Solid Propellant Additive Manufacturing (SPAM)

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The traditional method of solid rocket motor manufacturing—casting—is confined to a limited design space. The time required to manufacture and test new grain patterns limits the selection of usable grain shapes and consequently the available thrust profiles. Additive manufacturing is rapid in comparison, which facilitates the manufacturing and testing of multiple grain patterns and enables optimization of solid rocket motors for specific mission profiles. A CO_2 (10.6 micron) laser was used to sinter a powder of sucrose and potassium nitrate in 2mm layers to form a cylindrical solid rocket motor 72mm in height with a diameter of 40mm. The additively manufactured motors will be compared to traditionally casted motors to assess the changes in tensile strength, crush strength, density, and porosity. Current results of the project have produced functioning hardware that is capable of printing a sucrose-potassium nitrate solid rocket motor. Future development will provide calibration for the laser thermal model to increase safety as well as determine the functional differences between 3D printed and traditionally casted motors.

Nomenclature

Albedo	=	Absorption
CONOPS	=	Concept of Operations
C_p	=	Coefficient of Pressure
CPE	=	Critical Project Element
d_{spot}	=	Laser Beam Diameter
ΔT	=	Difference in Temperature
FDM	=	Fused Deposition Modeling
FSL	=	Full Spectrum Laser
ITAR	=	International Traffic in Arms Regulations
KNO_3	=	Potassium Nitrate
$\dot{m}$	=	Mass Flow Rate
PWM	=	Pulse Width Modulation
r_{slew}	=	Laser Slew Rate
SLS	=	Selective Laser Sintering
SPAM	=	Solid Propellant Additive Manufacturing
SRM	=	Solid Rocket Motor

I. Introduction

SOLID rocket motors (SRMs) are used extensively in the field of rocketry due to their low complexity and high thrust. However, controlling that thrust is one of the major challenges in designing SRM. For example, many rockets need to limit thrust during the early stages of launch in order to decrease the acceleration felt by sensitive payload instruments but then increase thrust once out of earth's lower atmosphere. This can present a problem for SRM because there is no way to manually throttle the motors after ignition. They produce thrust by burning a cylinder of propellant with a hollow core (whose shape is called a grain). This hollow cross section changes over time as the propellant burns away, thus changing the surface area that is burning. Due to this, changes in the grain shape of the solid rocket propellant are the only means of altering the motor's thrust profile as shown in Figure 1. Different missions call for different thrust profiles based on their demands, which brings the discussion back to the ability to manufacture many different grains.

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The current technique for manufacturing SRM is the hand casting method which involves pouring melted propellant into a mold and then boring out a grain shape in the center. Each new design must have a mold and shaped boring tool which requires time and cost to manufacture. This Solid Propellant Additive Manufacturing (SPAM) project sponsored by Special Aerospace Services (SAS) aims to develop a 3D printing method that will remove the time consuming and costly process of casting experimental SRM designs and allow for increased flexibility in testing new grain shapes and thrust profiles.

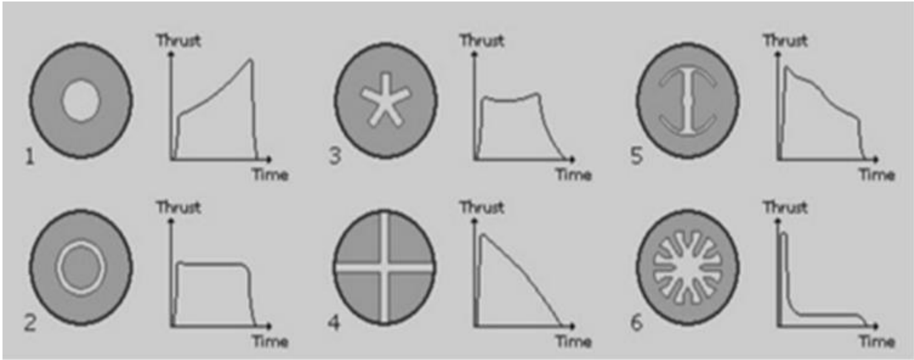

Figure 1. Example grain shapes and their associated thrust profiles[1].

