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THE USE OF MOLECULAR BEAMS TO SUPPORT MICROSPHERES DURING PLASMA COATING*

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Spherical laser fusion targets can be levitated on beams of Ar or other gas atoms. This is an especially useful and reliable technique for supporting microspheres during plasma coating or plasma etching. The reliability of this technique is principally the result of two things: the success of a special centering device which provides a lateral, stabilizing force on the levitated microspheres; and a gas handling system which is capable of controlling levitation gas flow in the microtorr liter/sec range. We have determined that the operational regime of this device is that of Knudsen's flow. This knowledge of the flow characteristics has been important in developing this device.

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I. INTRODUCTION

Levitation is a technique used to provide contact free support of laser fusion targets during coating. This technique for coating microspheres individually has several advantages over batch coating methods. Particulate contamination, which leads to large surface defects,¹ is minimized during plasma coating on levitated microspheres. Fragile, double shell targets, where one target is assembled within a larger shell, can be coated without being destroyed. A third advantage results from being able to coat limited stock items. For example, a target that has been coated with a first layer in a batch process might be selected for its high quality to receive a second coating of another material. The second coating could be done on the individual target using some type of levitation technique. Several different techniques for levitating laser fusion microspheres have been considered, including: electrostatic,² magnetic,³ optical,⁴ acoustic,⁵ and gas⁶ or molecular beam.⁷ Of these, molecular beam (or gas levitation) is most suited for supporting microspheres in a coating discharge (e.g. sputtering, plasma polymerization).

II. PRINCIPAL OF OPERATION

Lowe and Hosford first described gas levitation and its use with the sputter coating of metal and dielectric layers on glass microspheres.⁶ They used a stainless steel array of 50 μm diameter capillaries and Argon as the levitation gas. In addition to stainless steel arrays, glass arrays are available (Galileo Electrooptics) in a variety of sizes

starting from 2 μm diameter capillaries. The basic idea is to support the microsphere (70 μm - 300 μm diameter) by the gas flow from the capillaries (10 μm - 50 μm diameter) of the array. This levitation gas, typically Argon, forms collimated beams of atoms⁸ at the low pressures required for the coating process. Some type of confining structure ("centering ring") is usually included which serves a dual purpose of limiting gas flow and providing lateral stability to the levitated microsphere. The total levitation gas flow itself is low enough such that it is possible to coat a microsphere using a variety of coating techniques (e.g., sputtering, plasma polymerization, evaporation).

With the purpose of improving the stability of levitation we have made some careful measurements of the flow and pressure of the levitation gas. It is important to identify the gas flow regime (viscous or free molecular) in which levitation takes place because the associated forces are quite different. The data from one such measurement is shown in the graph in Figure 1, where the rise in chamber pressure, $P_2(t)$, was monitored as a function of different, fixed values of levitator back pressure, P_1 , for a 50 μm capillary array. The graph shows that for back pressures less than 1 torr, the data falls along the same straight line, corresponding to a constant, pressure independent value for conductance. At a back pressure of 10 torr the data deviates significantly, indicating that the conductance of the levitator has changed. Free molecular flow through cylindrical tubes is described by Knudsen's Equation⁹ which can be written in the following form:

$$P_2(t) = P_1 \left(1 - \exp\left(-\frac{C_{mol}}{V} t\right) \right) \quad (1)$$

where V is the volume of the chamber and C_{mol} is the conductance given by

$$C_{mol} = \frac{8}{3} \frac{r^3}{l} \pi \sqrt{\frac{kT}{2\pi M}}$$

and r and l are the tube dimensions. In the case of the viscous regime, Poiseuille's Equation¹⁰ describes flow through cylindrical tubes, and can be rewritten in the form:

$$P_2(t) = P_1 \tanh \frac{C_{visc}}{V} t \quad (2)$$

where

$$C_{visc} = \frac{\pi r^4}{8\eta l} \bar{P} \approx \frac{\pi r^4}{8\pi l} \left(\frac{P_1}{2} \right)$$

and η is the constant of viscosity for Argon. Based on the pressure independent behavior of conductance indicated in the data from Figure 1, it appears that the levitator operates in the free molecular flow regime for back pressures less than 1 torr using a 50 μm capillary array.

Figure 2 is a graph of total levitation flow vs back pressure for three different size capillary arrays. Also displayed on this graph are the ranges of levitation for two different glass microspheres using the three capillary arrays. The data from this graph supports the claim that levitation occurs in the regime of free molecular flow, even for the highest conductance, 50 μm array.

