ADVANCED MUNITIONS: 3D PRINTED FIREPOWER

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***Abstract*—3D printing or Additive manufacture is increasingly recognised as a technology of strategic importance to Defence organisations. In the weapons context, much of the focus to date has concentrated on the production of inert componentry. However, we foresee that 3D printing of energetic materials - such as propellants, pyrotechnics, and explosives - will also provide significant weapon performance, logistics, industrial and strategic advantages in the future. The Defence Science and Technology Group has initiated a Transformative Energetics research programme to advance these goals.**

This paper describes research underway at the Defence Science and Technology Group to develop 3D printing manufacturing processes for energetic materials, and to design and optimise new gun propelling charges which fully exploit the flexibility of this manufacturing method.

Keywords—additive manufacturing; 3D printing; gun propellant; interior ballistic modelling

I. INTRODUCTION

The majority of most modern gun propellants are made using essentially the same ingredients and methods devised in the late nineteenth and early twentieth century. The manufactured form of a propellant is referred to as a grain, with most gun propellant grains being produced as solid pellet, stick, flake, or ball geometries. The ballistic performance, mechanical strength, ignitability, and achievable packing density of a propellant all depend, in part, on the geometric grain form.

Large caliber and high performance guns typically use grains of a perforated cylindrical pellet or stick form, which are manufactured by extruding wet propellant through a die and then cutting and drying or curing. Thus for the last century the design of practical high-performance gun propellants has largely been constrained to extrudable grain geometries of constant cross-section. Increases in the complexity of propellant geometry may be possible with conventional methods, however this would be accompanied by greater manufacturing cost and plant requirements, and reduces the ability for required high production volumes. The application of 3D printed methods to propellant production, however, presents an opportunity to remove these constraints and considerably widens the possibilities for future propellant design and corresponding enhancements in ballistic performance. Analogous advantages for rocket propellants, and application to explosives and pyrotechnic manufacture are also easily foreseeable.

Preliminary modelling work described in this paper shows that significant muzzle velocity increase (and therefore range) can be derived by moving to a 3D printed grain form. Depending on design intent other types of performance benefits might instead be achieved, such as: reduced chamber pressures, leading to correspondingly lighter barrels; reduced barrel erosion and increased barrel life; and increased precision by reducing shot-to-shot variation in muzzle velocity.

The development of propellant 3D printing might also provide significant and strategic benefits beyond ballistic performance. The capital cost of conventional propellant manufacturing plants is high: the Australian Government has recently invested hundreds of millions of dollars in modernizing its Mulwala propellant plant, for example. This level of investment is generally prohibitive for small and medium enterprise, however we expect 3D printing methods will eventually offer a much lower cost of plant establishment and be better suited for smaller production runs of specialized ordnance. Besides the potential economic benefits, a stronger and more agile Australian industry base would offer Defence increased warstock security and may confer savings through reduced stockpile quantity requirements. The concept of 'print on demand' energetics, in-theatre or on-board military platforms, also has the potential to relieve logistics pressures, increase flexibility, and avoid capability-gaps during operational activity.

This paper describes research underway at the Defence Science and Technology (DST) Group to these ends. Our research covers two main themes which are being pursued concurrently: (1) To design and optimise new propelling charges which fully exploit the flexibility of this manufacturing method, and (2) to assess the utility of, and subsequently demonstrate, 3D printing processes for energetic materials, starting with gun propellants.

II. BALLISTICS RESEARCH

A simple gun system shown in Figure 1 comprises a projectile, barrel, igniter and propelling charge.

Once ignited, the propellant in the chamber starts to combust, producing high temperature (2000 - 3500 K) gaseous reaction products thereby increasing the chamber pressure behind the projectile. In the space of a few milliseconds, the chamber pressure becomes sufficient to overcome the projectile starting resistance, and the projectile commences travel down the barrel.

