Additive Manufacturing of Tactical Solid Rocket Engines

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Abstract
During a conflict, to be successful, it is imperative to quickly adapt to the changing battlefield or battle space. This requires forces and equipment to rapidly adapt for mission success. The philosophy of adaptation also applies to readying armed forces during times of peace. The manufacturing of weapons, supplies, and equipment must adapt to changing quantity requirements, supply chain disruptions, and mission changes to ensure the forces are prepared for war.

The manufacturing of tactical solid rocket motors has changed little over the years. From the formulas used in the propellant, to how the motors are manufactured, the process has been petrified, which can lead to failure in an ever-changing world. The process needs to be redesigned with greater flexibility and the ability to adapt to changes quickly, without disruption to order fulfillment. The ability to use off-the-shelf (OTS) binders, in an additive manufacturing system, would increase supply chain robustness, decrease manufacturing time, and provide greater flexibility for changes in demand.

Orbital Construction Pioneers, Inc (OCP), using the knowledge gained during the development of Stellamer, has been testing various OTS binders for suitability in solid rocket motors, and adaptability to an additive manufacturing process. This paper explains what we have discovered and provides a plan for future investigations.

Introduction
Orbital Construction Pioneers (OCP), a Texas corporation built on the foundation of Christ, is developing an expertise in additive manufacturing using multipart polymers and silicones. Our focus has been the construction of large space structures [1] but our expertise can also be applied to tactical solid rocket motors.

Solid Rocket Engines (SRE), also known as Solid Rocket Motors (SRM), are used in many different applications. From boosting the Space Shuttle off the launch pad to smaller motors in tactical missiles. [2] All SRMs share a basic structure and components.

The base SRM consists of the grain (propellant), a case (combustion chamber), insulating liner, nozzle, and an igniter. [3] Each component requires substantial manufacturing in separate processes that are time intensive. In a typical manufacturing process the nozzle, case, and end cap (igniter holder) are machined from metal and / or carbon fiber. The liner is affixed to the inside of the case and the grain, which has been mixed at an elevated temperature, is poured into the case. After the grain has cooled and solidified, the nozzle and end cap are installed. Each step is labor and time intensive and, in many cases, done at different locations; potentially susceptible to supply disruptions.

A modern SRM is a finely tuned instrument. Each part is calculated to get the maximum performance with a low probability of a catastrophic failure. The design of each component, including the formulation of the grain, is dependent on the design of the others. The rigid manufacturing process creates the SRM components to strict tolerances per the design. Any change in the design requires a new, or (highly) modified, manufacturing process, limiting the ability of the system to accept material substitutions. It can take years to develop / implement a new manufacturing process to accommodate any changes to the SRM design.

The goal is to make the manufacturing process of SRMs robust and flexible. Additive manufacturing has the potential to quickly change a process in response to design or supply chain changes. By using OTS components, limiting and / or eliminating traditional machining, and using a high degree of automation, it is postulated that old and new SRM designs could be manufactured in days as opposed to weeks or months.

Candy Engines

OCP has developed various processes for the 3D printing of polymers, silicones, and various other non-traditional material mixes. However, none of this experience was in the use of energetic materials such as rocket propellant, therefore, it was decided for safety, to manufacture "candy engines" as a proof-of-concept.

Candy engines use a mixture of oxidizer and sugar and, after burning out, leave a sweet, candy-like smell. Amateur model rocketeers have been safely producing this type of propellant for decades in kitchens across the globe using basic safety practices to prevent premature ignition. For the proof-of-concept experiments, OCP used Potassium Nitrate (KNO^3) as the oxidizer and ground table sugar combined with OTS binders.

The experiments had two objectives:

1. Prove or disprove that an additive manufacturing system could print rocket engine grain and,
2. That binders with different chemistries can be swapped.

We used two different binders for our experiments, a silicone based and a polymer based binder.

Steps

The program was done in systematic steps to ensure safety and repeatability.

1. Mix a small amount of binder and rocket propellant, allow it to cure, and observe if it will ignite.
2. Attempt to extrude the mixture from step 1 through a nozzle to determine its compatibility with 3D printing.
3. Use the mix in a small mold in the shape of a hollow tube and evaluate its performance after ignition.
4. 3D print a small hollow tube on a modified printer, or by hand extrusion, and compare its performance to the molded version.

