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ABSTRACT

Hohlraums are an integral part of indirect drive targets for Inertial Confinement Fusion (ICF) research. Hohlraums are made by an electroforming process that combines elements of micromachining and coating technology. We describe how these target elements are made and extensions of the method that allow fabrication of other, more complex target components.

I. INTRODUCTION

Until December of last year, details of indirect drive targets for ICF had been classified. Indirect drive inertial fusion uses a driver (a high powered laser or particle beam) to heat a radiation cavity called a hohlraum to hundreds of electron volts (1 eV is approximately 12,000 K). The x-radiation from the hohlraum wall can be used to implode a fuel pellet, or drive some other plasma experiment. This paper details the manufacturing process for hohlraums for a number of laser drivers. The basic process is not new;[1] but it hasn't been published in the open literature before, and we offer some novel refinements.

Because ICF lasers are energy limited hohlraums need to be small to reach the temperatures of interest. For the Nova laser at Lawrence Livermore National Laboratory (LLNL), the smallest hohlraums are cylinders 1.6 mm in diameter and 2.75 mm in length (in practice, length can vary considerably; we have made scale 1 hohlraums as short as 2.25, some as long as 4.0 mm). Hohlraums of this size typically reach temperatures of 250 eV. Larger sizes are used for lower temperature drives, and a hohlraum sizing system has evolved that scales the linear dimension of the hohlraum. Thus scale 2 and 3 hohlraums are 3.2 and 4.8 mm in diameter and 5.5 and 8.25 mm in length, respectively. Alternative designs make complete hohlraums from 3 cylindrical chambers or from two toroidal sections and a spherical section.[2] The same scaling system applies to these designs. Figure 1 shows a design drawing of a typical scale 1 hohlraum for Nova. Nova is the world's most powerful laser; for other laser systems [such as the Helen laser at Aldermaston Weapons Establishment in the UK, or the Trident laser at Los Alamos National Laboratory (LANL)], the hohlraums are smaller, less than 0.5 mm in diameter and length. All of these designs share the same manufacturing process. The process has a number of useful extensions that apply to the manufacture of other components of ICF targets.

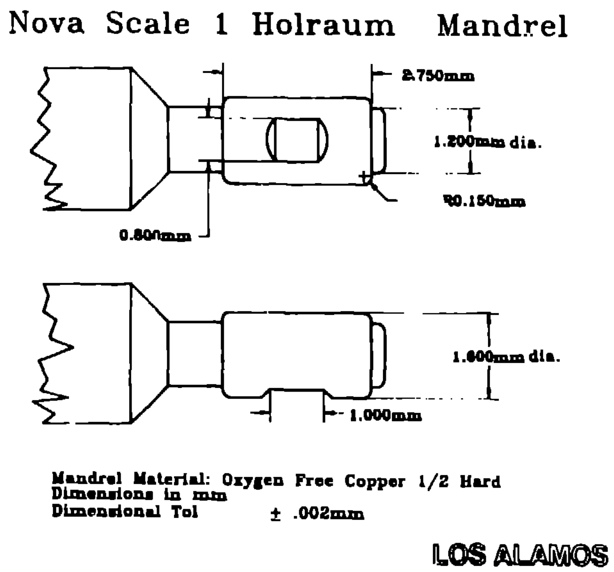


Figure 1. Typical scale 1 Nova hohlraum mandrel. The diagram shows the dimensions. Surface finish is typically 20 nm rms. The shank and the 1200 mm step on the right form the eventual laser entrance holes.

II. HOHLRAUM MANUFACTURE

In general, hohlraums for ICF are made by electroforming gold. In this process, a mandrel is machined from some material that has different chemistry from the hohlraum material (most often copper), the mandrel is coated with gold by electrodeposition to the proper thickness, the coating is breached by post-machining, and the mandrel is chemically dissolved or leached to leave a shell of the coated material. Thus, there is the choice of mandrel material, a mandrel machining operation, a coating operation, a post machining operation, and a leaching operation that produces a hohlraum for the ICF target.

