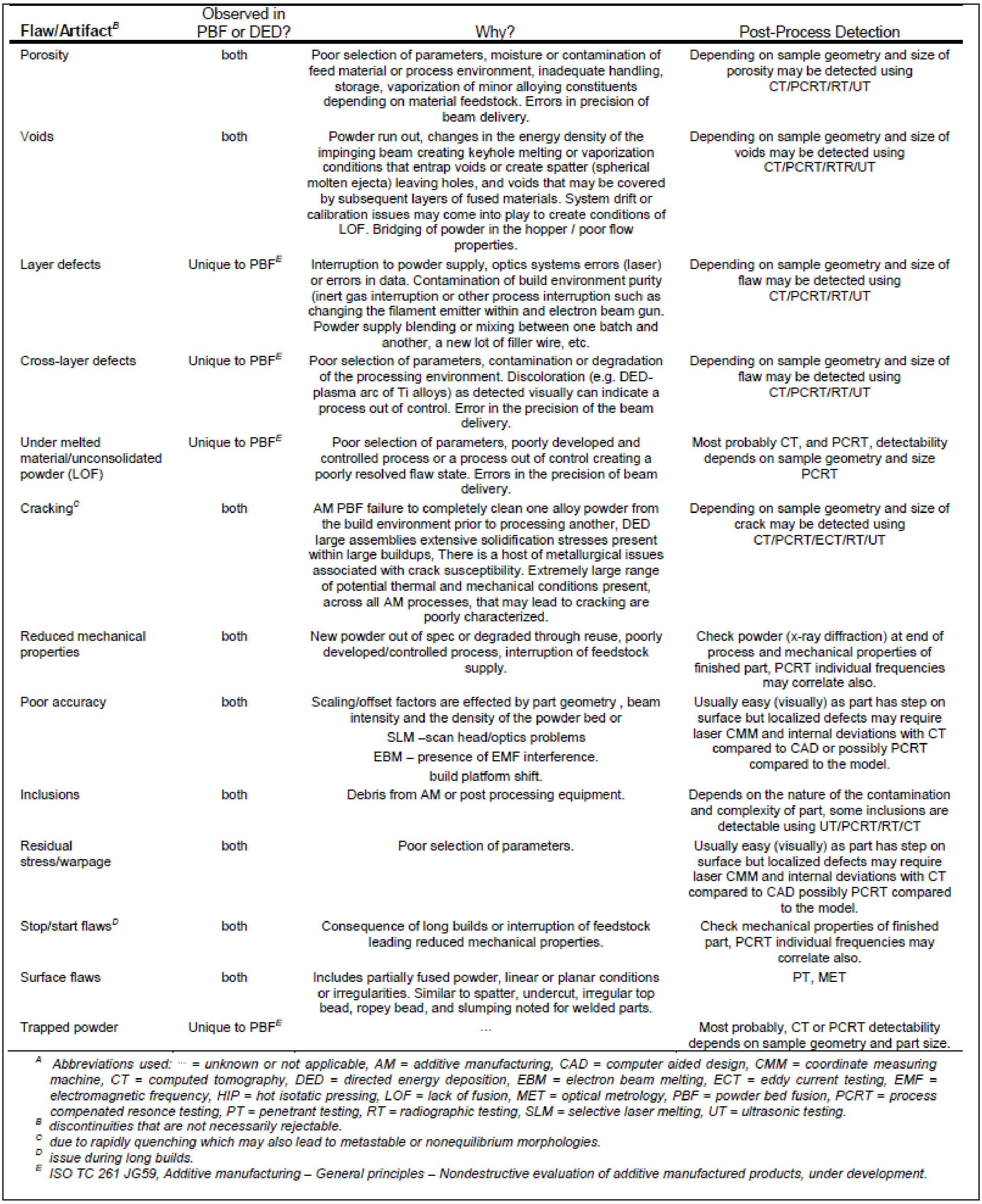
- Binder Jetting: A liquid bonding agent is selectively deposited to join powder materials
- Directed Energy Deposition: Focused thermal energy from a laser, electron beam, plasma arc, etc., is used to fuse materials, which are melted as they are being deposited
- Material Extrusion: Material is selectively dispensed through a nozzle or orifice (much like a caulking gun; the well-known term "3-D printing" is often this type or the next)
- Material Jetting: Droplets of build material are selectively deposited (much like an ink-jet printer; the well-known term "3-D printing" is often this type or the previous)
- Powder Bed Fusion: Thermal energy is directed at and selectively fuses regions of a powder bed
- Sheet Lamination: Sheets of material are layered (stacked) and bonded to form a part
- Vat Photopolymerization: Liquid photopolymer in a vat is selectively cured (solidified) by light-activated polymerization

All of these techniques involve various methods to raster a deposition-, laser-, or beam-emitting head assembly through at least two dimensions (x and y) and possibly a third (z), and further move either the part being created or the head assembly additionally through the third dimension (z). Binder jetting, material extrusion, material jetting, and sheet lamination are the methods most applicable and useable in the energetic materials fabrication space.