There are several problems associated with molecular beam levitation of microscopic spheres in a coating discharge. The ball must be confined by a horizontal component of force in order that it does not collide with other objects or bounce out of the levitator. There are complex electrostatic forces associated with a plasma and its sheath which may be much greater than normal gravitational forces. These forces must be overcome in order that the microsphere may be levitated in a stable manner. As the microsphere is coated its weight increases, requiring a corresponding increase in levitation gas flow. In order to avoid having an operator constantly monitor and adjust gas flow to maintain levitation, some type of automated system is needed.

Lateral stability on a levitated microsphere can be accomplished by several methods.^{6,7,11} Lowe and Hosford used a stainless steel capillary array in which they machined a tiny dimple (1/8 inch deep and 3/8 inch in diameter). The microsphere was levitated and coated inside the dimple. Goldstein¹¹ used concave glass capillary arrays (manufactured by Galileo Electrooptics). These arrays have a common focal point for their capillaries which is about 25 mm from the surface. This focusing of the

beams reportedly introduces some lateral stability to the levitated microsphere. Figure 3 shows three different techniques which have been successful for confining levitated spheres. In the first method¹², the microsphere is confined to the center of the capillary array in an area about 1 mm^2 supported by enough gas to maintain levitation. This center is surrounded by a regime of greater flow which prevents the microsphere from escaping the inner region. This technique requires control of two separate flows to the capillary array. In the second technique⁷ the back side of a stainless steel capillary array is machined, as shown in Figure 3, to form a graded conductance across the face of the array. This graded conductance results in the formation of a potential well in which the sphere levitates at the center of the array. The third and most successful method of creating a lateral, stabilizing force utilizes a small, flat ring with a bevel. The bevel acts as a circular deflector, providing a radially directed force on the microsphere. This force is spring-like in nature, creating a potential minimum which holds the microsphere firmly in place at the center of the ring.

When a metallic microsphere is placed in a gas discharge, strong electrostatic forces make levitation extremely difficult. These forces are associated with the gas discharge itself and cease when the glow discharge is no longer present (before breakdown, when strong electromagnetic fields are present, levitation is easily accomplished). These forces are peculiar to metal substrates for it is possible to levitate bare glass spheres under the same conditions, but, upon producing a continuous metal film (by sputtering) the glass sphere is suddenly forced to the surface. One likely explanation for this effect is a polarization force.

$$\vec{F}_p = (\vec{P} \cdot \vec{\nabla}) \vec{E}$$

where $\vec{P}$ is the dipole moment of the metal sphere and $\vec{E}$ is the nonuniform electric field which occurs in the plasma sheath. Similar forces appear to be present on microspheres in a bouncer pan.¹³ Various methods for measuring and dealing with this force are being explored.

As the microsphere is coated in the plasma its weight increases, requiring a corresponding increase in levitation gas flow. In addition to the ball, the capillary array is also coated, causing a change in the conductance of the levitator. As a result, the coating process must be frequently monitored and gas flow increased to insure continuous levitation. This is essentially a full-time job, and in the case of thick coatings or slow coating rates, levitation-coating may be a 24-48 hour job. In recording values for levitation back pressure during the course of a coating run, it was observed that these values follow an approximately linear relationship with time. As a result of this linear relationship one can operate the levitator in a semi-automatic mode by incrementing the gas flow at a fixed rate. This system, shown in Figure 4, disengages the operator from the continual vigilance required in the manual system.

A further advance in levitation-coating results from making the automatic flow incrementing device part of a system which detects the height of the levitated microsphere and uses the resulting signal in a control loop as shown in Figure 5. This system allows the operator to load

in a microsphere, set up the proper conditions for levitation and coating, then walk away to return several hours later to a finished product. The combination of position sensing detector (United Detector Technology PIN SC/4D) and PAR lock-in amplifier gives greater than 5 μm resolution to the detection of the height of the levitated microsphere. This is more than adequate for controlling the sphere during a coating run.

Coating Results

Plastic coatings (either fluorocarbon or hydrocarbon) produced on molecular beam levitated glass microspheres show remarkably good surface quality. The apparatus used for producing these coatings, shown in Figure 6, consists of an R.F. powered helical resonator which produces a discharge in a flowing gas mixture of organic monomer plus buffer¹⁴. The molecular beam levitated microsphere is located approximately one inch below the mouth of the discharge tube, surrounded by the glow discharge. A typical fluorocarbon plastic coating produced on a levitated glass microsphere is shown in Figure 7. The surface quality and concentricity of these coatings easily surpasses the standards required by the target designers at LLNL.