A. Mandrel Materials

The mandrel material must be chemically removed from the interior of the coated structure. For gold hohlraums, there is latitude chemically in the choice of mandrel material because gold is relatively inert. Our initial choice was free machining brass, however, this material proved to be riddled with voids on a sub-micron scale. The subsequent plating operation created warts of gold in the void locations. Many hohlraums are assembled from several parts and the warts use up tolerance and prevent the parts from fitting properly. Following a suggestion from our British colleagues,[3] we next tried Si/Bronze brazing rod. This material has hard inclusions, but is fully dense and is useful for the small Helen and Trident hohlraums. Currently for the Nova hohlraums, we use half hard, oxygen-free copper, which we can dissolve completely with nitric acid without harming the gold surface.

B. Mandrel Machining

Hohlraum interiors need smooth surfaces. Ours are turned on a computer-controlled (either Allen Bradley or Aerotech controllers), air bearing lathe (either a Pneumo 2000 or a Moore M-18). We use diamond tools, as many as three, to turn the copper mandrels to specification. Generally the tolerances on dimension are $\pm$ 2 µm, and the surface finish on the mandrel sides is less than 25 nm rms. The majority of the Nova hohlraums can be machined with a collet on the 0.125 inch shank However, when the post-machining is especially close, or the hohlraums are small (as is the case for the Helen or Trident hohlraums), we designed re-usable centering bases that are not coated, but are used for the mandrel machining and post-machining operations. The bases have fiducial surfaces machined on the face of the base and on the barrel to provide for accurate repositioning in the lathe. The mandrel shank inserts into a blind hole in the barrel of the fixture and is held in place with a set-screw. A spring loaded fixture holds the mandrel and the base to the lathe spindle and allows centering on the fiducial surfaces. The mandrel is rough cut on a CNC conventional lathe (not an air bearing) to within about 10 mm of finish dimension and transferred to the air bearing machines above for finishing. The laser entrance holes (LEHs) are electroformed also; that is, a sharp step is cut on the end of the mandrel, (see Figure 1; the 1.200 mm diameter is the LEH) which becomes the LEH when the gold coating is removed and the mandrel is dissolved (more on this step follows in the section on post machining).

Some hohlraum variations call for a flat which is useful for mounting an experiment. The flat is cut on the side of the mandrel with a fly-cutter; an air spindle mounted on the cross feed of a lathe that spins a diamond tool about a 3-4 inch radius. This tool cuts a flat section typically 1 mm long and 0.8 mm wide (for scale 1 dimensions) in the side of the mandrel, again under numerical control.

Other hohlraums are assembled from multiple parts. Here the fabricator has some options. The hohlraum can be made longer than the design to allow for a kerf, and cut in half after the coating operation. This procedure produces two parts which are later butt-joined. Alternatively, the halves can be made on separate mandrels. In the later case, an assembly flange can be made by making a sharp step in the mandrel diameter at the proper length. A male half can be made by postmachining to the step and a female half by machining past the step 5 µm or more. The halves are assembled by inserting the male half into the female half until it bottoms on the step. This provides a more precise assembly than the simple butt joint.

The mandrels are inspected using a laser micrometer (Lasermike model 60-05 by Techmet Co.) to ensure that they are within tolerance, and they usually are because of the lathe controls. Surface finish is checked with a Wyko 3-d profile interferometer on the first part, a part from the middle of the production run, and the last part made. The parts are rinsed thoroughly with methanol and blown dry with pure nitrogen. The cleaning step is quite important because improper cleaning is a major cause of coating failure. The freons or "canned air" are especially pernicious to the electroplating process presumably because of materials dissolved in them and deposited on the part in the spraying process; in our experience these materials can be next to impossible to remove. Cleaned, inspected mandrels are delivered in their respective bases to the coating operation. Figure 2 shows a number of machined hohlraum mandrels.

<insert Figure 2.>

Figure 2. Gold coated hohlraum mandrels. Nine gold coated hohlraum mandrels are shown with the PTFE electroplating fixture. The empty space shows the O-ring seal.

C. Mandrel Coating

The mandrels are racked up to 16 at a time into a PTFE fixture incorporating O-rings that are a tight fit on the mandrel shank. The fixture regulates the length of mandrel exposure to the bath and facilitates the determination of the current required for the deposition. By exposing a constant cathode area for plating we eliminate a time-consuming masking step and shield the mandrel bases from plating solution that would destroy the fiducial surfaces. The fixture hangs partly submerged in a 5 gal gold plating bath.

