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Providing glow discharge polymer (GDP) coatings is a key step in Inertial Confinement Fusion (ICF) target production. Typical target delivery quantities may require several GDP coating runs consisting of up to 80 mandrels per batch. This work undertakes research and development to create a new configuration for the GDP coating apparatus that will enable batch sizes into the hundreds or thousands. This will reduce costs associated with target production and make delivery of ICF targets more efficient. In addition, there is a synergy between this work and Inertial Fusion Energy's (IFE's) need for half a million targets per day for energy production, as well as future commercial applications. Recently we have demonstrated the capability to meet the NIF CH surface standard, confirmed via statistical sampling, in a 400 capsule batch coated with 10 µm of GDP, a key benchmark for successful coatings.

I. INTRODUCTION AND BACKGROUND

We are developing a system to enable glow discharge polymer (GDP) coating of hundreds to thousands of spherical mandrels in one coating run. Our concept is a horizontal rotary configuration, an evolution from a first generation fluidized bed system.[1] Currently, GDP coating is performed in systems that have adequately produced CH capsules meeting NIF smoothness specifications. These systems utilize a 2.5 in. coater pan (Fig. 1), to hold up to 80 capsules depending on capsule diameter. The pan is placed into the standard GDP coater chamber[2] and agitated via one of three methods, tapping, bouncing, or rolling. Our rotary coater design evolved from a previous study for mass production capsule coatings, which utilized a fluidized bed configuration. This first generation system did produce GDP coatings, however, it had less than desirable results in two key areas. One, differences in mandrel thickness combined with the vertical geometry of the fluidize bed resulted in capsule-to-capsule wall thickness non-uniformity. Two, the increased capsule-to-capsule collisions resulting from the coupling of the gas flows for both coating (low flow) and fluidization (high flow) resulted in poor surface finish. We intend that the new rotary coater design will mitigate both issues via its horizontal geometry and removal of the need for a fluidization flow.

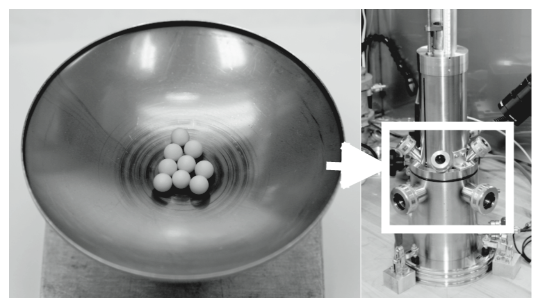

Figure 1. A bounce pan pictured on the left (with 9 2 mm diameter foam capsules) is placed inside the GDP reactor chamber, pictured on the right.

II. EXPERIMENTAL APPARATUS AND PARAMETERS

Figure 2 shows a simplified schematic of the rotary coater design. We utilize two MKS mass flow controllers for the precursor (trans-2-butene, T_2B) and etching gasses (H_2). Nominal mass flow rates for the T_2B and H_2 are 0.4 and 10 sccm respectively. The vacuum system enables us to keep the reactor chamber pressure to <100 mtorr at these flow rates. A third MKS mass flow controller is installed and available for future dopant studies.

The coating chamber itself is a 5 in. diameter, 20 in. long glass reactor customized from a commercially available controlled atmosphere/vacuum rotary kiln rotated by a motor with programmable motion. The glass reactor is attached to two metal end caps vacuum-sealed via 2 polymer o-rings on each end coupled with rotating vacuum

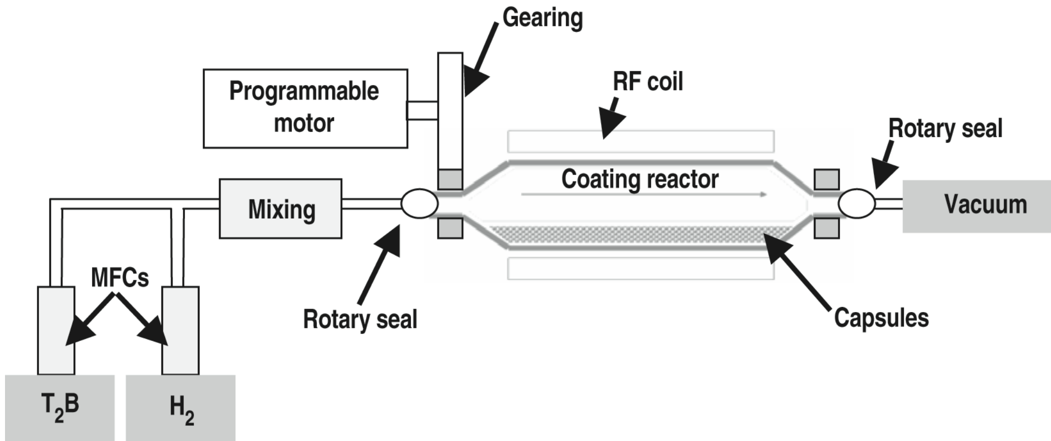

Figure 2. Schematic of rotary coater (adapted from Huang, 2005). Gas flow is from left to right in the illustration.

seals on the end caps. The system has 0.25 in. inlet and 2 in. diameter outlet ports to decrease the pressure in the chamber down to 10^{-4} Torr without gas flow, established by a turbo and scroll pump system. Two Convectron pressure gauges upstream and downstream of the reactor chamber provide pressure readings down to 10^{-4} Torr. The downstream pressure is utilized to control a butterfly valve, via an MKS pressure controller, just before the turbo pump which in turn controls the pressure within the reactor.