3.0 MATERIAL DEFECT CLASSIFICATION

Another area of codification is AM defects. Seifi [6] provides a summary of the defects common in AM techniques and the realistic capability to apply non-destructive testing (NDT) to identify them, illustrated in Table 1. The focus in this work was for aerospace manufacturing applications, but the discussions are applicable to the energetics community.

Table 1. AM defects and application of NDT techniques, from Seifi [6].



Flaw/Artifact[B]	Observed in PBF or DED?	Why?	Post-Process Detection
Porosity	both	Poor selection of parameters, moisture or contamination of feed material or process environment, inadequate handling, storage, vaporization of minor alloying constituents depending on material feedstock. Errors in precision of beam delivery.	Depending on sample geometry and size of porosity may be detected using CT/PCRT/RT/UT
Voids	both	Powder run out, changes in the energy density of the impinging beam creating keyhole melting or vaporization conditions that entrap voids or create spatter (spherical molten ejecta) leaving holes, and voids that may be covered by subsequent layers of fused materials. System drift or calibration issues may come into play to create conditions of LOF. Bridging of powder in the hopper / poor flow properties.	Depending on sample geometry and size of voids may be detected using CT/PCRT/RTR/UT
Layer defects	Unique to PBF[E]	Interruption to powder supply, optics systems errors (laser) or errors in data. Contamination of build environment purity (inert gas interruption or other process interruption such as changing the filament emitter within and electron beam gun. Powder supply blending or mixing between one batch and another, a new lot of filler wire, etc.	Depending on sample geometry and size of flaw may be detected using CT/PCRT/RT/UT
Cross-layer defects	Unique to PBF[E]	Poor selection of parameters, contamination or degradation of the processing environment. Discoloration (e.g. DED-plasma arc of Ti alloys) as detected visually can indicate a process out of control. Error in the precision of the beam delivery.	Depending on sample geometry and size of flaw may be detected using CT/PCRT/RT/UT
Under melted material/unconsolidated powder (LOF)	Unique to PBF[E]	Poor selection of parameters, poorly developed and controlled process or a process out of control creating a poorly resolved flaw state. Errors in the precision of beam delivery.	Most probably CT, and PCRT, detectability depends on sample geometry and size PCRT
Cracking[C]	both	AM PBF failure to completely clean one alloy powder from the build environment prior to processing another, DED large assemblies extensive solidification stresses present within large buildups, There is a host of metallurgical issues associated with crack susceptibility. Extremely large range of potential thermal and mechanical conditions present, across all AM processes, that may lead to cracking are poorly characterized.	Depending on sample geometry and size of crack may be detected using CT/PCRT/ECT/RT/UT
Reduced mechanical properties	both	New powder out of spec or degraded through reuse, poorly developed/controlled process, interruption of feedstock supply.	Check powder (x-ray diffraction) at end of process and mechanical properties of finished part, PCRT individual frequencies may correlate also.
Poor accuracy	both	Scaling/offset factors are effected by part geometry , beam intensity and the density of the powder bed or SLM –scan head/optics problems EBM – presence of EMF interference. build platform shift.	Usually easy (visually) as part has step on surface but localized defects may require laser CMM and internal deviations with CT compared to CAD or possibly PCRT compared to the model.
Inclusions	both	Debris from AM or post processing equipment.	Depends on the nature of the contamination and complexity of part, some inclusions are detectable using UT/PCRT/RT/CT
Residual stress/warpage	both	Poor selection of parameters.	Usually easy (visually) as part has step on surface but localized defects may require laser CMM and internal deviations with CT compared to CAD possibly PCRT compared to the model.
Stop/start flaws[D]	both	Consequence of long builds or interruption of feedstock leading reduced mechanical properties.	Check mechanical properties of finished part, PCRT individual frequencies may correlate also.
Surface flaws	both	Includes partially fused powder, linear or planar conditions or irregularities. Similar to spatter, undercut, irregular top bead, ropey bead, and slumping noted for welded parts.	PT, MET
Trapped powder	Unique to PBF[E]	…	Most probably, CT or PCRT detectability depends on sample geometry and part size.