An Enthone Sel-Rex® BDT 510 gold-sulfite electrolyte is used to deposit 22 ± 2 mm of gold (typically) onto the mandrel surface. The bath is maintained at a temperature of 45 C with a pH in the range of 8.7 to 9.0. The bath is continuously agitated and filtered throughout the coating run. A current density of 3 amps per square foot is used and the concentration of the bath is kept at approximately 1 tr oz/gal. A coating fixture showing a run of gold coated mandrels is shown in Figure 3. Due to trace quantities of arsenic, the resulting deposit is harder and thus more machinable than pure gold.

D. Post Machining

The coated mandrels for the typical Nova hohlraums are centered on a Dover air bearing spindle using a wobble chuck designed by one of us (LS). The wobble chuck both centers the hohlraum and aligns its axis to the axis of the spindle. Facing cuts are made by hand (not under computer control) across the end and into the mandrel shank to expose the copper in the LEH region using a square tipped cut-off tool. Other holes or slots may be necessary for the diagnostic access to the experiment; these must be carefully located because they refer to specific instrument locations on the target chamber wall. We hold about 0.2 degree tolerance on the holes; this corresponds to about 3 mm on the hohlraum surface and about 10 mm on the target chamber wall. The diagnostic holes and slots are milled on a Hauser jig borer with miniature end mills. Hole locations and sizes are verified on an optical comparator.

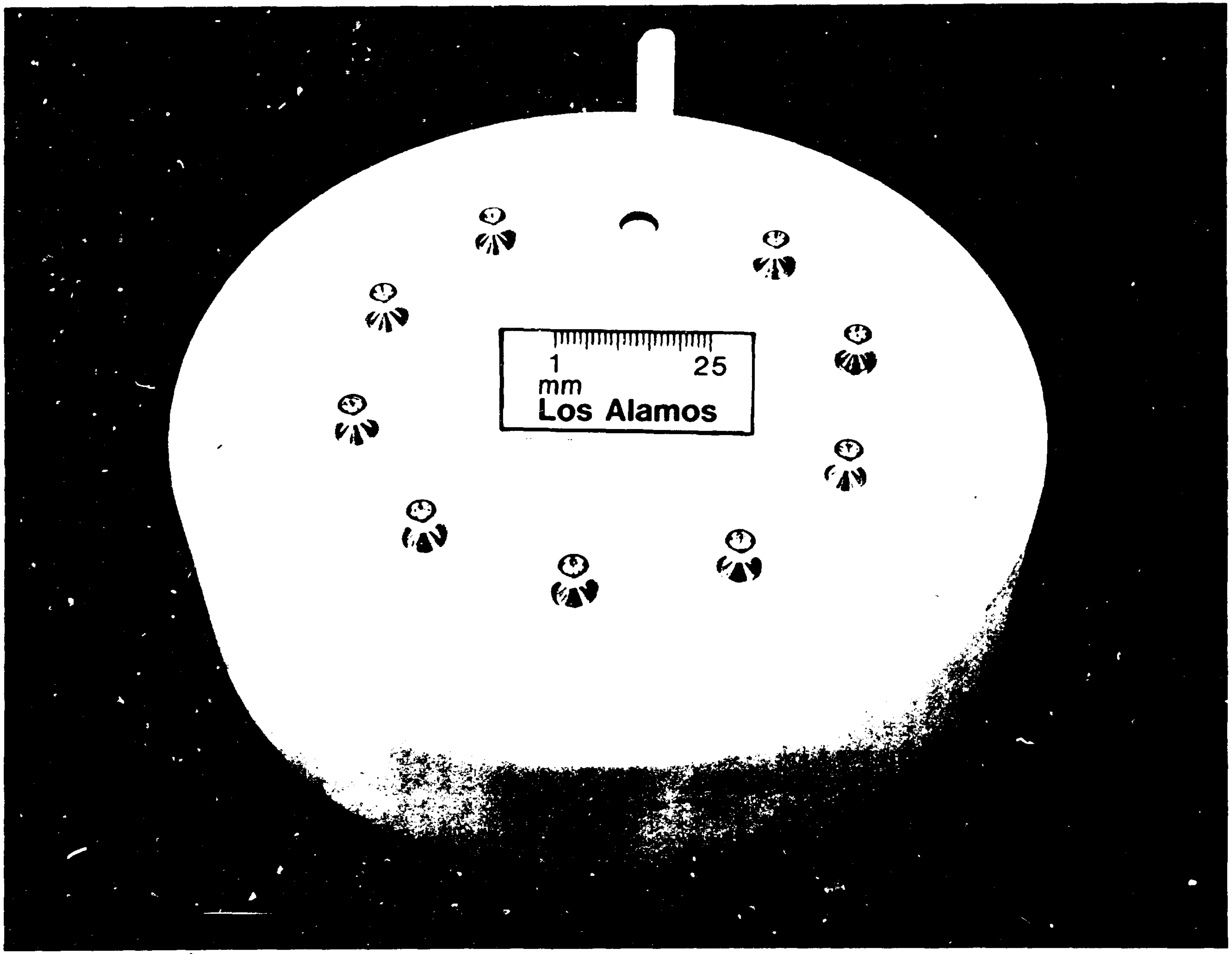
Coated mandrels for the precision hohlraums, still registered in their uncoated bases, are recentered in the CNC lathe. Using the fiducial surfaces the operator can reposition with a total run-out of less than 0.2 µm. After post-machining, the mandrel and the base part company.

