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Abstract

This paper summarizes the current techniques used in the U.S.A. for fabrication of targets for inertial confinement fusion (ICF) experiments at the five ICF Laboratories in the USA. It reviews the current target specifications that can be achieved, and discusses directions for development of targets for ignition in the National Ignition Facility.

1. Introduction

Development and fabrication of targets for inertial fusion in the USA is conducted by the five U.S. ICF Laboratories and by the ICF Target Support contractor, which is General Atomics (GA) and our partner W. J. Schafer Associates. The focus of this effort is production of targets for current inertial confinement fusion facilities, with emphasis on producing small, unique batches of targets that meet exacting specifications, providing a variety of diagnostic signals, and delivering a complete characterization pedigree for each target. Relevance to future inertial fusion energy (IFE) applications, which will require low cost, mass-produced targets, is not a consideration at the present time.

Targets for direct-drive experiments consist of a spherical capsule made of glass or plastic that contains the D_2 or DT gas used in these experiments. Direct-drive capsules for the Omega laser at the University of Rochester Laboratory for Laser Energetics are about 1 mm in diameter and are coated with plastic ablation layers. Several different layers may be used and various dopants may be added to tailor absorption of driver energy and to provide diagnostic signals. A final layer, usually very thin aluminum, acts as a permeation barrier to help retain the fill gas and acts as a shine-through barrier to prevent the laser beams from pre-heating the inner fuel.

Indirect-drive targets consist of a similar capsule mounted inside a high-Z metal container called a hohlraum. Laser beams are focused through holes in the hohlraum into the interior creating a sea of x-rays which then illuminate the capsule, causing it to compress. Targets for indirect-drive experiments on Omega and on the Nova laser at Lawrence Livermore National Laboratory (LLNL) consist of capsules about 0.5 mm in diameter mounted inside hohlraums with characteristic dimensions of several millimeters.

Targets for ignition experiments in the National Ignition Facility (NIF) will be similar to those for Omega and Nova, but of larger size. Capsules in the range of 2–3 mm diameter will be needed, and hohlraums ~1 cm in size will be used. Ignition targets will require a layer of frozen DT ice, 100–200 μm thick on the inside surface of the capsule wall, surrounding the DT gas core.

Cryogenic target experiments are planned for the Omega laser in the 1999 time frame to explore and develop cryogenic targets for the NIF.

2. Capsules

The spherical capsules that contain the DT fuel are currently made by three techniques. The drop tower technique [1] is used for glass and polymer shells and has been used for most capsules for the Nova laser. Droplets of polystyrene dissolved in solvents or pieces of gel containing glass precursors and gas-formers are dropped down heated towers. The solvents boil or the gel melts and decomposes, blowing tiny bubbles that emerge at the bottom of the tower as microballons. This technique achieves excellent clarity and surface finish, but sphericity and concentricity are limited by gravity and aerodynamic forces. A polyvinyl alcohol (PVA) gas permeation barrier is added, which can increase wall non-uniformity. The shell is coated with a polymer ablation layer which acts as the ablator. Capsules for experiments on Nova are typically 440 μm in diameter with a wall thickness, W, of about 5 μm, and we can achieve non-sphericity, as measured by $(d_{max}-d_{min})$, of ≤ 1 μm, and non-concentricity, as measured by $(W_{max}-W_{min})$ of ≤ 1.7 μm. As the size of the capsules is increased, however, these defects increase quickly.

The density-matched microencapsulation technique developed by the Osaka University Institute of Laser Engineering [2] became the preferred technique for producing the larger (~1 mm) shells needed for experiments on the Omega laser because of the good sphericity and concentricity characteristics achieved with this technique. The microencapsulation technique makes use of a triple orifice droplet generator. The inner fluid is a droplet of pure water. The middle fluid consists of polystyrene dissolved in solvents. The outer fluid is water with a small amount of surfactant added to keep the microencapsulated droplets from coalescing as they cure in a heated water bath. Omega capsules are typically 900 μm in diameter, and we can achieve non-sphericity ≤ 2 μm and non-concentricity ≤ 1 μm. It is difficult to obtain thin walls with microencapsulation. For Omega-sized shells the thinnest walls we have made is 7 μm. As the shell diameter is increased, concentricity and sphericity become more of a concern, and the minimum wall thickness also increases.