Casting is a common, although rudimentary method that limits engineers to relatively simple grain patterns. The salient advantage of 3D printing is that it permits the ability to quickly design and manufacture more complex grain shapes without the need for new casting molds. Engineers can use this design flexibility to tailor a rocket's thrust profile for a specific mission. Previous work in producing additively manufactured motors has been completed by Stratasys, a 3D printing company, who have successfully printed a hybrid rocket motor. Their design uses Fused Deposition Modeling (FDM) to additively secrete a plastic based fuel from a nozzle layer by layer. However, hybrid rocket motors store their fuel and oxidizer separately, because of this only the fuel is additively manufactured[2]. Project SPAM is novel in the fact that it will be the first recorded attempt to print propellant as a complete fuel and oxidizer mixture.

This project, working under ITAR restrictions, uses a propellant popularized by the film *October Sky* nicknamed 'Rocket Candy'. This propellant is a mixture of sucrose (fuel) and potassium nitrate (oxidizer). The fine powders of both ingredients are mixed and heated until the sugar caramelizes and solidifies with the oxidizer intermixed. While transitioning from powder to a coherent solid, the sugar transitions through a phase of high viscosity liquid (essentially caramel in layman's terms) then cools to a solid within minutes. Due to the granular form of the raw material and the short period in which it remains molten, Stratasys' FDM method for printing would not work for Rocket Candy. In order to overcome this problem, another method of 3D printing called Selective Laser Sintering (SLS) was selected and implemented. SLS uses a laser to partially melt—or sinter—a specific area of powdered material one layer at a time. After each layer cures, a powder bed mechanism transfers a new layer of powder over the previously formed layer to continue the process until completion. The SLS method was determined to be the most feasible for Rocket Candy propellant due to previously successful results in sintering sucrose. The key issues in moving from sintering pure sucrose to a sucrose-potassium nitrate mixture include creating a thermal model for the energy output of the laser and manufacturing a powder bed mechanism that can handle the tolerances needed to form a hobby-sized solid rocket motor. This paper covers these main obstacles in using SLS as an alternative to the traditional casting method by presenting the design objectives and obstacles for the project and its critical elements, discussing the design methodology, and delineating the project results and critical path at the time of writing.

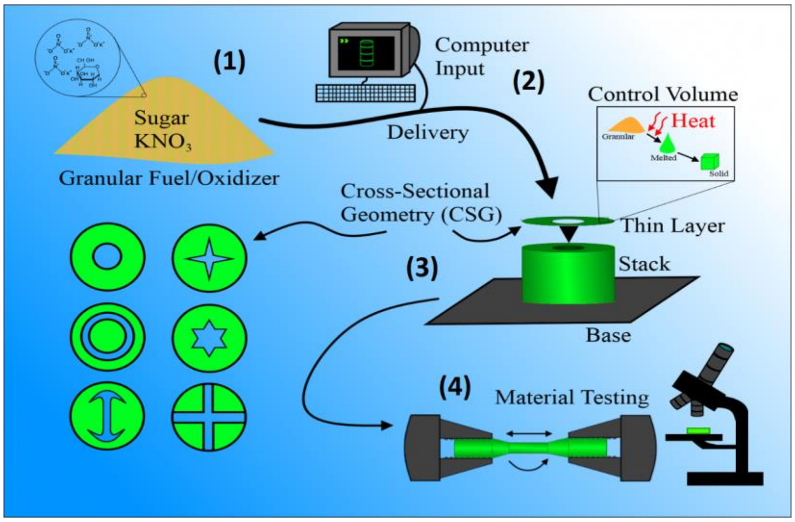

Figure 2. CONOPS for solid propellant additive manufacturing.

II. Design Objectives

A. Concept of Operations

SPAM's objective is to create an SLS printer capable of sintering a sucrose-potassium nitrate propellant mixture. Due to the excessive price of SLS machines, the scope of this project includes the purchase of a standalone laser cutter with the integration of a manufactured powder bed mechanical system into its base. A functional concept of operations is shown in Figure 2 where the process can be broken down into four crucial steps.

First, a powdered mixture of fuel and oxidizer, marked by the **(1)** in Figure 2 will be delivered to the printing location using the manufactured powder bed mechanical system. Meanwhile, a computer-generated file is input by the user to indicate the desired geometry of the printed motor as marked by the **(2)**. Next, a thin layer of propellant is repeatedly added and then sintered to the previous layer, marked by the **(3)**. Thus generating a 3-dimensional geometry composed of many accumulated layers. The final product of this process is a sugar-based, solid rocket motor with a specific grain pattern, and thrust profile, corresponding to user input that will be material tested as marked by the **(4)**.

