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MASS PRODUCTION METHODS FOR IFE TARGETS

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We are performing research and development to increase production quantity and yield for Inertial Fusion Energy targets for laser fusion. A key component of the laser fusion target is an approximately 4 mm diameter foam shell. To facilitate large-scale production, research into optimization of foam shell gelation and hardening times to reduce non-concentricity of the foam shell is underway. Additionally, we are examining methods to modify the current laboratory bench scale process for initial foam shell formation, various fluid exchanges, and sealcoat chemistry into a continuous process in collaboration with Schafer Corporation. The proposed process utilizes porous tubing sections to perform fluid exchanges in a long (200 m–1 km) continuous path of tubing extending from the triple orifice generator currently used to encapsulate and form the foam shell.

Real-time process control has been applied to the triple orifice generator to control the diameter of the foam shell. The system makes use of a pair of photodiode sensors in a closed loop feedback control system incorporating a variable speed process pump. Empirical results indicate the process control loop is capable of identifying wet shell diameters to an approximate standard deviation of 80 to 90 μm, on par with characterization results indicating true shell diameter standard deviations of 30–80 μm.

I. INTRODUCTION

A laser fusion IFE power plant will require an estimated 500,000 targets per day for a 1,000 MW power plant. A robust, high yield, continuous mass production process for fabrication of the IFE targets is required to reduce manufacturing expenses to approximately $0.25 per target[1] which has been identified as a goal for cost-effective IFE power plant economics, a 10^4 reduction from the current estimated batch scale per unit cost of $2,500. Current laboratory fabrication techniques produce approximately 1,000 targets per year. These techniques must be reexamined to identify aspects suitable for mass production.

IA. Laser Fusion Target Design and Specifications

The laser fusion IFE program utilizes a direct drive target design as illustrated by NRL's high-gain target.[2,3] The target, explained simply, consists of a carbon-hydrogen, CH, low-density foam shell with a full-density CH sealcoat chemically bonded to the surface. The foam shell forms the structure for containing the cryogenic DT, while the sealcoat acts as a permeation barrier to prevent DT from dissipating during handling, as well as providing a smooth outer surface for application of a high-Z layer. On top of the sealcoat a thin layer of high Z material reflective to IR radiation, possibly Au or a mixture of Au and Pd, is added for target survivability. The completed target must be capable of permeation fill with DT at room temperature. The low-density foam shell requires high sphericity and wall uniformity as the final symmetry of the DT in the cryogenic target is determined by the initial geometry of the foam layer.

The foam wall thickness is approximately 300 ± 20 μm with an outer diameter of 4.1 ± 0.2 mm. Foam density is approximately 100 mg/cc with an acceptable pore size of less than approximately 1 μm. The shell out-of-round and non-concentricity specifications are identified to be 1%. Seal coat thickness is 2 to 5 ± 1 μm with a density of 1.4 ± 0.2 g/cc. Surface finish must be consistent with a final target surface finish of <50 nm RMS over lengths of 50 to 100 μm. The high Z layer is approximately 500 Å thick, with a deviation from uniformity less than 10%. While the preliminary specifications for the high Z layer have been identified, the research covered by this article focuses on the fabrication of the foam shell and sealcoat bond.

IB. Laser Fusion Shell Fabrication Batch Process in the Laboratory

The current method for shell production starts with microencapsulation, a well documented process[4-7] applied with success in the Inertial Confinement Fusion target production program. Microencapsulation makes use of a triple orifice generator, depicted in Fig. 1, to fabricate the

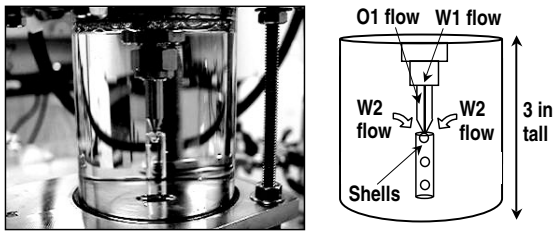

Fig. 1. Picture and schematic of triple orifice generator employed for foam shell microencapsulation.

initial foam shell. As illustrated, an inner drop of water (aqueous phase, identified as W1 flow) is encapsulated by a solution of divinylbenzene, DVB, a dual radical initiator combination and dibutyl phthalate as solvent (non aqueous polymer solution, O1 flow). The W1 flow and O1 flow control the wall thickness of the foam shell. The encapsulated drops of water surrounded by the DVB solution are stripped from the triple orifice generator by a flow of aqueous polyacrylic acid (aqueous phase, identified as W2). The W2 flow controls the diameter of the foam shell.