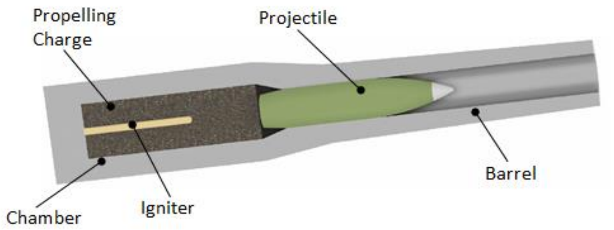

Figure 1 Simple Gun System

As the projectile travels, the chamber and barrel volume occupied by the gaseous products and solid propellant increases. Early in the ballistic cycle, the rate of gas production and energy release typically exceeds the work done on the projectile and the increase in free volume, leading to a net pressure increase. As the projectile accelerates, however, the latter processes dominate and the pressure behind the projectile starts to reduce, as depicted in curve A of Figure 2. Eventually, the projectile exits the muzzle and the interior ballistics process is complete.

A faster muzzle velocity can be achieved by holding the chamber pressure higher for longer, subject to permissible barrel and projectile pressure limits. In practice, this can be achieved by using a propelling charge which is tailored to progressively increase its rate of gas generation towards the end of the ballistic cycle, to counter the depressurization which occurs when the projectile is quickly exposing free barrel volume (curve B in Figure 2). For a given propellant burning rate, the gas generation rate is proportional to the total exposed burning surface area of the propellant grain at any instant, and thus a progressive charge must employ progressive propellant grain geometry configurations which increase in surface area as combustion progresses.

Commonly-used extrudable, progressive grains include 7- and 19-perforated cylinders and rosettes as depicted in Figure 3. Alternatively, if increased muzzle velocity is not a design priority, then a flatter, broader pressure-time curve can still be employed to achieve comparable muzzle velocity performance with a lower peak pressure, thus reducing barrel strength requirements (curve C in Figure 2).

In addition to barrel pressure limits, the propelling charge design must satisfy some additional constraints. These include ensuring complete propellant combustion prior to projectile exit; minimizing muzzle blast and flash; retaining mechanical integrity through the entire ballistics cycle; providing uniform ignition to promote consistent performance; minimizing recoil; and achieving a compact packing density which accommodates sufficient charge weight. Classes of new, non-extrudable grain geometries achievable through 3D printing may better address each of these design constraints, although not necessarily simultaneously.

Based upon the performance of existing grain forms, new propellant geometries are being proposed that may offer better performance. These geometries and their regression are then described through analytical equations and used as inputs into an interior ballistic model that also accounts for propellant thermochemistry to determine their performance.

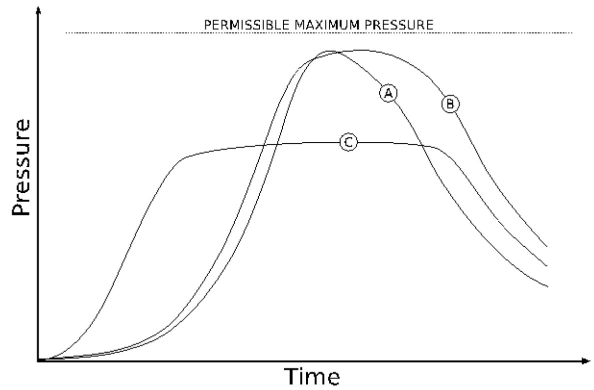

Figure 2. Pressure-time curves for (A) a typical large calibre gun; (B) a more progressive propelling charge providing higher muzzle velocity; and (C) a progressive charge with low peak pressure.

III. Interior Ballistic Modelling

To demonstrate the levels of performance gain achievable, a number of new 3D printed candidate geometries (not described here) were tested using an interior ballistics model.

A lumped parameter interior ballistic model developed in the C programming language [1] was used to perform this analysis. A lumped parameter model is based on a set of equations derived from a conservation of energy and mass analysis of the system. These equations take a number of input parameters describing the gun, projectile, and propellant (including geometry) and are solved in a time marching fashion. The resulting output provides internal projectile trajectories (velocity, acceleration etc.) along with internal propellant gas temperature and pressure histories. The code was specifically developed to be fast running, and thus well-suited to allow for parametric optimization to be conducted in order to optimise the dimensions of the proposed propellant grains.