The mandrel with the necessary holes cut through the gold is submerged in a mixture of HNO_3 and a surfactant. It dissolves in about an hour. Figure 3. shows some spherical gold hohlraum parts.

< Insert Figure 3>

Figure 3. Gold hohlraum parts. Parts for a McFee hohlraum are shown together with a post-machined, coated mandrel (at 8 o'clock) and an uncoated mandrel (at 10 o'clock).

This description represents what we would call the standard hohlraum electroforming process. As we indicated in reference 1, the process has evolved at at least four laboratories and is detailed in documents that remain to be declassified. The following sections give some contributions we have made to the electroforming process that have allowed manufacture of unprecedented targets and hohlraums.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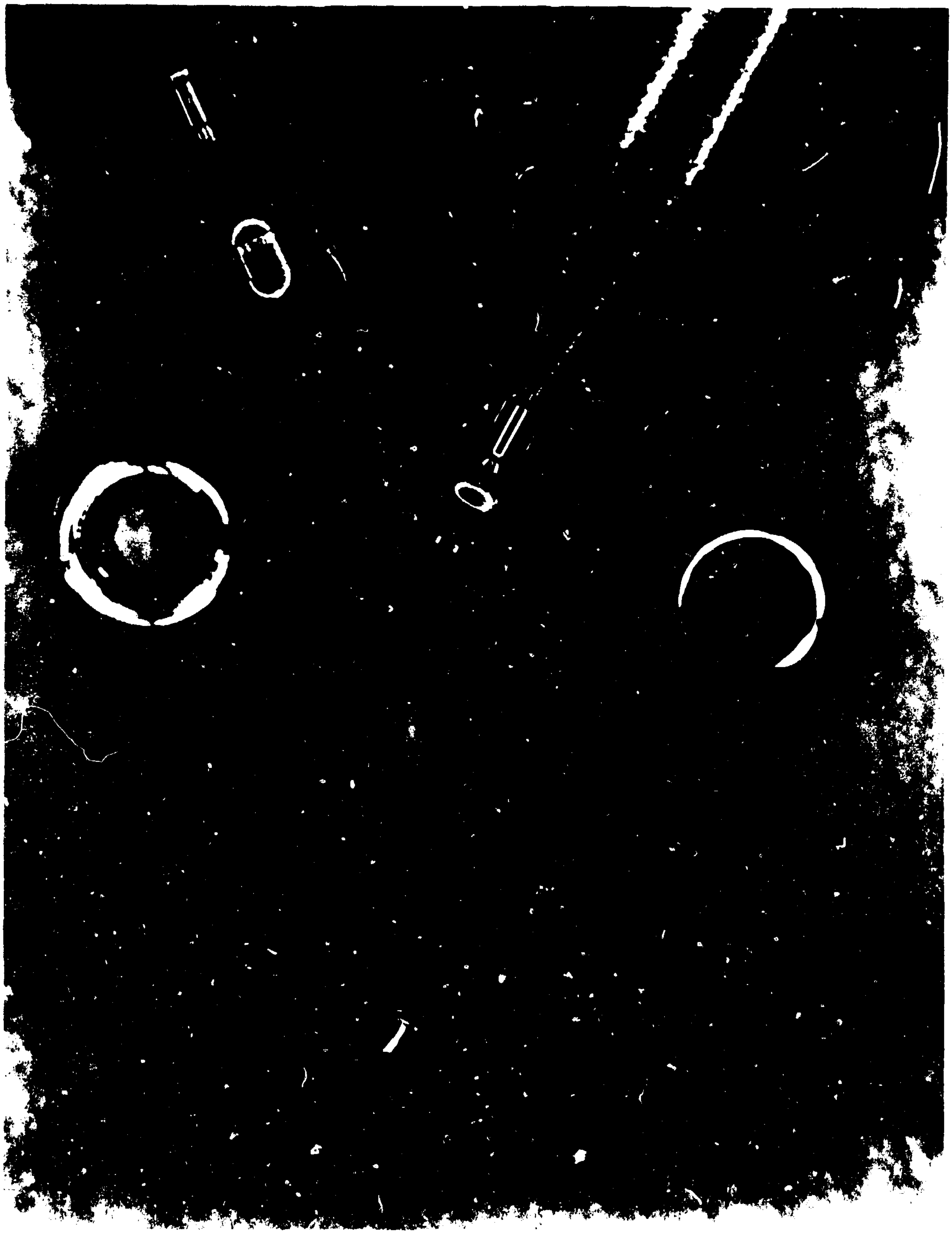