Once the shells are stripped from the triple orifice generator, they are collected into rotary evaporator containers and placed into heated water baths to begin the polymerization reaction forming the foam shell. After the shells are gelled and hardened, they undergo several water washes to remove particulate contamination from the surface. Next, isopropanol, IPA, extraction of the water inside the shell is performed to enable advancement to the sealcoat process.

During the sealcoat process, the IPA inside the shell is exchanged to a mixture of diethyl phthalate, DEP, and isophthaloyl dichloride, IPC. The shell surface must be cleaned of excess DEP/IPC solution with an aqueous solution of polyvinyl alcohol in order to improve sealcoat bonding to the foam layer. The next stage is to add an aqueous solution of polyvinylphenol, PVP. A polycondensation reaction takes place at the interface of the DEP/IPC and PVP solutions forming the full density sealcoat. At the end of the laboratory process, CO_2 critical point drying is performed to dry the shells once they have been dehydrated with IPA.

II. CHEMISTRY

In order to modify the microencapsulation process from laboratory batch scale to a continuous process, one aspect of the IFE shell chemistry has been identified for initial study. The gelation and hardening times, defined as the time required for the foam shell to center the inner encapsulated water drop and to completely harden the foam to a rigid form, respectively, need to be optimized for the shortest time in which the required non-concentricity and sphericity can be achieved. In the desire to scale up to mass production, the interdependency of the process variables needs to be taken into consideration. For example, if it is desired to shorten the time it takes to gel and harden the shells, one could simply increase the temperature of the water bath to accelerate the polymerization reaction. However, empirical evidence indicates rapid gelling of the foam shell before centering of the encapsulated water drop leads to unacceptably poor non-concentricity. Thus one process variable change, water bath temperature, leads to significant alterations in final shell characteristics.

The current laboratory process for shell fabrication is a small quantity batch process; a few hundred shells are processed per production run. The shells are collected in a rotary evaporator container with washes and exchanges performed in laboratory beakers. As we are concerned with modifying to a continuous process, we are evaluating a method to replace the standard batch scale laboratory equipment with continuous process apparatus. One option for such a continuous process is a flow tube device, a schematic of which is provided in Fig. 2. This device consists of a long tube in which the newly formed foam shells will flow, advanced down the tube by the pump that controls the W2 flow. The residence time of the apparatus will be the same as the residence time of the shells in the rotary evaporator containers. This time, assuming a flow velocity of 1 to 2 cm/s (depending on the diameter of the shell desired and size of the collection tube, generally 0.25 in diameter) results in a tube from 200 m to 1 km long, depending on the gelation and hardening times of the foam shells combined with in-line apparatus for fluid exchanges. Experimentation is underway to identify the tube length corresponding to the time for the shells to gel and harden.

In addition to identifying the gelation and hardening times for the continuous tube length, shell non-concentricity is empirically linked to both the length of time to full gelation and the amount of agitation to which the shell is subjected. Generally, longer gelation times and lack of agitation result in poor non-concentricity. A series of experiments are being performed to explore both phenomenon in greater detail. The current control procedure for gelation is to apply heat via the water baths at 38°C for over 12 h, then a sharp increase to 68°C to completely harden the shells. This technique generally

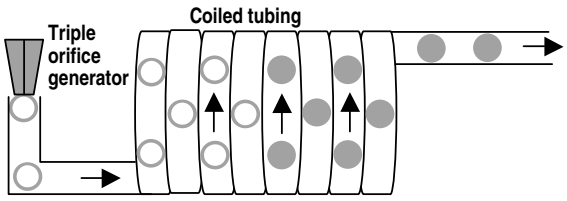

Fig. 2. Schematic illustrating proposed continuous tube generator, adapted from illustration courtesy of Jon Streit, Schafer Corporation.