For both Nova and Omega capsules, the inner mandrel is coated with an ablation layer, ~30–50 μm thick, and frequently also with doped diagnostic layers, using glow discharge polymerization (GDP) [3] to produce a smooth, uniform polymer coating. In this process hydrocarbon gases flow through a radio-frequency discharge, creating a low-temperature C–H plasma. Shells are placed in a vibrating bounce pan in the plasma and a smooth, uniform polymer layer is deposited. Various dopants can be added to the gas to produce doped GDP layers, and multiple layers can be produced with different compositions.

The decomposable mandrel technique, conceived at LLNL [4] and developed at GA [5], is becoming the primary capsule fabrication method in the USA. Inner mandrels of poly(alpha-methyl styrene) (PAMS) are made by density-matched microencapsulation. These are overcoated with a polymer layer by the GDP process and are then heated to 310˚C. The PAMS decomposes into the monomer which permeates out, leaving the GDP shell. This technique has the benefit of excellent sphericity and concentricity, good clarity and surface finish, and also allows full control

over the thickness and composition of the outer layers. Shells with walls as thin as 1 μm and diameters of 1 mm have been made using this technique.

The non-sphericity of the PAMS mandrel is limited by the microencapsulation process and is typically ≤ 1 μm for Nova capsules and ≤ 2 μm for Omega capsules. Since the non-concentricity of the inner PAMS mandrel disappears with the PAMS as it is decomposed, the wall thickness uniformity of the finished capsules is excellent. The PAMS-GDP process currently does have somewhat rougher surface finish as shown on Table 1, where a typical drop tower Nova capsule is compared with a Nova capsule made by the PAMS-GDP process and a typical microencapsulated Omega capsule is compared with an Omega capsule made by the PAMS-GDP process. The atomic force microscope (AFM) measurements represented in this table are described in the characterization section below.

Table 1
Typical Capsules

	Nova Capsules		Omega Capsules	
Capsule Property/Type	Drop Tower Mandrel	GDP Mandrel	Microencapsulated Mandrel	GDP Mandrel
Non-sphericity	1.1 μm	0.7 μm	1.0 μm	0.5 μm
ΔW	1.7 μm	0.4 μm	0.4 μm	0.5 μm
Fringe Wobble	0.5 fringes	0.1 fringes	0.1 fringes	0.1 fringes
AFM, modes 2–10	274 nm	67 nm	396 nm	86 nm
AFM, modes 11–50	5 nm	22 nm	6 nm	18 nm
AFM, modes 51–100	1 nm	4 nm	2 nm	6 nm
Small optical features (2–5 μm width)	few	many	many	many

Capsules for ignition experiments in the National Ignition Facility will be ~2 mm in diameter with ~100 μm thick walls for indirect-drive experiments and ~3 mm diameter with very thin (~ few μm) walls for direct-drive experiments. For direct-drive targets the PAMS-GDP process is probably the only technique that could work, although the higher mode roughness of shells made by this process currently exceeds expected NIF requirements and must be reduced. For indirect-drive targets, the PAMS-GDP process is the prime candidate but microencapsulation is also a possibility as are more developmental techniques such as interfacial polycondensation. Use of stronger polymers, such as polyimide, or of beryllium metal would allow room temperature transport of filled capsules and is also being pursued.

3. Hohlraums

The hohlraums for ICF targets are made by depositing a metal layer on a machined mandrel which is subsequently etched away or dissolved, leaving the metal hohlraum vessel. The inside surface finish and the dimensions of the hohlraum are of critical importance so it is required that the surface finish and the dimensions of the mandrel be well controlled. Hohlraum mandrels are

machined to shape in very precise air-bearing lathes using single-crystal diamond cutting tools. These lathes are called diamond turning machines. Hohlraums for current experiments are typically 2 to 10 mm in diameter and 2 to 20 mm long. Tolerances of $< \pm 2$ μm and surface finishes of 200 Å RMS are routinely obtained.