E. Gas-Filled Hohlraums

An unusual hohlraum designed to study laser plasma instabilities in gas filled hohlraums was recently designed by Fernandez and Wilde.[4] Data from this target and its cousins played a major role in our understanding of laser-plasma instabilities at scale lengths relevant to the National Ignition Facility.[5] It utilized a toroidal segment similar to a McFee scale 2 end section(D= 3.2 mm), but slightly stretched to include a 200 μm cylindrical center section to provide for diagnostic holes and slots. A diagram is shown in Figure 4. This shape gives 220 eV temperatures and 2 mm long laser path lengths inside the hohlraum. This hohlraum differed in manufacture from the "standard" variety in three important aspects. First it was a "thin wall"; that is, the gold electroplated layer was only 2 μm thick. After the plating operation, the Au coated mandrel was coated with 160 μm of Epon 815 epoxy, cured and then post-machined, cutting the epoxy to constant thickness and exaggerating the flat section in the LEH area. The thin gold wall was designed to show the location of the laser illumination spots through the gold without having to bore diagnostic holes in the hohlraum wall, and the epoxy wall added reinforcement to the structure.

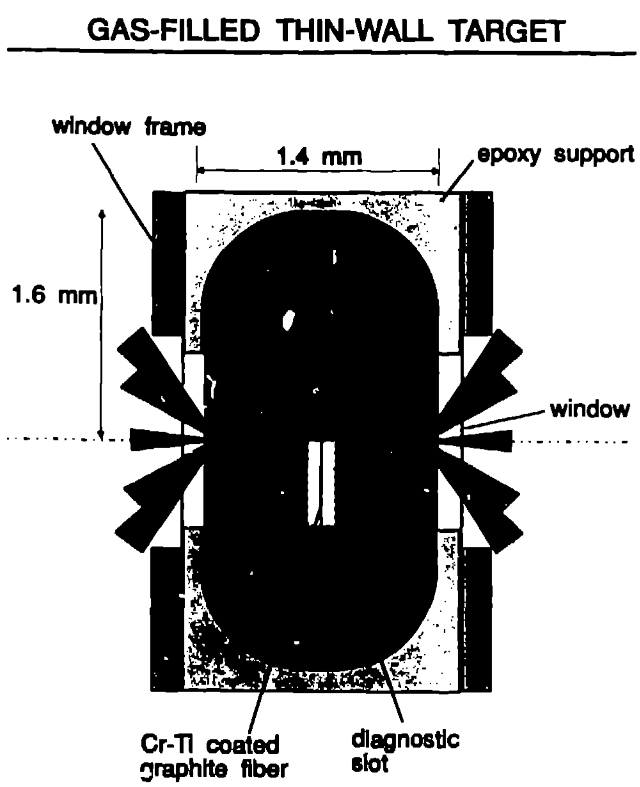


Figure 4. Diagram of a gas filled hohlraum.