B. Laser Sintering Thermal Model

Accurately sintering the powdered propellant is the crux of project SPAM. Thoroughly modeling the sintering process provides the essential criteria for meeting the requirements for additively manufacturing solid rocket propellant. The functional requirement related to laser sintering include modeling the heat transfer from the laser in order to melt sucrose between 180°C-185°C at 1 atm. This model accounts for sintering depths up to 2mm to ensure the method will bond each sintered layer to the previous. The error on the estimated sintering depth shall be less than 0.3mm to avoid over sintering and overheating the propellant. Fulfilling these requirements achieves level one success for this project by providing proof of concept for using SLS in manufacturing solid rocket propellant.

C. Powder Bed Mechanical System

In order to print multiple consecutive layers, a mechanical system—referred to as the powder bed—must be manufactured and integrated into the purchased laser cutter. This subsystem has many crucial design requirements to assist in achieving the second level of success proposed for this project. The first design requirement is to provide vertical positioning control to within 0.3mm. This requirement is built on the thermal model sintering depth requirement to ensure that the new layers of powder are not deeper than the sintering depth of the laser. This handles level two success for the project by allowing the team to additively manufacture full 72mm tall and 40mm diameter solid rocket motors. Full automation between the laser cutter and powder bed makes up the second functional requirement for the mechanical system. Automation of the printing process further assists in decreasing the time and effort required to print an SRM compared to the traditional casting method.

D. Material Testing

The next step of the project is to compare an SRM from the additively manufactured method to the hand casted. This comparison verifies and validates the 3D printing system as a viable alternative to the traditional casting method. Material testing includes comparisons of tensile strength, crush strength, and density, between the two manufacturing methods. These measurements will be determined using instruments with 0.005N accuracy or better, and validation of the SLS method will be proven if the results are within 30% of each other.

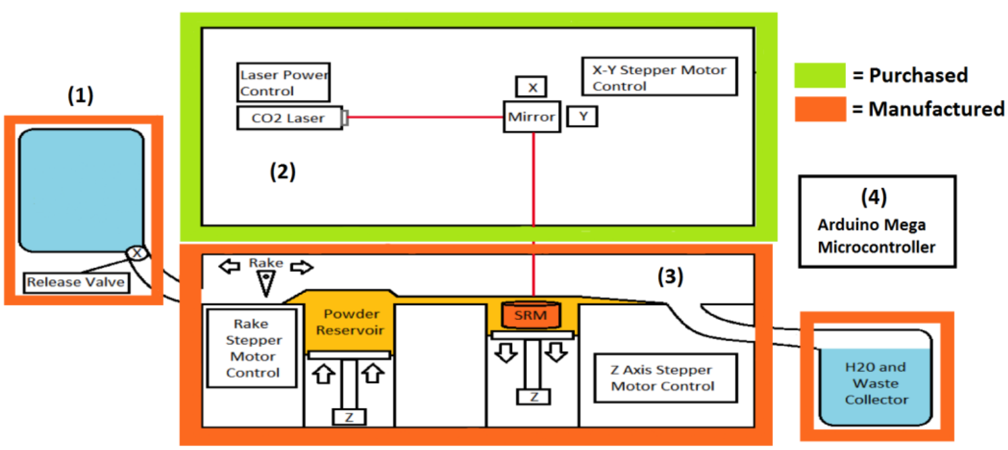

Figure 3. Purchased and manufactured components of the full system.

E. Advanced Printing

Project SPAM will achieve the final goal and level three success if it successfully prints all six grain shapes from Figure 1 with deformities of less than 5%. This will indicate that additive manufacturing of an SRM is not only a viable option, but possibly a replacement for the production of motors with advanced and complicated grains.

The laser sintering thermal model, the mechanical powder bed integration, and the material testing form the three Critical Project Elements (CPE) for reaching all levels of success in this project. The method for implementing these subsystems and test results are further detailed in the Design Methodology sections of this paper.