[A] Abbreviations used: ··· = unknown or not applicable, AM = additive manufacturing, CAD = computer aided design, CMM = coordinate measuring machine, CT = computed tomography, DED = directed energy deposition, EBM = electron beam melting, ECT = eddy current testing, EMF = electromagnetic frequency, HIP = hot isotatic pressing, LOF = lack of fusion, MET = optical metrology, PBF = powder bed fusion, PCRT = process compenated resonce testing, PT = penetrant testing, RT = radiographic testing, SLM = selective laser melting, UT = ultrasonic testing.

[B] discontinuities that are not necessarily rejectable.

[C] due to rapidly quenching which may also lead to metastable or nonequilibrium morphologies.

[D] issue during long builds.

[E] ISO TC 261 JG59, Additive manufacturing – General principles – Nondestructive evaluation of additive manufactured products, under development.

It is helpful to elaborate on the defects, including typical causes, detection, and ramifications.

3.1 Porosity

Classic porosity as understood in metals is usually the result of processing steps that allow trapping or agglomeration of gas, either from the liquid state prior to solidification, or migration in the solid state. Pores can also be created by multi-phase solids progressing through volumetric phase changes, or through some deformation processes.

Pores have a direct impact on bulk properties such as elasticity, toughness, ductility, and overall compressive or tensile strength. In AM, pores are most often the result of raw material or processing parameter selection, either of which (or their interaction) can lead to pores whose geometry varies across the spectrum from uniformly spherical (bubbles) to incredibly complex (rough, jagged.)

3.2 Voids

While fundamentally similar to porosity, voids are generally much larger in scale, or are the result of a lack of material present, as opposed to a displacement of material. The “lack of material” argument seems arbitrary, but is critical in that voids in this context are usually artefacts of a machine or process setting (one of the many adjustable parameters) which allow raw material to fail to fill a space.

3.3 Layer / Cross-Layer Defects

A number of AM methods involve defined layers in their build up processes. Situations may arise where a deposition tool may “drag” particulate, through mechanisms such as static attraction, contamination, or agglomeration of deposited material. This may not only affect the deposition layer, but may impact layers below and above the current deposition layer. Again, the layer defects may affect the energy deposition possible with beam systems, as density, voiding, and other bulk parameters of beam dynamics will be affected.

3.4 Under-Melted / Under-Consolidated Raw Material

Dynamic beam parameters (primarily beam energy and rate of travel) determine the amount of melting and consolidation that occur in the product material. Higher energy flux is required for higher raster rates, while a slower raster rate will allow a lower energy flux to be used (as illustrated in Figure 1), although the net amount of energy input may be the same. The base raw (input) material and its ability to absorb and transfer input energy must also be considered and compared to established thermal processing techniques. Many energetic materials are not only sensitive to thermal energy in general and can react chemically, but can also have widely varying thermal conductivity and capacity. In cases where it is desired to create a final product whose composition varies with geometry, one can see immediately the difficulty in planning AM deposition parameters that also vary during the build.

3.5 Cracking

The main driver for cracking in AM parts is residual stress and strain created during the drastically localized and extremely fast heating, together with very fast cooling, which are typical of many AM methods. The community, particularly in the aerospace fields, are quickly adapting methods to control residual stress and strain, as well as NDT techniques to detect them.

3.6 Surface Finish

A topic that many researchers are starting to note is that final surfaces obtained with AM are not behaving in the same manner as their raw, legacy material counterparts. A prime example of this is work on stainless steels that has shown that the powder-based AM processes with their multiple melting and re-melting steps, creates surfaces that do not form the protective chromium oxide coatings of traditional stainless steel alloys. Additionally, the surface roughness inherent to the powder fusion processes creates micro-morphology that behaves very differently in corrosive environments.

4.0 THE AM IMPLEMENTATION CHALLENGE

One of the most exciting applications for AM is to create limited-run parts that were previously made with traditional manufacturing methods. The legacy part can no longer be fabricated as it was before, usually because it was manufactured on a massive scale by a technique that is only cost-effective when making thousands or hundreds of thousands of parts. This is particularly applicable to military systems still in use that are no longer in production, but the stockpile of spare parts has been exhausted.