Copper is most commonly used for mandrels when the hohlraum is to be made of gold although occasionally poly(methyl methacrylate) has also been used. Copper and poly(methyl methacrylate) both are machinable with diamond tooling, and copper can be dissolved with HNO_3 while poly(methyl methacrylate) can be dissolved with acetone, neither of which affect gold. Note that the use of diamond tooling to obtain the dimensional control and surface finishes required for hohlraums restricts the mandrel materials to those that do not form carbides. Otherwise, the sharp diamond edge will be rapidly degraded during machining. Aluminum mandrels have been used for uranium hohlraums since aluminum is dissolvable in NaOH, a base that does not affect uranium. Zinc mandrels have been used for silver hohlraums with the mandrel being dissolved in HC1 which does not affect the silver.

The hohlraum walls are typically 2 to 100 μm thick, with tolerances $\pm < 1$ μm and surface finishes of < 200 Å. Gold most often is deposited on the mandrels by electroplating; uranium is deposited by physical vapor deposition; and silver is deposited using electroplating. When poly(methyl methacrylate) is used as a mandrel it is first necessary to deposit a thin conductive layer on it by physical vapor deposition before electroplating can be carried out. Sputter coating of various metals onto the mandrels is also used.

Before dissolving the mandrel, a cut will be made through the coating on the small diameter region at each end of the hohlraum. Then when the mandrel is dissolved, a small hole will be left on each end of the hohlraum, and these holes will become the laser entrance holes. Many of the hohlraums have flats on the barrels which are cut out before dissolution of the mandrel to become sites for mounting of witness plates.

Current techniques appear well-suited for fabrication of hohlraums for ignition experiments on the NIF.

4. Characterization

Adequate characterization is critical to shell deliveries in two ways. Batch specifications give the acceptable parameter range for a delivery of shells, whereas the shell pedigrees which accompany them describe each individual shell. The specified parameter range for batch specifications and the allowed uncertainty in measurements slowly change and become more rigorous with time as experimenters need more sophisticated shells, and the target fabrication specialists develop processes and characterization capabilities to match. A list of techniques used is shown in Table 2; we will discuss some of these techniques below.

With regard to the batch specifications, our objective is to develop shell production processes with sufficient uniformity and control that we can eliminate culling steps, and need only measure a few shells of a batch to verify that they all meet the requirements. With the PAMS/GDP technique, for instance, diameter and surface quality of the PAMS mandrel are sufficiently tightly controlled that we need only examine a few shells (for diameter and surface flaws) to determine the acceptability of the batch. More than 50% of the batches have acceptable diameters. Creating the

Table 2
Typical Capsules

Name	Parameter	Limitations	Precision	Comments
Non-destructive techniques				
White light interference microscopy	Diameter	< 3000 μm	0.2 μm	Using reflections from layer surfaces
	Layer thickness	index mismatch	0.2 μm	
	Non-concentricity (total)	> 2%	2%	Using light transmitted through capsule
Digitized microscope image analysis	Diameter	–	1/4%	
	Out of Round	> 1/4%	1/4%	
X–radiography	Diameter	–	1/4%	
	Out of Round		0.5 μm	
	Layer thickness	> 0.3 μm	0.2 μm	Capability affected by layer dopants
Micro-balance	Layer thickness		0.2 μg	In grams/cm^2
AFM spheremapper	Power Spectrum	< 7μm O.o.R.		
XRF analysis	Dopant level (Cl, Si, Ge, Ti)	> 0.01 g/cc	10%	Can be used for any element with Z > 11
	Diagnostic Gas (Ar)	> 0.01 atm	10%	
Destructive Techniques				
Rutherford Back-Scatter (RBS)	Dopant concentration and homogeneity	< 20 μm deep	10%	
Nuclear Resonance Analysis (NRA)	Deuterium concentration and homogeneity	> 1%	10%	
Auger Spectroscopy	Dopant homogeneity	< 10 μm deep	10%	
Scanning Electron Microscope (SEM)	Surface features		< 1 μm	
Mass spectrometer	H/D ratio	500 μg	2%	

GDP mandrel by coating and then thermally decomposing the PAMS works well: ~75% of these shells are accepted for further processing. A big bottleneck for Nova capsules is application of the PVA permeation barrier. Losses and flaws limit the throughput here to ~3%. Subsequent GDP

coating steps are under good control, and ~50% of these shells pass the more intensive final inspection and are finally delivered.