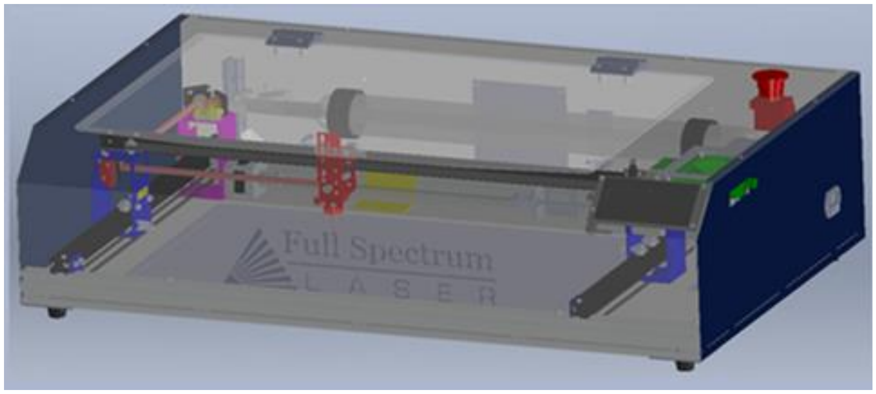

Figure 4. Laser cutter purchased from FSL with color coded components: pink power supply, blue linear rails, red lens (center), green electronics, and red emergency shutdown button (top right).

III. Design Methodology

This design includes four major subsystems that must be integrated together to produce an SLS printer. Figure 3 shows a high level overview of each subsystem including a manufactured water safety system **(1)**, a purchased CO2 laser cutter **(2)**, a manufactured powder bed system **(3)**, and a software and electronics integration system **(4)**.

The FSL laser cutter works by shooting a high-powered 40Watt CO_2 laser off of two mirrors directly into a focusing lens. This lens focuses the laser into a narrow beam that can then cut or engrave a stationary material. The positioning of the lens is accurately controlled by the linear rails mounted along the length and width of the laser cutter. The FSL laser cutter is shown in Figure 4 with the mounted lens colored in red, the linear rails colored in blue, and the electrical components colored in green.

In order to create an SLS machine, a powder bed was added underneath the laser cutter to provide the necessary Z-axis control. The removal of the base plate inside the FSL laser cutter allowed for the integration of the powder bed. As shown in Figure 5, the powder bed system has three moving parts. The sintering region and reservoir contain the excess powdered solid rocket propellant. These components move 1.5mm and 2.0mm respectively at the start of each cycle to provide at least 133% of the needed material that must cover the print area since some powder may be lost while in transport to the sintering region. A rake then waits until both reservoirs have been displaced and slides across the surface pushing the powder raised by the reservoir piston onto the sintering region. Excess powder falls harmlessly into

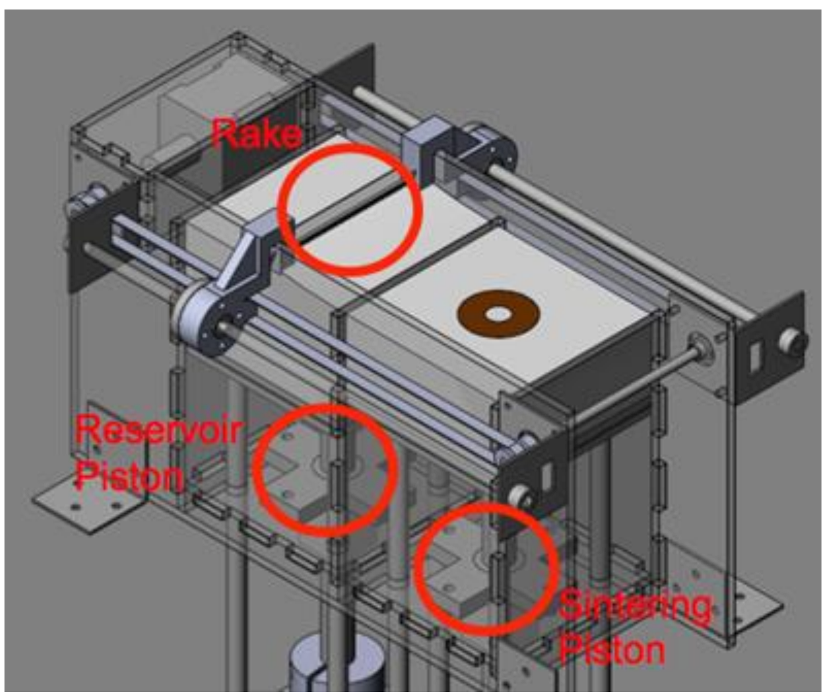

Figure 5. Powder bed system depicting the area for excess powdered propellant (Reservoir Piston), the area for sintering each SRM layer (Sintering Piston), and the Rake mechanism that transports and smooths each new layer of propellant.