In this case, it is desirous to create a “drop-in” replacement for the legacy part using AM. However, the traditional qualification and certification process for parts in the aerospace community (and not too different in the munitions design space), is driven by statistical analysis, process controls, final inspection, and routine inspection during service [7].

AM presents a host of issues, including:

- a continually variable, local processing environment, that is dependent on changes in local geometry and can affect process parameters;
- raw materials whose fundamental properties/composition/microstructure may be unknown when processed with AM methods (i.e., these materials may have decades of knowledge surrounding their use, of which most must be re-discovered when used in AM);
- a fundamental lack of constrained process controls (AM’s flexibility is a disadvantage in production of critical parts);
- stochastic formation of parts whose geometry and internal volumes are inherently difficult to inspect (AM’s ability to create parts that can’t be created with traditional methods, means that these parts also do not lend themselves to traditional inspection techniques);
- residual stress, strain, and distortion created during the deposition process (often including multiple melting and re-melting cycles)
- undefined post-processing procedures to ensure properties desired for service life.

The variability in AM occurs on many levels. It can be within one build (location dependent), between multiple builds on the same machine with the same settings or across multiple builds on the same machine with varied settings, between different machines from the same manufacturer, and across similar machines (intended to be the same) from different manufacturers. This variability is definitely not quantified at the present time, and is arguably unquantifiable in the near future at reasonable expense of time and resources.

5.0 UNDERSTANDING THE PROCESS-STRUCTURE-PROPERTIES-PERFORMANCE RELATIONSHIP AS IT APPLIES TO AM

The relationship and interdependence of processing, structure, properties, and performance are fundamental tenets of materials science and engineering. The overarching concept is that processing dictates the structure of the material, the material’s structure is what controls material properties, and the material properties are what enable an intentionally-designed performance of a finished engineering product. These relationships enable intelligent control and optimization of materials for specific applications [8].

There is a general lack of understanding in the AM design space of these inter-relations, as the inherent flexibility of AM methods tends to create a multi-variant problem. One should keep in mind that the vast understanding of traditional metallurgy and subsequent effects on fatigue and fracture behaviour were largely arrived at through decades (sometimes centuries) of Edisonian trial-and-error experimentation. The multitude of processing parameters available in AM and the subsequent variability in structure and properties have already become the subject of significant research in materials science, Sames, et al for example [9].

Using anisotropy as one example, Hrabe, et al [10], emphasized the importance of understanding the processing conditions that lead to anisotropy, in addition to characterizing the effect that anisotropy has on properties of interest such as fatigue and fracture. Quoting from the NIST/ASTM workshop findings report:

> *“Crystallographic microstructure includes phase composition, grain size and shape, and dislocations. Internal defects include inclusions and porosity, and the morphology of both types of defects is important to characterize as (to) the magnitude of effect on fatigue and fracture properties.”*

The workshop participants also identified some of the current deficiencies in understanding defects, when the formation mechanisms of those defects aren’t yet understood. Powder-bed fusion methods provide a good example, where pores can contain void space, partially melted particles, and all manner of surface morphologies. These may be due to powder packing inefficiencies and/or under-melting from non-optimized beam energy or travel speed. A possible solution to improve packing efficiency would be to include multi-model particle size powders, but the effect of these variable-sized particles on the other processes such as raking, sieving, and beam/energy penetration is yet to be characterized.

In bulk energetic fills, defects on the surface (crack in a propellant grain) as opposed to near- or non-near-surface internal defects will cause unpredictable changes in burn rate, pressure, and possibly failure. In AM composites, near-surface defects should be distinguished from non-near surface defects, with bias toward their eventual mechanical and energetic failure modes. External defects can include incomplete bonding material injection, under-melted or under catalyzed matrix binder materials, and possibly loose particles trapped in tortuous concave surface features.

A topic that has gotten significant interest in the energetic materials community is the suitability of raw materials for use in AM. The metal alloys of choice as feedstock for powder methods are low-carbon austenitic 316L stainless steel (with chromium and vanadium,) the Ti-6Al-4V titanium alloy, and a variety of general purpose aluminium alloys and high-temperature special purpose austenitic nickel-chrome super alloys. 316L and Ti-6Al-4V have excellent corrosion resistance, strength, and ductility, while the aluminium is incredibly versatile and capable of very thin parts. The most common polymers are acrylonitrile butadiene styrene (ABS), polylactide (PLA), nylon, polycarbonate (PC), and polyvinyl alcohol (PVA).