When the processing is finished we check the outer surface finish using an Atomic Force Microscope (AFM) Spheremapper. This instrument was originally developed at LLNL [6] and enables one to bring an AFM up to a shell mounted on a vacuum chuck which is rotating on an airbearing. The high sensitivity of the AFM combined with the smooth rotation of the air bearing enables very precise measurement of the shell profile. To fully characterize a shell, we measure three mutually orthogonal sets of three parallel traces, then average their Fourier Transforms to get a power spectrum for the shell surface (Figure 1). This measurement requires ~1 hr/shell, so measurements on a few shells are used to establish batch characteristics. (In special cases, we measure every shell.) In addition to meeting batch specifications, it is necessary to characterize each individual shell to determine where it lies within the range of allowable specifications. We always measure diameter, wall thickness, non-concentricity, out-of-roundness, and may also measure dopant concentration, burst strength, and shell gas permeation half-life.

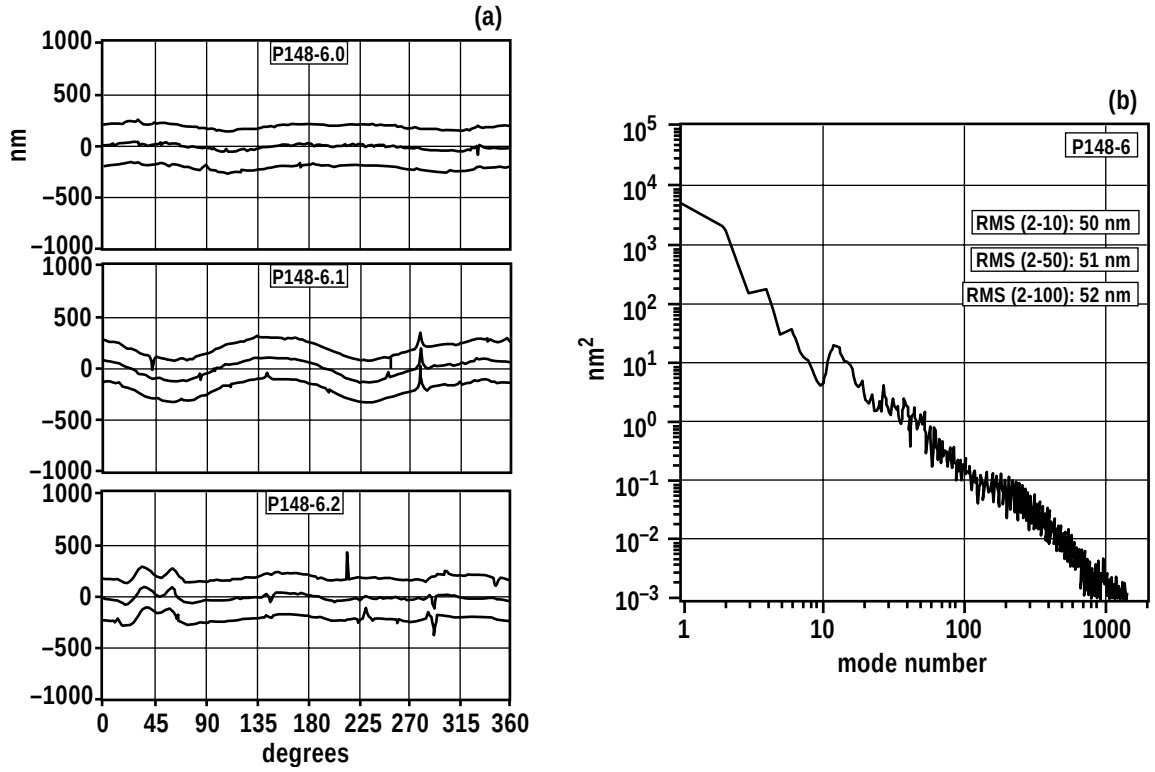

Fig. 1. (a) Shell profiles and (b) the resulting roughness power spectrum measured for a GDP/PAMS shell using the AFM Spheremapper.