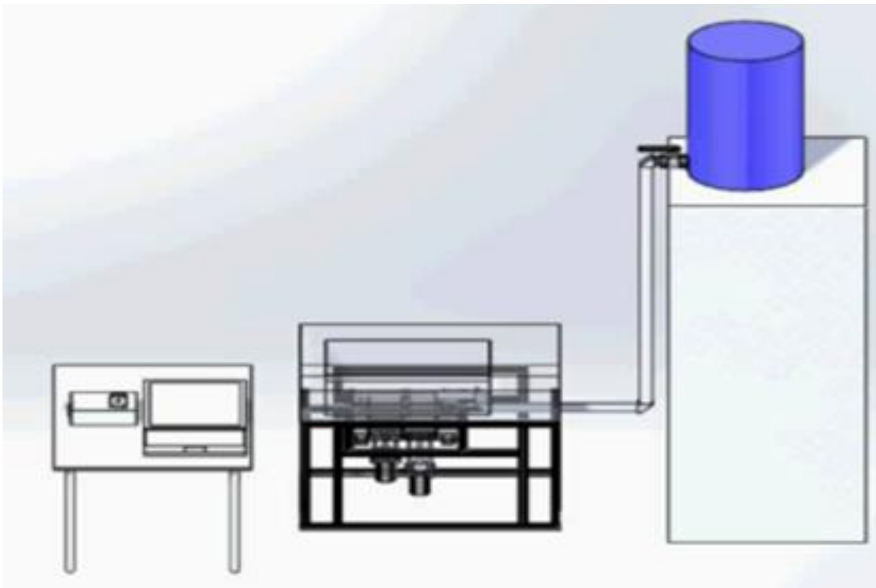

Figure 6. Entire high-level system setup with electronics (left), SLS machine (center), and safety system (right).

a hazardous materials containment unit below. After reaching the far side of the powder bed, the rake moves back to its starting position.

In order to mitigate the effects of a fire during the sintering process, a water safety system was introduced. Integration of this design includes a 15 gallon water container, a 1" manual ball valve, 1"ID 1.5" OD PVC tubing, and clamping mechanisms to hold the tubing in place over the print area. The container rests above the print area by approximately 3 feet to provide high flow rate. After flushing the print surface in the event of a fire, the excess waste and water collect beneath the print bed in a large container for hazardous waste disposal.

In addition to the water safety system, a state of health (SoH) system is also integrated into the laser cutter. The SoH system consists of an infrared thermometer sensor hooked up to the Arduino Mega. If the propellants surface temperature goes above the 200ºC safety limit, the Arduino will activate a bright LED light and a loud mechanical buzzer to warn the operator of a dangerous temperature spike or ignition. A carbon monoxide detector is located outside the print area to act as a redundancy and alert the operator to unsafe CO levels including but not limited to propellant ignition.

The main software elements for this design are based around the RetinaEngrave proprietary program provided by FSL with the purchase of one of their laser cutters. For full automation, a program called Sikuli is used to repeat the cycle of printing and running the powder bed for as many layers that are needed in the solid rocket motor design.

During the sintering process we discovered that airborne particulates were present due to the phase change of the sugar. In order to contain these contaminants, a tarp was erected around the entire frame and a complete enclosure was formed. Two additional fans were then attached to the inside of the laser cutter, which directed the particulates to the air exhaust vent where they were vented to a fume hood. The entire high-level system setup is shown below in Figure 6. Note that the ventilation enclosure encompasses the laser cutter frame in the center of the figure but is not physically depicted.

IV. Design Results

A. Theory

A numerical model was developed in MATLAB to predict the temperature of the powder given the laser's lateral travel rate and beam power. The model is based on thermodynamic principles, employing the specific heat capacity and the powder's absorption spectrum. Several assumptions were made in order to simplify the model. For one, conduction was ignored while blackbody radiation emission from the powder was considered as a negligible form of heat transfer. Furthermore, it is assumed that all laser energy is deposited uniformly into the powder and that steady state is reached instantaneously.