The plasma is generated by a custom designed RF coil operating at 35 MHz and approximately 25 W. The coil is currently located in the middle third of the reactor but its position can be modified upstream or downstream of center. The coating rate within the actual coil length is slightly lower than up or downstream of the coil as witnessed by a lighter colored and thinner coating in that region.

The capsules are inserted by taking the end cap off the upstream side of the reactor and manually placing the capsules in the glass reactor chamber. Once the system has been pumped down the coating gases are introduced and plasma is activated. Currently, we employ an intermittent rotation scheme to reduce capsule-to capsule collisions; more detail is provided in Sec. III.A. Additionally, we introduced a piezoelectric motor to tap the glass periodically to prevent the capsules from sticking to the reactor walls due to static charge buildup.

III. RESULTS

We have successfully coated hundreds of 1.7 mm diameter PAMS mandrels with 10 μm of GDP in individual batches. Approximately 50% are free of gross defects, defined as cracks, scratches, or other large surface defects. In addition, we have improved surface finish and can meet NIF CH smoothness specifications via reduced capsule to capsule collisions and elimination of stress induced flaking and peeling, as well as reduction in gas phase precipitation. Additionally, we have improved coating uniformity compared to the first generation fluidized bed system, and successfully produced gas tight coatings on both full density plastic and foam capsules.

III.A. Surface Finish Improvement

During the GDP coating process capsules require agitation; otherwise, a non-uniform, non-spherical coating will result. However, the act of agitation induces capsule-to-capsule collisions creating pits and domes on capsule surfaces as GDP is deposited and increasing surface roughness. As indicated in previous work[3] roll and tap agitation coating results in smoother surfaces than bounce agitation (Fig. 3). The horizontal geometry of the rotary coater is well adapted to roll agitation, and the need to

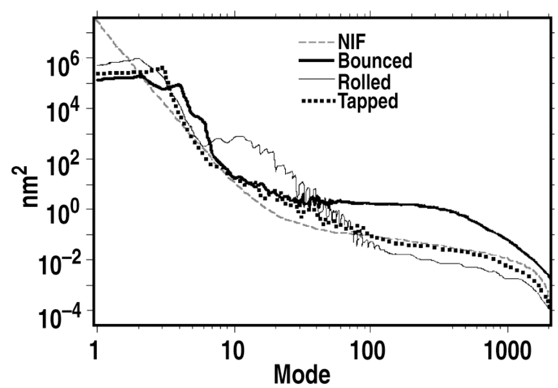

Figure 3. Roll and tap coating demonstrate generally reduced roughness versus bounce coating, especially in the mid to high modes. Data averaged and smoothed for clarification and to aid in the reader's review.

prevent capsules from sticking to the reactor walls due to static requires we employ tapping. Initially, coating runs in the rotary coater were run at a constant velocity and had poor quality coatings. We switched to intermittent rotation with 30 s dwell times followed by a slow, 5 s long, quarter revolution of the chamber to reduce the number of collisions the capsules see over the coating run time of several days. With the reduced agitation rate resulting from intermittent rotation, the measured 4 $\pi\Delta$wall is less than 0.5 µm for the rotary coater system, comparable to conventional bounce pan GDP coater runs. AFM measurements indicate that with the intermittent agitation parameters we have achieved ignition CH smoothness specifications for three out of five capsules sampled from a 400 count capsule batch, a key benchmark for successful coatings. This result is comparable to surface finish achieved by bounce pan GDP coater systems. Figure 4 is a summary of AFMs for five PAMS mandrels from the 400 count batch coated in the new rotary system with 10 µm of GDP. Compared to the first generation fluidized bed coater, we have improved the overall surface roughness of the capsules in all modes; please see Table I for a summary.

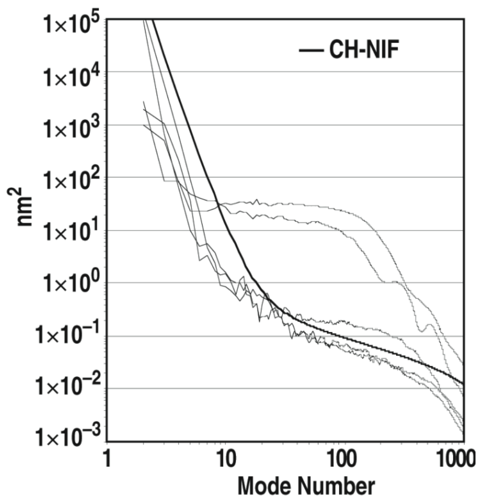

Figure 4. Five AFMs from 400 count rotary coater batch. Three of five are acceptable compared to CH-NIF smoothness specification. Coated to 10 µm with GDP.