We use x–ray fluorescence to measure the concentration of elements with Z > 11 with elaborate procedures to allow precise quantification of dopants in our shells. The x–ray beam is collimated so the shell is bathed in a uniform x-ray flux. The flux reaching any particular part of the shell, and the resulting fluorescence reaching the detector are attenuated to varying degrees, so we must calculate a correction to the signal which depends on sample geometry using a modeling program which sums the attenuation-corrected fluorescence from all parts of the shell. For each

element, it relies on a sensitivity coefficient determined by the flat film calibration for that element. With these precautions, we can quantify dopant concentration with an uncertainty of 5 to 10% for Cl, Si, Ge, Ti, and Ar.

The diameter and wall thickness are measured using a white light interference microscopy with a precision z-stage. We vertically translate a shell under the microscope, bringing successive layers to the same height. Using white light interferometry, and combining light reflected off the surface with that reflected off a static reference mirror, we can set successive surfaces to the same height within < 0.1 μm. With the precision transducer on our z-stage, we can then read off the change in height with a precision of 0.01 μm, and an accuracy ~ 0.2 μm over a range of 3000 μm. The sensitivity of this system is such that we can locate all the interfaces in a multi-layer composite shell and determine the thickness of each of those layers.

The non-concentricity of the shell is measured with white light interferometry, set up to detect interference fringes from light passing all the way through the shell. The outer and inner surfaces of the wall form lenses and any offset in their centers causes an offset in the interference fringes. We have determined the relationship between the surface offset (the non-concentricity) and the fringe offset with a ray-tracing program which calculates fringe position. For shells currently of interest to the ICF program, we have developed the empirical relationship:

$$NC \equiv \frac{\Delta_C}{W} \cong \frac{1}{C} \times \frac{\Delta_f}{OD} \times \frac{(n-1)}{\sqrt{n}}$$

where NC = fractional nonconcentricity
Δ_C = offset of the surface centers
W = wall thickness
Δ_f = offset of the fringe center
OD = outside diameter of the shell
n = average index of refraction of the shell wall
C = 0.367 for plastic shells (tested between OD = 0.4 to 1.1 mm, and W up to 50 μm.
Using high magnification lenses to detect the fringe offset, we can measure NC down to ~2%.

We also use x–radiography for characterizing shell layers, particularly the gas barrier (poly-vinyl alcohol). Since it contains more oxygen than the other plastics, there is often sufficient contrast in the image that by taking a second radial derivative, we can measure the layer thickness with a resolution of ~0.2 μm, even when it is sandwiched between other plastics [7].

5. Ignition Targets

Targets for ignition experiments in the National Ignition Facility are expected to be similar to targets for current experiments, and to require similar fabrication techniques, with two exceptions: they will be larger and they will require an inner spherical shell layer of frozen DT ice. Capsules for direct drive ignition experiments will be polymer shells about 3 mm in diameter with walls as thin as possible. The shell will be lined with a smooth, uniform DT ice layer about 300 μm thick. Capsules for indirect-drive ignition experiments will be about 2 mm in diameter and will consist of a polymer shell over-coated with about 150 μm of doped polymer ablator and

lined with about 100 μm of smooth, uniform DT ice. Beryllium metal capsules lined with DT ice are also being pursued. The DT gas in the center of the capsules will be at a density in thermal equilibrium with the DT ice (~0.3 mg/cm^3). We believe the PAMS-GDP capsule fabrication process is well-suited for production of polymer ignition capsules and development is underway to achieve the large diameters, precision and smoothness needed. Development of beryllium capsules is also under way. Los Alamos National Laboratory (LANL) is working on precision micro-machining and joining of beryllium hemispheres, and LLNL is working on overcoating a polymer mandrel with sputter-coated Be.