The laser beam deposits energy into the powder through the area of the beam spot, defined as the area swept out by the spot per one second of movement, as the optics carriage travels laterally. The area is approximated as a rectangle with width equal to the laser spot diameter and length equal to the distance the laser beam spot travels in one second. Therefore, the distance depends on the slew rate setting, which controls the laser lateral travel rate. A visual depiction of the model is shown in Figure 7.

The change in temperature, ΔT, is proportional to the amount of energy received, and uses a room temperature of 23°C for the initial powder temperature. The melting temperature of sucrose is approximately 185°C, indicating that

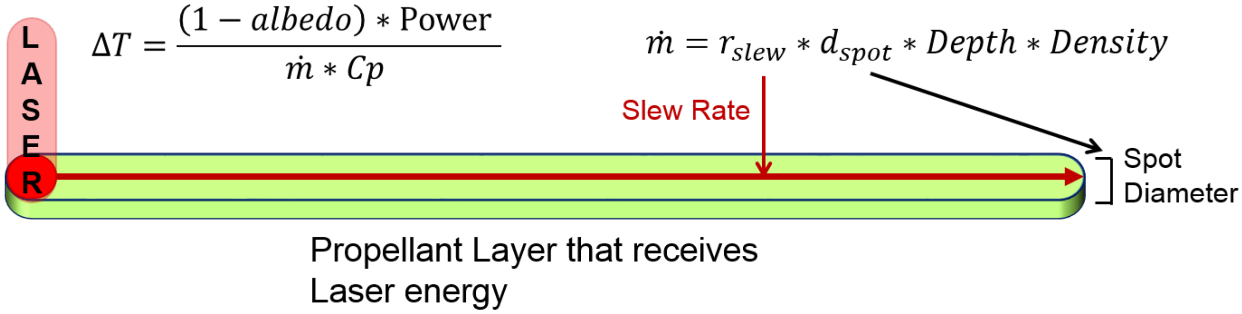

Figure 7. Depiction of the temperature change (ΔT) caused by a laser traveling from left to right at a controlled slew speed (r_{slew}) and laser beam diameter (d_{spot}).

a temperature change of about 160°C is required in order to reach theoretical sintering temperatures[3]. The equation is re-arranged to solve for the depth of a propellant layer. Using these results, laser cutter power and slew rate were characterized and used to predict the sintered sugar depth.

Since the model is general, it can analyze many materials through input of the specific heat, albedo, and density of the material to be analyzed. In this case, table sugar (sucrose) was used to characterize the laser cutter control parameters and to verify the model. However, once the KNO_3 was introduced, the only values that changed were the specific heat and density. The albedo/absorption was the same for both cases since the sugar absorbed 95% of the laser power while the KNO_3 absorbed less than 2%, at an operating wavelength of 10.64 microns (infrared) [3,4]. The density and specific heat of the sucrose-KNO_3 mixture was computed according to the Rule of Mixtures, according to the 35%-65% (by mass) fuel-oxidizer mixture.

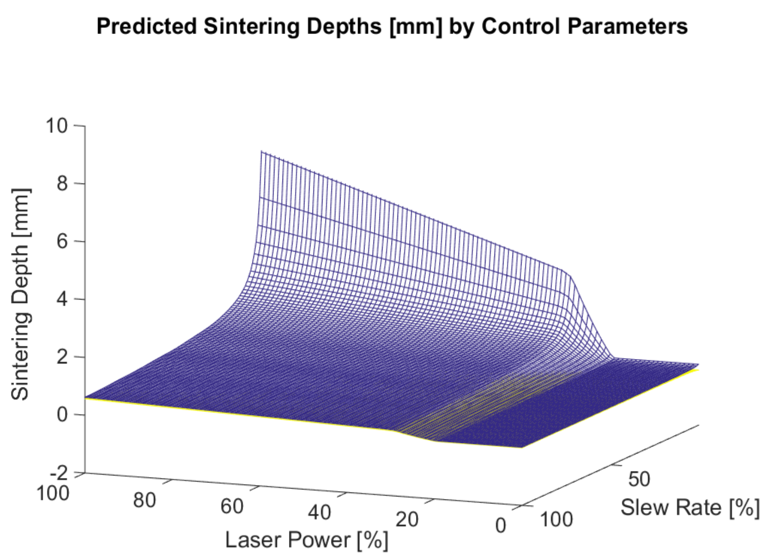

Figure 8. Theoretically predicted sintering depths for powdered sucrose based on controlled laser power and slew rate.