The LEHs of this hohlraum were sealed with silicon nitride windows on Si frames. These windows trapped an atmosphere of neopentane ($C(CH_3)_4$) in the hohlraum interior. The window has a clear 1.2 μm square aperture and is only 0.2 μm thick. They withstand a pressure difference of about 20 psia in the direction of the frame (much less in the other direction). The target support is a hollow tube connected to a pressure transducer and a small valve. The miniature manifold is pumped out and filled with neopentane to a pressure of 1 atmosphere. The windows are quite well sealed and the tubing and transducer provide plenty of reserve capacity to keep the hohlraum pressurized for many hours in vacuum. Via the transducer, the experimenter can read hohlraum pressure while the target is inside the NOVA target chamber[6]. Figure 5 shows an example of this hohlraum target over a postage stamp for scale.

<insert Figure 5>

Figure 5. A gas filled hohlraum for long scale length plasma studies. Gas filled hohlraums like the one above are manufactured for long-scale-length plasma studies on the NOVA laser. This hohlraum is shown over Jo's face from a Louisa May Alcott commemorative stamp. The dimensions of the target are shown in figure 4.

This target is also fabricated in a normal walled (nominal 22 μm gold) version with a 2 500 μm long diagnostic slot on the equator. This slot showed the full length of a 6 μm carbon fiber mounted across the center of the hohlraum interior. The fiber is located using a 50 μm hole bored in the wall (before leaching) and sealed around the fiber with epoxy. The fiber is co-sputter coated with a homogeneous 50/50 Ti/ Cr mixture. Careful

How to insert
Figure 5

spectroscopy of the x-ray emission of these two elements gives the temperature inside the hohlraum as a function of position and time.[7]

F. Cylinder Implosion Targets

Targets designed to measure instability growth in cylindrical geometry provided a showcase of hohlraum-like processing. The heart of the target is a cylinder mounted across the axis of a scale 1 Nova hohlraum and designed to implode when the hohlraum was driven. The cylinder is 640 µm in outside diameter and its ends extend outside the hohlraum wall. Made of polystyrene, the interior bore is smooth, 430 µm in diameter, but the midline incorporates a band of chlorinated polystyrene to serve as a spectroscopic marker to track the implosion. The exterior of the cylinder reduced to a waist 430 µm long and 520 µm in outside diameter at the midline. The waist had a dodecahedral section (12 sides) machined onto the outside surface. These flats function as triangular wave regular perturbations on the cylinder. As the cylinder implodes, these perturbations feed through to the interior surface, where the 4 µm thick layer of chlorinated polymer marks the inner edge.

Fabrication of the cylinder begins by machining an aluminum mandrel, in the relocation base, to 430 µm, the bore of the implosion cylinder. The mandrel is dip coated with chlorinated polystyrene dissolved in toluene and cured. Back on the lathe, this layer is trimmed to a thickness of 4 mm, and a length of 160 µm. Next the mandrel coated with approximately 5 µm of parylene (di-paraxylylene) to immobolize the chlorostyrene. The mandrel is dip coated with polystyrene dissolved in toluene, building up a layer of cured polystyrene at least 180 µm thick. The mandrel returns to the lathe where the outside of the cylinder is cut to dimension and the midline waist is cut. The spindle is locked and registered in one of twelve locations separated by 30°. The fly cutter, previously described, cuts the first facet on the exterior of the waist. The chordal flat is only 4 µm deep . The process continues until the central section of the cylinder is dodecahedral. Now the mandrel can be removed; it dissolves in NaOH without harming the polymer structure built up on it.

G. Further Refinements

Using the precision bases, the thickness of the gold coating can be removed from a region of the hohlraum surface without reducing the diameter of the mandrel significantly. We have used this technique to make gold hohlraums with a plastic extensions (for diagnostic purposes). The gold is machined away from the extension and the entire mandrel, partially-Au-coated, is coated with polymer. When the mandrel is leached after the two coatings, the product is a shell with a gold and polymer wall in one region and only a polymer wall where the gold was removed.