Early trials with the rotary coater resulted in flaking and peeling, as well as evidence of gas phase precipitation witnessed visually by an irregular rough surface. Borrowing from previous experience gained from the GDP coater process,[4] we reduced the ratio of precursor to etching gas from 2:10 sccm to 0.2:10 sccm, and additionally, reduced the coater chamber pressure to less than 100 mTorr. These process parameter modifications eliminated the incidence of flaking and peeling and greatly reduced overall surface roughness as indicated earlier in this section. However, the resulting coating rate is approximately 0.02 µm/h, lower than standard GDP coaters. We will be exploring opportunities to increase the coating rate in future experiments.

Table I. We have reduced overall surface roughness compared to earlier efforts with the fluidized bed coater system. Data is average of 5 randomly chosen capsules.

Mode Number	2	3-10	11-50	51-100	101-1000
400 count rotary coater batch at 10 µm (nm)	238	48	4	2	5
Fluidized bed coater batch at 4 µm (nm)	255	266	36	6	20

III.B. Coating Uniformity Improvement

We have successfully maintained capsule-to-capsule wall uniformity with larger batches in the rotary coater. Figure 5 compares a 20 capsule batch with the largest batch coated to date at approximately 400 capsules. We maintained the capsule-to-capsule wall thickness uniformity to within ±10% of the mean wall thickness (typical specification for current GDP coaters is ±5%). We believe the slight increase in wall thickness variation in the larger batch results from the reduced coating rates to be found in the middle of the reactor. During long coating runs some capsules, on a time average basis, preferentially remain within this area. We intend to design a glass reactor with internal fins to roll the capsules back and forth along the length of the reactor as it rotates to mitigate the variation in coating rates with reactor length.

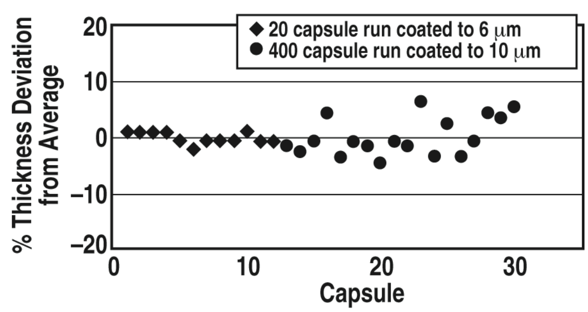

Figure 5. We maintained capsule-to-capsule wall uniformity to acceptable levels in larger batches.

III.C. Gas Tight Coatings

We have produced gas tight coatings on both full density plastic and foam capsules with the rotary coater. We coated approximately 20, 2 mm diameter PAMS mandrels with GDP in the rotary coater and achieved gas tight coatings on 50% of the batch. Of those capsules that held gas, the average argon half-life was 27 minutes with a standard deviation of 1.9 minutes, confirmed with an x-ray fluorescence half-life measurement technique, nominal for this material and size of capsule. Additionally, we also successfully applied a gas tight coating on 20 resorcinol formaldehyde low-density foam capsules, once again 50% holding gas with a 4 min Ar half-life with a standard deviation of 0.7 minutes, nominal for this material and size capsule. These half-lives are consistent with a diffusion of the gas through the GDP coating and not through small pinholes.

IV. CONCLUSIONS AND FUTURE WORK

We have successfully coated batches of capsules numbering in the hundreds utilizing a new horizontal rotary GDP coater system. We have improved surface finish and can meet NIF CH smoothness specifications, a key benchmark for successful coatings. We reduced capsule-to-capsule collisions, stress induced flaking and peeling, and surface roughness associated with gas phase precipitation. We maintained coating uniformity in larger batches and successfully produced gas tight coatings.

Future work will focus on further improving surface finish to increase the yield of capsules that meet the entire NIF CH surface standard, reducing capsule to capsule wall thickness variation down to current levels achieved in standard bounce pan GDP coaters, and performing combustion analysis of the coating to determine carbon to hydrogen ratio to compare to standard GDP coatings.

To improve surface finish, we intend to reduce rotation and tapping frequency until the coatings begin to show increased non-concentricity and out of round, thereby establishing minimum agitation parameters that maximize surface smoothness. To reduce capsule-to-capsule wall thickness non-uniformity we intend to add fins to the inner wall of the reactor tube to roll the capsules up and downstream through the reactor chamber thereby averaging the time capsules spend in different coating rate regions of the reactor. The combustion analysis will indicate whether we are achieving coatings similar in carbon to hydrogen ratio to those produced in current GDP systems.

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