B. Predictions

Figure 8 shows the theoretical control space achievable by the laser cutter corresponding to a sintering depth of 0-10 mm. The jump at 25% power is due to the power at which the CO2 gas laser is able to operate; below these levels the laser does not emit energy. Sintering depths were predicted to vary linearly with power and exponentially with slew rate, confirming higher sensitivity to slew rate control. However, at slow slew rates (<10%), the heat conduction and transient effects are unaccounted for in the model. We did not expect the model to accurately reflect the behavior of the powder in these regimes, and empirical test confirmed this expectation. Experimental results with sucrose show that the sinter depth is at least a rough average of 60% less than predicted and the resulting material is burnt.

Beam power is controlled using a PWM (Pulse-Width Modulation) scheme in the proprietary laser cutter software. Power was measured and values confirmed using a blackbody meter. However, the blackbody meter is subject to a high margin of error which has been estimated to be within 5 Watts. The source of error is currently under investigation, however this is a minor obstacle.

Travel rate of the laser beam was measured by video-recording the movement of the optics carriage and tracking the optics in LoggerPro. Due to the nature of the measurement, slower carriage movement speeds (5-30% slew rate) result in smaller errors in the data. Conveniently, these are the rates at which sintering is predicted to be most successful.

The theoretical model was then updated and calibrated based on sintering tests performed on inert sugar with oxidizer (KNO_3). Coarse (table) sugar was sintered at varying power levels and slew rates. The resulting sample layers were measured with calipers. Ten trials were performed for each pair of control values and the variance was computed to estimate the errors in measurement.

C. Primary Results

The black vertical lines in Figure 9 are error bars while the black dots represent actual measurement data. Most of the measurements lie well above the predictions, over one standard deviation (>1 STD). We computed the reduced χ2 Goodness-of-Fit for this model and found a value of 9.057 which is 9 times worse than the target significance of 1. This indicates our theoretical model is highly unreliable to predict the actual behavior of the sintering process.

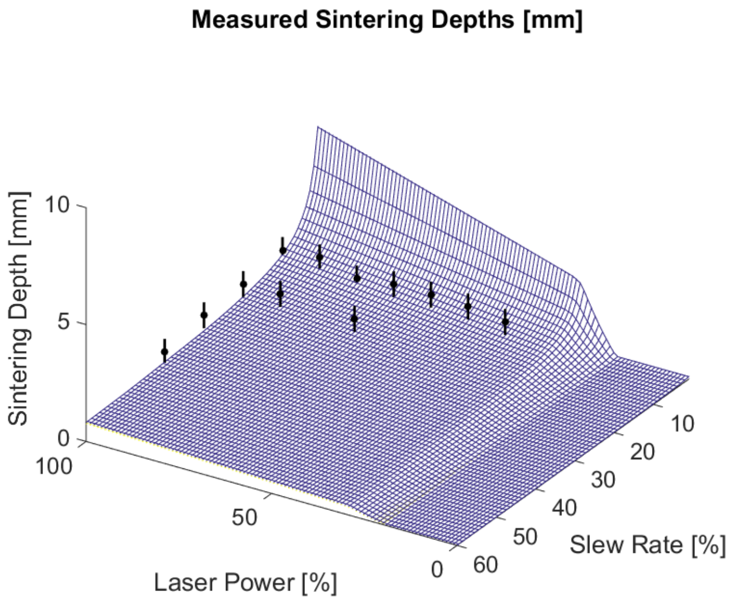

Figure 9. Empirically measured sintering depths of course sucrose with error bars (black vertical lines) centered on the measured depths (black dots).

Using these measurement points; however, we adjusted and calibrated the model. Two significant updates were made to the model. Firstly, since the sugar would not sinter below some combinations of power and slew rate, we empirically determined the minimum sintering depth and adjusted the predictions to zero for anything below that control regime. Second, the model was updated to take into account the average size of the granulated sugar particles. Originally, the model was designed to account for finely milled (150-200 micron) sucrose so particle size was not a consideration. However, upon observation and measurement, the coarse sugar granules are sufficiently large; often thicker than 1mm. Therefore, the radius of the average particle was assumed to be 0.72 mm or about 720 microns, 3-4 times thicker than fine particles and closer to ½ the thickness of a predicted sintered layer. Applying these calibrations made the χ^2 analysis give a result of 1.002, a vast improvement over the first iteration model and indicates a very small error in the predictions.