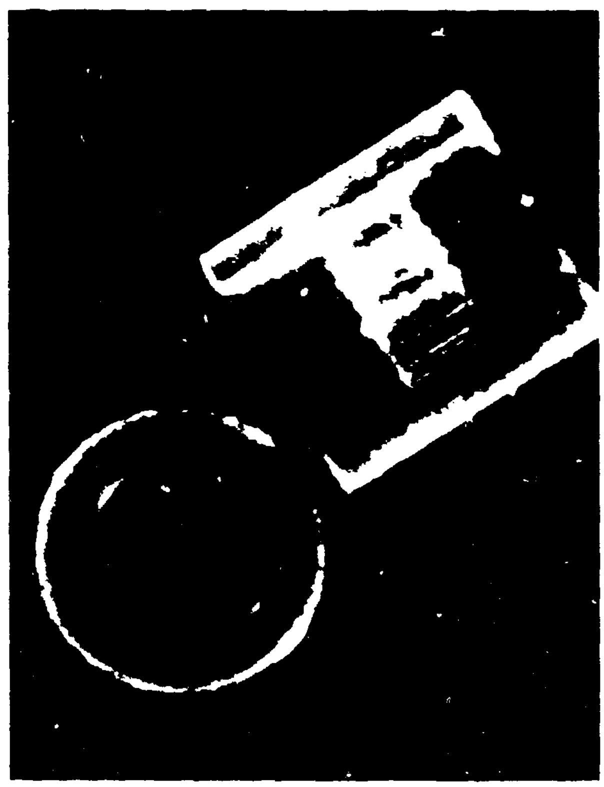
Another application locates a gold band marker layer in the center of a polymer cylinder. An aluminum mandrel is coated with 2-5 µm of layout fluid, a polymeric material used for marking machine parts. The coating is simple; the part is sprayed with the fluid while it is still in the lathe. It dries in a minute or two. The layout fluid is machined off the central portion of the cylinder. The mandrel is coated with gold by physical vapor deposition (PVD). The remaining layout fluid is removed with acetone in an ultrasonic bath, and it takes the gold with it leaving a gold band on the aluminum mandrel. The mandrel is dip coated with polystyrene in toluene, cured, and machined to dimension. The mandrel is dissolved in NaOH leaving the cylinder with an interior gold band as shown in Figure 6.

<insert Figure 6>

Figure 6. Polymeric cylinder with an internal gold band. This target component is 700 µm long, 630 µm in diameter with 100 µm thick polystyrene walls. The gold band is 200 µm long and 0.5 µm thick.

III. CONCLUSIONS

Hohlraum manufacture, recently declassified, combines precision micromachining and electroplating processes to produce parts for indirect drive ICF and physics research at high temperatures. Refinements to the technique by fixturing for precise relocation in the diamond turning machine and



reusing the mandrel in a series of coating processes allows fabrication of novel experimental targets for the ICF Program.

REFERENCES

1. We credit William Ramer (ret.) and his micromachining group at EG&G Rocky Flats, Boulder, CO, who did pioneering work on the hohlraum electroforming process, based on technology transferred from LLNL (C. W. Hatcher, private conversation). This capability has recently been transferred to General Atomics, San Diego. Doug Sutton (ret) at Aldermaston Weapons Establishment, UK, also established a hohlraum manufacturing capability based on the same technology. Many references await declassification.

2. The McFee hohlraum, named for its inventor, R. McFee, LANL.

3. Doug Sutton, AWE, UK, Private Communication.

4. J.C. Fernandez, K. S. Bradley, J. A. Cobble, N. D. Delameter, P. L. Gobby, R. G. Hockaday, W.W. Hsing, M. A. Salazar, and B. H. Wilde, "Plasma Instability Measurements in Hohlraums", presented at the 24th Annual Anomalous Absorption Conference, Monterey, CA, June 1994.

5. The National Ignition Facility (NIF) is a laser ICF facility designed to reach ignition and is under consideration by the Department of Energy.

6. We acknowledge LLNL employees Dino Ciarlo for fabricating the windows, Marita Spragge for her advice on mounting the windows, Gary Stone for his help fielding the gas system, and Russell Wallace.

7. W.W. Hsing, R.E. Chrien, B.H. Failor, J. C. Fernandez, J.D. Colvin, N. D. Delameter, N.E. Elliott, P.L. Gobby, M.A. Salazar, B. H. Wilde, H. N. Kornblum, T. Murphy, T.D. Shepard, and G.F. Stone, "Creation and Charaterization of a Long-Scale-Length Plasma in a Toroidal Gas-Filled Hohlraum", presented at the 24th Annual Anomalous Absorption Conference, Monterey, CA, June 1994.