results in a non-concentricity of 3% to 7%. When higher heat, 68°C, is applied at the beginning of water bath immersion, or a short two hours after initially at 38°C, the measured non-concentricity of the foam shell rises to an average well over 50%. Additional experiments are planned in order to identify the optimum time and temperature for achieving the specified 1% non-concentricity, including keeping the newly formed shells at room temperature for over 24 h, and at a reduced temperature in an ice bath for a similar time period. Both techniques are intended to provide additional time for the foam shell to center its inner encapsulated water drop before gelation is allowed to take place. Agitation requirements will be explored in the continuous tube apparatus via slight pinching of the tube at regular intervals. We hypothesize the pinching of the tube, requiring the shell to deform slightly to pass the pinch point, mimics the agitation effect imparted to the shell during rotation in the water bath.

III. PROCESS SCALE-UP

Looking beyond the continuous tube apparatus, we are evaluating a method to perform the various fluid exchanges required in the IFE shell process, yet keep the shells within the flow tube. The device utilizes porous tube sections to allow for fluid exchange. Keeping the shells within the main flow tube is desirable for improving production yield, as it will reduce the amount of handling to which the fragile shells are subjected. Fluid exchanges would be performed using a standard counter current configuration with sequences of steadily increasing concentrated porous tube sections. Along with the various fluid exchanges, a method for performing sealcoat chemistry was required, as this process step includes the requirement to keep the shells separated during the time it takes to form the seal coat. Pictured in Fig. 3 is a schematic of the proposed apparatus. The sections of porous tubing have a small 30 μm pore size (smaller pore size tubes are also being tested), allowing for fluid exchange with a large pressure drop for uniform fluid addition along the length of the section. This will enable the shells to be separated in preparation for the polycondensation reaction to take place. If required, the porous tube section will incorporate an automatic diagnostic system to measure shell separation distance and correct via fluid addition or subtraction between individual shell pairs. The diagnostic system is a variation of the closed feedback loop system discussed in Section V.

Putting all the various apparatus described in the last three sections sums to a continuous process line for fabrication of IFE shells. Starting out, the shells are formed using the triple orifice generator and immediately enter the continuous tube apparatus for gelation and

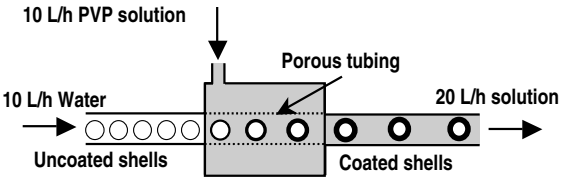

Fig. 3. Porous tube section demonstrating fluid addition for PVP polycondensation chemistry.

hardening. After which fluid exchanges are performed in porous tube counter current fluid exchange sections, then the shells are taken right into the sealcoat bonding sections where PVP coating solution is added to the main flow tube to separate and begin the polycondensation reaction.

IV. REAL-TIME PROCESS CONTROL

In order to scale-up IFE target fabrication to 500,000 shells per day, automatic process control systems require development to allow for increased production. The first such system, designed to control the shell diameter as it forms in the triple orifice generator, has been assembled with testing under way, please reference (Fig. 4) for illustration. The system is an automatic closed feedback process loop utilizing two pairs of laser/photodiode sensor pairs. The lasers are class IIIr line lasers with a power output of 0.5 mW at 670 nm. The lasers are beamed across the collection tube (7 mm OD) approximately 6 in. below the exit of the triple orifice generator. Photodiode sensors receive the line laser beams and output a current amplified via photodiode amplifiers to a range of 0–10 V. The signal is sampled at 1000 Hz for 30 s intervals via a LabVIEW data acquisition system. As the shell passes the sensor, a drop in voltage is registered. A typical raw data sample is shown in Fig. 5.

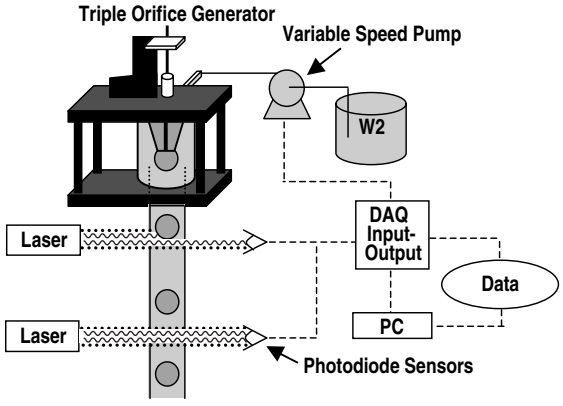

Fig. 4. Illustration of the closed loop process control system for automatic diameter control during foam shell production.