The proposed 3D printed candidate geometries were compared against a baseline case of a conventional 7-perforated cylindrical grain. This baseline case has been well validated previously and represents a gun system with conventionally manufactured propellant that produces high performance [2]. The resulting muzzle velocities and barrel pressures are summarized in Table 1. Pressure-time curves are also shown in Figure 4 with more detail described in [3].

The Equal Propellant Mass case, represents a 3D printed candidate propellant with the same overall mass optimised to provide a maximum muzzle velocity, whilst not exceeding the barrel pressure of the Baseline case. The resultant muzzle velocity for this geometry is 743 m/s, which represents approximately a 10% increase over the Baseline.

Figure 3. Conventional extruded propellant grain geometries, from left to right: 7-perforated cylinder; 7-perforated rosette; and 19-perforated cylinder.

TABLE 1. SUMMARY OF BARREL PRESSURE AND MUZZLE VELOCITY FOR THE FOUR PROPELLANT TYPES

Type	Test Case	Propellant Mass (kg)	Max. Peak Pressure (MPa)	Muzzle Velocity (m/s)
Conventional Extruded	**Baseline**	9.53	360	677
3D Printed	**Equal Propellant Mass**	9.53	360	743 **(+10%)**
	Equal Fill Volume	14.69 **(+54%)**	360	830 **(+23%)**
	Equal Muzzle Velocity	9.81	233 **(-35%)**	677

The Equal Fill Volume case shows the result from exploiting the higher loading density of a proposed 3D printed grain geometry, and filling the chamber with a greater mass of propellant (whilst keeping the overall fill volume the same). In this case the mass of propellant in the chamber has been increased from 9.53 kg to 14.69 kg, resulting in muzzle velocity increase of 830 m/s or 22.5% over the base line case. This is in addition to keeping the overall peak barrel pressure the same as in the Baseline case.

The Equal Muzzle Velocity case presents an alternative interpretation of performance increase, where a 3D printed candidate propellant was tuned to retain the Baseline muzzle velocity whilst minimizing the chamber pressure. A lower barrel pressure can lead to either increased barrel life due to reduced wear, or allow for development of a lighter barrel and hence a lighter overall gun system. In this instance it was possible to reduce the barrel pressure to 233 MPa, or a reduction of 35% in pressure from the Baseline case. Also of note, a reduction in barrel internal pressure will also correspond to a similar reduction in peak acceleration of the projectile. This 'soft launch' condition will lower inertial forces on the projectile and internal components, and will allow easier deployment or greater survivability of sensitive electronic-containing 'smart munitions' or projectiles.

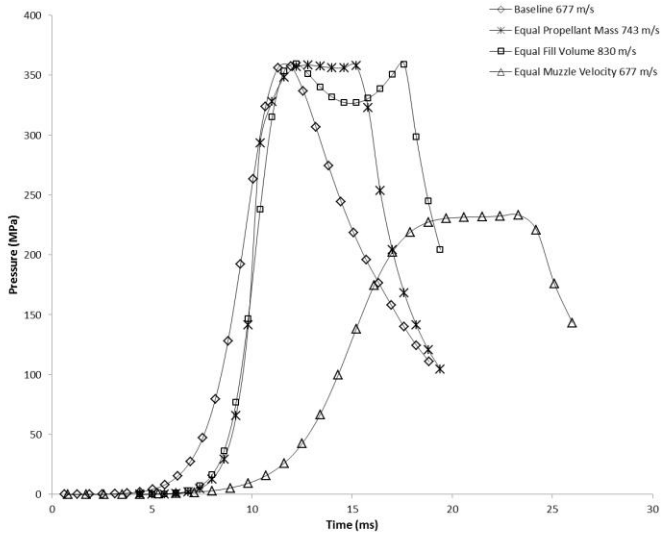

Figure 4. Pressure Time curves as predicted by interior ballistic model for four propellant types.