Hohlraums for ignition targets will be similar to those used in current experiments. Gold cylinders 5 mm in diameter by 10 mm long with 30 μm walls made by the machine-plate-leach process described above are the primary candidate, although other shapes and materials are also being pursued. Ignition hohlraums will probably need to be filled with about 1 atm of He or H/He gas, which will require thin polymer windows over the laser entrance holes. Because ignition hohlraums will contain capsules with an inner layer of frozen DT ice, mechanisms for cooling these targets to about 20K and for precisely controlling their temperature profiles will have to be provided. A candidate ignition target design is shown in Figure 2.

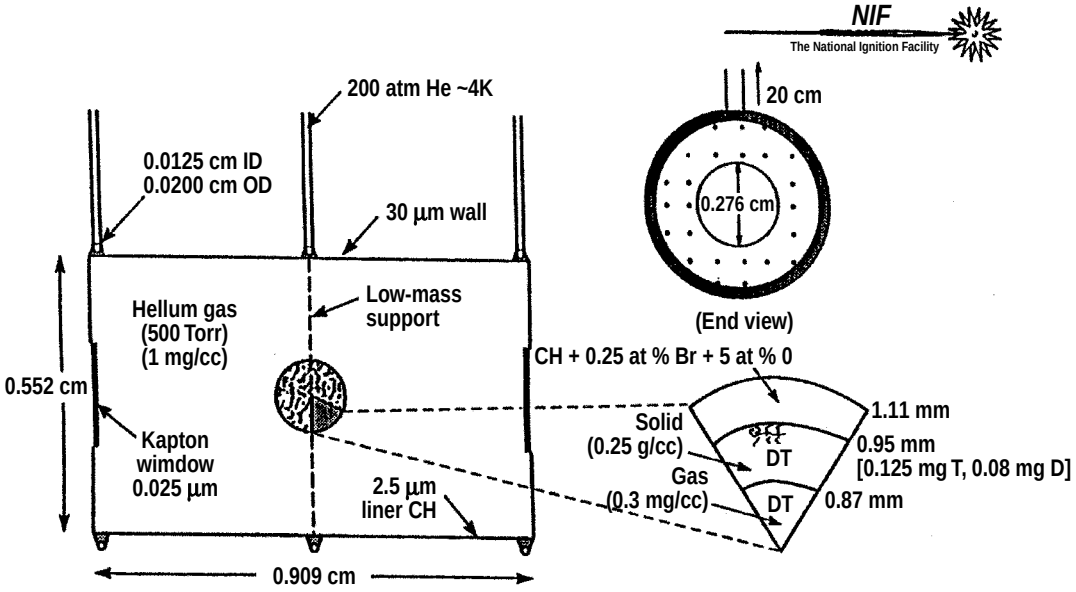

Fig. 2. Candidate indirect drive ignition target.

The thick DT ice layer required inside ignition capsules requires significant development effort to fabricate, characterize and field. The ice layer will be produced by filling the capsule with up to 1000 atm of DT gas and then cooling the capsule to 20K to condense and freeze the gas. The natural beta decay of the tritium provides a heat source that can be used to redistribute the DT ice into a uniform layer inside the capsule in a process called ‘‘beta layering’’ [8]. The inner surface smoothness of this ice is a major concern. Indirect-drive targets with beryllium capsules can probably tolerate a smoothness of ~5 μm RMS; indirect drive with polymer capsules may require a smoothness ≤ 1 μm RMS; and direct-drive capsules may require a smoothness ≤ 0.1 μm RMS. Natural beta layering with very precise temperature control appears to achieve smoothness ≈1 μm

RMS, and provision of additional heat in the DT fuel by infrared or microwave heating to augment the beta layering can further reduce surface roughness, as shown in Figure 3.