The updated model with measured data is given in Figure 3. This shows how the "no-sinter" control areas were set to a depth of 0 and the effect of grain size results in a much better fit to the empirical data.

Next, the thermal properties of the model were updated to reflect a mixture of fuel and oxidizer, 35% to 65% by mass, respectively. The new model was used to predict the ensuing sintering depths for solid rocket propellant and the results are shown in Figure 10.

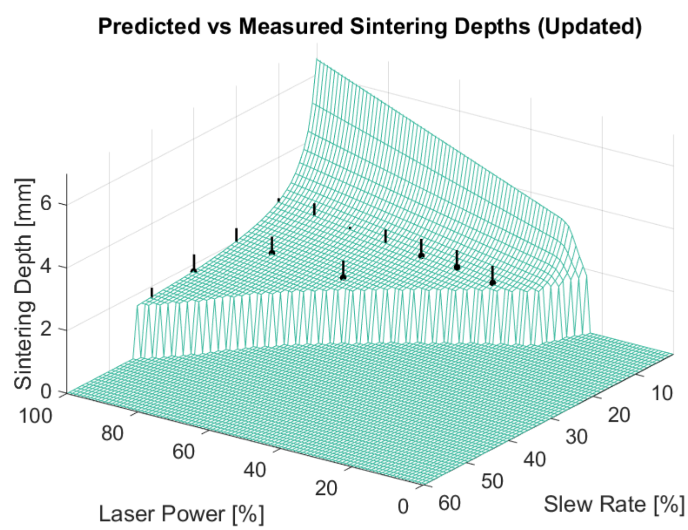

Figure 10. Predicted and empirically measured sintering depths for a 35% sucrose and 65% potassium nitrate propellant mixture.

Empirical evidence determined that course sugar resulted in a more uniformly sintered layer than powdered sugar. A cohesive balling phenomenon prevents the powdered sugar from forming a uniform layer resulting in "bubbles", while the coarse sugar does not experience this problem. The team decided that an analytical explanation for this occurrence is beyond the scope of this project and accepted the qualitative improvement made by using coarse granules over the finely milled sucrose powder. Since the main method of binding has to do with melting the sugar such that it bonds with adjacent granules, a coarse grain size will be beneficial in capturing the finely milled KNO_3 particles in a matrix.

V. Conclusion

Inert sugar testing shows that sintering is achievable in layer depths of 2-4mm by varying the control parameters of slew rate and power which have exponential and linear sensitivities respectively. Preliminary propellant mixture sinter tests result in low-risk ignition scenarios which are easily extinguished without the use of the full fire control safety system. The next step involves increasing the fidelity of the thermal model so that it more closely resembles the physical phenomena of sintering the propellant mixture of sugar and KNO3. This will involve modeling the temperature gradient along the depth of the sintered layer, as well as possibly accounting for transient effects. A more robust control scheme will also be developed which will involve the use of low power and slow slew rates with multiple passes, thereby operating within the lower bounds of the theoretical predictions for successful sintering. Initial testing with multiple low-power passes to sinter one layer shows promising results with fewer instances of ignition but has yet to produce a full 2 mm layer of sintered propellant. This is the final hurdle before achieving level one project success. While easily extinguished, each ignition is a setback for testing, since the optics and equipment need to be cleaned of the smoke particulates after a fire.

The powder bed controlling the printing z axis and delivering the propellant powder mixture consistently performs within design specifications. Given this and since sintering two layers of inert sugar has been accomplished, the team is confident in the method to print a test grain from sucrose powder. Upon completion of the sucrose test grain and successful sintering of the propellant, a full motor print is expected to be readily attainable.

Once the laser control is sufficiently calibrated and characterized, the sintering process can begin and Success Levels 1-3 can be handily accomplished by early May, 2016. Successful completion of this project could open a path to more timely production of SRMs with greatly reduced personnel requirements. Additionally, the ability to additively manufacture motors could be extended to create unique, dynamically changing burn profiles by custom tailoring the propellant grain to exactly match mission criteria. This in turn would result in better fuel efficiency and possibly bring previously difficult missions for specific rockets into the realm of accessibility.

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