For step 1, we used a silicone binder provided to us by Momentive Performance Materials which was, and still is, used for the development of Stellamer. While the donated binder is an excellent choice for Stellamer, it was not an ideal substance for a rocket engine. The binder is fire-resistant, slowing the propagation of flame. The result was lower thrust, and the test items were difficult to ignite. Initially we used a propane torch to ignite the propellant but, as the test sample size grew, safety required us to develop a remote ignition method. Considerable effort was expended in developing an electrically activated igniter that would produce sufficient heat and pressure to consistently ignite the test samples.

After much trial and error, we have named the chemical mixture used for the igniters Ocimite. The igniters can be sized according to the engine requirements and use a 12V DC system. Future development will make the igniters waterproof and resistant to impacts.

Silicone hand printed

Observed during Step 1, the ignition of the small quantity resulted in jets of flame and total consumption of the propellant. The mixture used a minimal amount of binder to increase the thrust and ignition capabilities of the test sample but was not easily extruded.

Step 4 firing test

In step 2, we added additional binder to increase the flowability of the material, making it hand extrudable from a syringe. The consumption observed after ignition was slower compared to the sample with less binder.

For step 3, a small plastic double-shot glass was used as a mold. A hole was drilled halfway through the sample, after it cured, to provide a port for the igniter. The sample ignited and was consumed completely.

Step 4 involved hand extruding the silicone material using a syringe and a Lazy Susan. The resulting tube had a diameter of 40 cm, a length of 50 cm, and a hollow core diameter of approximately 20 cm. Ignition resulted in a 30 cm to 40 cm jet of flame and a run time of approximately 30 to 40 seconds.

Change of Binder

For the manufacturing of tactical solid rocket motors to be resistant to supply disruptions, it must be able to handle substitutions of base chemicals / parts. Using OCP corporate knowledge, a polymer based binder was selected for the next series of experiments which had a better flame propagation characteristic than the silicone based binder.

Polymer hand printer cylinder

The ignition of a small amount for step 1 resulted in an energetic, but controlled, consumption of the propellant. The observed reaction was greater than what was observed with the silicone based binder.

Steps 2 and 4 were combined and step 3 was eliminated for expedience, due to the experience gained from silicone based binder testing. The resulting hand extruded cylinder was shorter, than the silicone version at 32 cm, and had a larger diameter at 54 cm. The variation is due to the inexact nature of hand extrusion of a circle.

Ignition of the hand printed cylinder resulted in flame propagating over the edge and down the sides, consuming the entire structure quickly and without directional thrust.

2nd print

Modified printer

Hand extrusion proved that binders with different chemistry can be used in an additive manufacturing system, but to emphasize the point, we used an Creality Ender 3 consumer grade printer and modified it to use multi-part polymer as the printing material. The material extrusion system of the printer was replaced with an in-house developed mechanism that could be controlled independent of the printer controls.

The first print resulted in a tube approximately 24 mm in diameter and 45 mm in height. The print was inconsistent and had voids between the layers. The second print resulted in a tighter structure with no voids between the layers. The diameter was approximately 24 mm with a height of 50 mm. This proved that the material was printable using a mechanical printer.

Both printed cores ignited and burnt energetically.

Next Steps

1. Consult with binder manufacturers to determine a product more suitable for the application. The binder must be printable and have good flame propagation.
2. Determine the best material for use in the additive manufacturing process for the case, thermal layer, nozzle, and cap.
3. Develop a specialized printer that can manufacture a complete SRM.

Conclusions

We were able to prove that by using OTS binders, additive manufacturing can be used to create SRM grain. We also proved that the process could work even with alternative binder chemistries. Further research is required, but these experiments show that additive manufacturing tactical rocket motors is not only possible but can also use OTS materials and be tolerant of supply chain variations, substitutions, and disruptions. It is possible that a trailer-based manufacturing system could be mobilized to anywhere in the world, be supply chain resilient, and adjust SRM designs, in real time, to meet supply requirements.

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