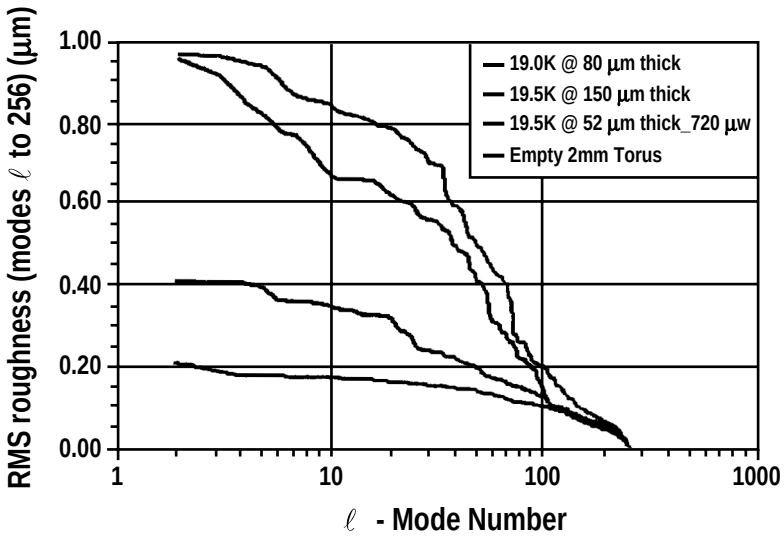

Fig. 3. Beta-layered DT ice surface finish (from experiments at LANL).

6. Conclusions

This paper summarizes the techniques used to fabricate ICF targets for current experiments. These techniques meet current requirements but require continuous development and improvement to keep up with the improvements being made in ICF driver uniformity, target design and ICF physics understanding. Extension of the current fabrication techniques to the development and production of targets for ignition experiments appears possible,but will require development effort to achieve the larger sizes, high precision and cryogenic DT ice layers needed. The fabrication techniques currently used for ICF targets were developed without serious consideration to their eventual extrapolation to the fabrication of low cost, mass-produced targets for inertial fusion energy applications. For the most part, the current techniques do not appear to extrapolate easily to low cost mass-production, and further development will be needed to achieve this ultimate goal of inertial fusion.

7. Acknowledgment

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References

[1] R.J. Crawley, A hollow droplet generator for polymer shell production, J. Vac. Sci. Technol. A 3 (1986) 1138–1141.

[2] T. Norimatsu, C.M. Chen, K. Nakajima, M. Takagi, Y. Izawa, T. Yamanaka, S. Nakai, Cryogenic taragets are related technologies at ILE Osaka University, J. Vac. Sci. Technol. A 12 (1994) 1293.

[3] S.A. Letts, D.W. Myers, L.A. Witt, Ultrasmooth plasma polymerized coatings for laser fusion targets, J. Vac. Sci. Technol 19 (1981) 739.

[4] S.A. Letts, E.M. Fearon, S.R. Buckley, M.D. Saculla, L.M. Allison, R. Cook, Fabrication of polymer shells using a depolymerizable mandrel, Fusion Technology 28 (1995) 1797-1802.

[5] B.W. McQuillan, A. Nikroo, D.A. Steinman, F.H. Elsner, D.G. Czechowicz, M.L. Hoppe, M. Sixtus, W.J. Miller, The PAMS/GDP process for production of ICF target materials, to be published in Fusion Technology 1997.

[6] R.J. Wallace, R.L. McEachern, and W.W. Wilcox, Laser ablation machining of ICF capsules, ICF Quarterly Report 4 (3) (1994) 79, UCRL-LR-105821-94-3.

[7] R.B. Stephens, Precision shell characterization using radial averaging of x–ray images, J. Vac. Sci. Technol. A 13 (1995) 979; R. B. Stephens and D. Bernat, Algorithm for better x–radiography analysis, Fusion Technol. 29, to be published July 1997.

[8] J.K. Hoffer, L.R. Foreman, L.R. Mapoles, and J.D. Simpson, Forming a 'perfectly' uniform shell of solid DT fusion fuel by the beta layering process, in Proc. 14th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion, Würzburg, Germany, September 1992.