An important feature of levitation coatings is the isolation of the substrate from particulates generated at the various surfaces exposed to the plasma. This isolation is not total, however, because the microsphere is still exposed to particulates generated in the discharge, which may rain down on the levitated sphere, causing defect nucleation sites. The problem of discharge generated particulates can be solved by adjusting parameters such as monomer flow.¹⁴

The real benefits of levitation - coating are derived from the ability to handle and coat individual targets - in particular limited stock and specialty targets. A good example is the double shell target. This target is made up of a small ($140\text{ }\mu\text{m}$) inner, D-T filled sphere sandwiched between two thin (500A) FORMVAR films. The outer part is a larger plastic sphere ($\sim 300\text{ }\mu\text{m}$ diameter), consisting of two, thin, parylene hemishells which are assembled and epoxied together around the inner, suspended microsphere, resulting in a concentric, spherical, double shell target as shown in Figure 8. The final step is to take this fragile, double shell target and coat it with several tens of μm of hydrocarbon plastic--forming a thick, seamless, ablative outer layer. Immediately prior to coating, the double shell target is placed in the levitator and etched in a hydrogen discharge for approximately 30 minutes. This process removes the final skirt of FORMVAR film which protrudes from the seam. If not removed, this vestige produces a major defect along the seam of the target, as shown in Figure 9a. After etching the double shell target is coated with either fluorocarbon or hydrocarbon plastic. Figure 9b shows a SEM photograph of the seam of a double shell target that has first been etched, then coated with $30\text{ }\mu\text{m}$ of fluorocarbon plastic. The seam defect is still apparent, but much reduced in magnitude compared to the photo in Figure 9a. There are still some rather serious problems associated with producing the ablative, outer coating of double shell targets using the levitation-coating system. If the inner ball is not well centered (to within a few μm), the assembled target does not rotate freely, and a non-uniform coating is produced. The outer shell is difficult to assemble and oftentimes a small edge results from a slight misalignment. This ledge produces a major defect in the

outer coating. A third problem arises from the difficulty in producing a nearly perfect sphere from two assembled hemispheres. Frequently the product is slightly prolate. Many of these problems may be corrected in the assembly process using recently developed interferometric techniques.¹⁵

Conclusion

Molecular beam levitation has proven to be a very useful tool for supporting laser fusion targets during discharge coating and processing. In fact, it may provide the only means for coating limited stock substrates such as double shell and multi-coating targets. We have developed a means for automating the levitation-coating process, thus eliminating the need for constant monitoring of the system. Further work in the area of electrostatics is needed to fully understand and control the electrostatic forces on metallic spheres in a glow discharge.

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Figure Captions

1. This graph shows the increase in chamber pressure, $P_2(t)$, as a function of fixed, levitator back pressure, P_1 .
2. Total levitator flow is plotted against levitator back pressure for three different size capillary arrays.
3. Three different techniques for creating lateral stability on a levitated microsphere.
4. A modification of the MKS 170M-48A pressure controller allows automatic incrementation of the levitator gas flow.
5. The block diagram shows the electronic components of the optical feedback, automatic levitation control system.
6. A helical resonator, R. F. discharge produces fluorocarbon or hydrocarbon coatings on molecular beam levitated spheres.
7. These electronmicrographs show a $300\text{ }\mu\text{m}$ diameter glass sphere coated with $27\text{ }\mu\text{m}$ of fluorocarbon polymer using plasma polymerization.
8. The double shell target consists of an inner, glass microsphere assembled inside a larger, plastic sphere.

9a. This double shell target was coated with a thick (30 μm) fluorocarbon coating. The large defect is due to the FORMVAR skirt which protrudes from the seam.

9b. This double shell target was etched in a H_2 plasma for about 30 minutes, prior to coating, thus reducing the FORMVAR skirt and resulting in a reduced defect at the seam.

Fig. 1

Range of levitation for
 $300 \times 5 \mu\text{m}$ glass sphere

Range of levitation for
 $140 \times 5 \mu\text{m}$ glass sphere

▲ $50 \mu\text{m}$ capillary array
 $C = 1.4 \times 10^{-2} \text{ l/sec}$

● $25 \mu\text{m}$ capillary array
 $C = 7.8 \times 10^{-3} \text{ l/sec}$

■ $10 \mu\text{m}$ capillary array
 $C = 4.0 \times 10^{-3} \text{ l/sec}$

Fig. 2

Fig. 3

MKS – 170M-48A automatic pressure controller

Programmable
feedback
resistor unit

Fig. 4

Fig. 5

Fig. 6

10 μm

1 μm

Fig. 7

360 μm

Fig. 8

Fig. 9