IV. MANUFACTURE RESEARCH

To fully exploit the potential benefits associated with the use of 3D printing to produce propellant geometries unachievable with traditional manufacturing techniques, any propellant formulation to be used as printer feedstock needs to be compatible with the intended printer type.

There are seven broad classes of additive manufacturing (3D printing) technology [4]. Some of these technologies (i.e. selective laser sintering and directed energy deposition) are ill-suited for use with energetic materials owing either to the energy that they impart to the printer feedstock, or due to the type of feedstock employed by the printer. For the potentially viable printing techniques that remain each has its pro's, cons and limitations from the perspective of: process safety; process robustness; scalability and; printer flexibility, including ease of production of multi-material structures. The degree of printer suitability, in turn, varies depending on the class of energetic material in question and the intended application of the munition in which the 3D printed energetic material is employed.

For the energetic material applications of interest for this work, on grounds of energy density and performance, it is necessary to incorporate a high proportion of energetic material solids into the printer feedstock with solids loading levels in excess of 60% v/v (75-85% w/w) being a typical requirement. This poses a number of printing challenges in terms of the ability to reproduce and safely print highly solids-loaded structures that have adequate print precision, print homogeneity from a compositional stand-point, and structural integrity such that they can reliably fulfil the necessary operational requirements. From the foregoing, it can be concluded that 3D printing at the charge level will require implementation of a hybrid printing process where different printing techniques are employed to produce different sub-components of a charge system.

A number of printing techniques also employ materials that, to date would be considered atypical in the energetic materials community, such as photosensitive resins as used in UV curable 3D printed systems. This will necessitate a rigorous evaluation of the physicochemical degradation mechanisms of energetic material formulations containing such materials as it may affect the long term safety and suitability for service of munitions based on these chemical constituents and manufactured using 3D printing techniques.

In conjunction with collaborative partners in industry and academia, both in-country and overseas, and also with international Government Defence Agencies, DST is undertaking research to assess the utility of potentially viable printing technologies for energetic material manufacture with a focus on the aforementioned considerations. DST's research is centred on UV paste extrusion and Digital Light Projection printing techniques. To progress this research, commercial-off-the-shelf Hyrel 30M and Gizimate 130 Basic printers which have undergone extensive in-house hardware and software modification to confer improved process control and safety are being employed.

Allied to the above, DST and its partners are undertaking research programs into: resonant acoustic mixing as a novel processing technology to enable the effective and efficient mixing of highly viscous materials, including in-situ in 3D printer syringes and vats; and also the production and use of polymer coated nanometric scale energetic materials for improved performance and safety. The incorporation of such materials into 3D printed propelling charges is of particular interest as it affords additional flexibility to the propellant developer in controlling the surface chemistry of the solid filler material and its interaction with the printer feedstock resin. In turn, this can assist in mitigating a range of rheological, mechanical and chemical compatibility challenges likely to be encountered with the 3D printing of energetic materials. This is addressed in further detail in [3].

V. Conclusion

This paper has described the Defence Science & Technology Group's ongoing research into the development of 3D printing for energetic materials, with an initial focus on gun propellant.

Our initial modelling work has shown that 3D-printable gun propellant geometries can offer significant performance and logistical advantages, when compared to conventionally-manufactured propellant grains. Several candidate geometries for 3D printing have been developed and optimised, with interior ballistics simulation results indicating that substantially increased muzzle velocities (or reduced barrel pressures) are achievable. Ballistics research will continue along these paths in the pursuit of generating an expanded library of candidate geometries that offers greater performance.

In conjunction with collaborative research partners, the manufacturing research stream is assessing the utility of 3D printing techniques of potential relevance for energetic material system production. Outcomes from this work will enable the feasibility, and limitations associated with the production, of the optimised propelling charge geometries across the candidate 3D printing techniques to be determined. Should feasibility be demonstrated, this will serve as a precursor to the 3D printing and subsequent characterisation of the affected propelling charges.

References

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