Attributes used to choose materials as fit for purpose will be different for AM than for conventional processes. The ability to withstand the energy input flux rates of the various techniques, as seen in Figure 1, and to respond well to the rapid melting, solidification, and remelting (multiple times) required in some AM processes, as seen in Figure 2, will be a determining factor. Many of the metals and polymers in current use are chosen due to availability and versatility, as opposed to specific finished bulk characteristics, and are not necessarily optimized for AM [4]. Many exhibit defects and anisotropy in AM processes, and some of these are novel types heretofore unseen.

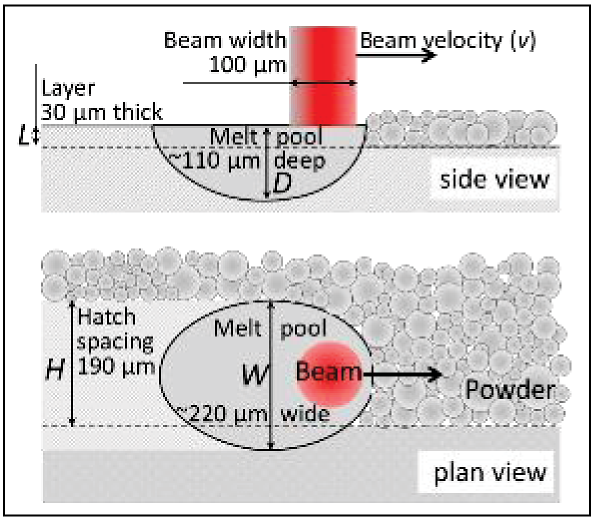


Figure 1. Typical melt pool geometry for a powder bed fusion AM process, from work by C. Pistorius & M. Tang, Carnegie Mellon University [4].

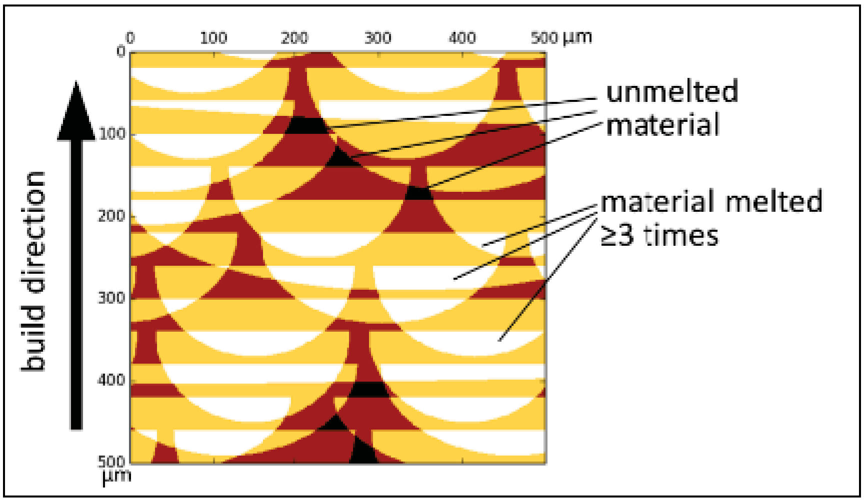


Figure 2. Graphical representation of melt pool overlap across layers,
from work by C. Pistorius & M. Tang, Carnegie Mellon University [4].

Many energetic materials, especially composite propellants, are highly solids-loaded with a relatively small amount of binder matrix. Understanding how these non-optimized composites (at least in terms of structural and mixing characteristics) behave will require research.

Materials for use in AM are evolving, and the trend will continue as applications and experience grows. An area of improvement in the coming years will be the development of industrial or national material standard specifications and characterization tests that will assist in classifying raw materials specifically for use in AM.

6.0 CONCLUSIONS

Current work in the aerospace industry to address the qualification and certification of critical parts in airframe and engine applications made with AM, closely mirrors the efforts being pursued in the munitions community. The aerospace community is further along the path of discovery and is primarily focused on metal alloy parts. Munitions efforts are looking at various polymer materials and metals, although the propensity of high-solids-loaded polymer matrix composite energetic materials will be a unique challenge.

NATO’s Munitions Safety Information Analysis Center is reviewing the types of materials currently being used in additive manufacturing (AM) technology, the resultant material properties achieved, and the main issues that will face munitions science in utilizing these AM-created materials. This review, expected to be published in Summer 2018, will describe the key issues, provide a comparison of the materials possible, and assist practitioners who plan to employ AM in the munitions design space.

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