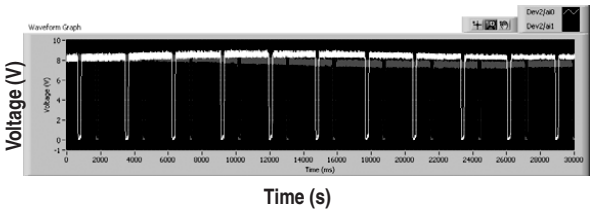

Fig. 5. Screen shot from a typical 30 s raw data sample. The white data line represents the top laser/photodiode pair; the secondary gray line is the lower pair.

The data acquisition software program employs an edge detection trigger that acquires approximately 98% of the total shell diameter. The remaining shell diameter currently left out of the measurement will be accounted for in future versions of the program, either by improvement in the edge detection trigger or incorporation of a correction factor. The sensors are utilized to determine shell velocity; each sensor's leading edge trigger is used to determine shell velocity within the tube. Once velocity is calculated, the width of both sensors' shell trace is averaged to determine generation rate and shell diameter. Approximately 100 samples were acquired in 4 separate laboratory production runs. Foam shell samples were chosen at random for characterization corresponding to particular acquired LabVIEW data sets. Characterization employs a very accurate telecentric lens imaging system with a typical measurement error of 0.1% of diameter (correlates to below ± 5 μm for the shells under consideration), with a random count of 20 shells imaged from each corresponding batch. Image characterization is time-consuming as shells must be isolated one at a time and kept from moving for the imaging system measurement to occur. Measured diameters from the LabVIEW diagnostic system and corresponding characterization results are provided in Table I. Early results indicate the LabVIEW diagnostic system is capable of measuring wet foam shell diameters as they exit the triple orifice generator to an approximate standard deviation of 80–90 μm, while characterization results indicate shell diameter distribution standard deviations of 30–80 μm. This indicates LabVIEW adds a measurement error of approximately 50 μm or less to the distribution curve of shell diameter. However, both the characterization and LabVIEW system measurements are well within the ± 200 μm specification for shell diameter.

TABLE I. Initial Test Results with Diameter Diagnostic System

Test ID	Real-time system Dia. (SD), μm	Characterization Dia. (SD), μm	Δ Dia. μm
DVB082504-A	4074 (80)	3938 (76)	136
DVB082504-C	3978 (83)	3888 (43)	90
DVB082504-F	3776 (93)	3918 (31)	142

Testing has begun to incorporate the variable speed pump to control shell diameter via the W2 stripping flow (Section IB for explanation of the three flows in the triple orifice generator). The pump speed (process variable) is controlled by a 0–10 V input signal calculated and provided by the LabVIEW program. The input signal voltage varies with the calculated diameter (control variable) of the foam shell.

V. CONCLUSIONS AND FUTURE WORK

We have focused research and development on the tasks of increasing production quantity and yield for Inertial Fusion Energy shells. Optimization of foam shell gelation and hardening times to reduce non-concentricity of the foam shell has begun, with early empirical results indicating slowing down the gelation time improves non-concentricity. Additionally, we have begun to modify the current laboratory bench scale process, including redesign of apparatus for the initial foam shell formation, various fluid exchanges, and sealcoat chemistry. The continuous flow tube design will have a length of approximately 200 m to 1 km, depending on the optimum time for gelation and hardening. The porous tubing sections for fluid exchange and sealcoat chemistry utilize tubing with 30 μm pores to create a large pressure drop across the tube facilitating even dispersal of the fluid into the main flow tube.

An automatic real-time closed feedback loop incorporating dual laser/photodiode pairs has been designed and tested. Results indicate the diagnostic system within the loop is capable of measuring wet shell diameters to an approximate standard deviation of 80 μm, on par with characterization results indicating shell diameter standard deviations of 30–80 μm. Further testing is underway to add a variable speed process pump to complete the real-time process control loop.

ACKNOWLEDGMENTS

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