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Micromachining of Inertial Confinement Fusion Targets*

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Many experiments conducted on today's largest inertial confinement fusion drive lasers require target components with sub-millimeter dimensions, precisions of a micron or less and surface finishes measured in nanometers. For metal and plastic, techniques using direct machining with diamond tools have been developed that yield the desired parts. New techniques that will be discussed include the quick-flip locator, a magnetically held kinematic mount that has allowed the direct machining of millimeter-sized beryllium hemishells whose inside and outside surface are concentric to within 0.25 micron, and an electronic version of a tracer lathe which has produced precise azimuthal variations of less than a micron.

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Introduction

Targets used in inertial confinement fusion (ICF) experiments are small, with linear dimensions measured in microns and surface finishes measured in nanometers. Many of the parts of these targets are fabricated using precision lathes, either by directly machining the part or by first machining a mandrel, coating it with the desired material and then chemically removing the mandrel.

Innovative techniques are constantly being developed which allow more and better parts to be fabricated using these lathes. In this paper we describe the fabrication of four different ICF target parts, each of which were made possible by a new development using the precision lathes.

Precision Lathes

Central to the micromachining effort at Los Alamos are the precision lathes. These are air-bearing spindle, two axis, computer numerical control (CNC) horizontal lathes, each

with encoders and laser interferometers on both axes. There are 4 such machines currently in use (2 Moore M-18's, a Pneumo 2000 and a Pneumo 325). The resolution (minimum single axis movement) is 10 nm for each machine. Using a 25 micron radius diamond tool a single axis (facing) cut on copper routinely results in a 3-4 nm rms surface. Though diamond cutting tools are not used for machining all materials, the high precision and surface finish that are attained with these lathes using diamond tools lead many to commonly refer to them as diamond turning machines (DTM's).

Thinwall Hohlraums

A major component of an indirect drive ICF experiment is the hohlraum, a high-z enclosure in which the laser light is absorbed and thus converted to soft x-rays. Such hohlraums have been produced in both cylindrical and spherical shapes with linear dimensions ranging from a few hundred microns to several millimeters [1]. In the simplest case a copper mandrel is machined using the precision lathe, and then electroplated with gold to a thickness of 25 microns. When the copper mandrel is removed using nitric acid, the gold hohlraum is self-supporting.

As a more complicated example we discuss the fabrication of cylindrical, thinwall hohlraums used in experiments at both the Omega laser at the University of Rochester and the Nova laser at Lawrence Livermore National Laboratory [2].

For these hohlraums the gold wall thickness is required to be only 2 microns. At this thickness, the >10 keV x-rays produced where the laser beam interacts with the gold are partially transmitted through the remaining gold. By imaging these transmitted x-rays with pinhole cameras, the laser beam locations can be monitored.

The 2 micron gold walls of these hohlraums are not self-supporting, so a uniform 100 micron layer of epoxy is added to provide support. Consisting of low-z elements, the epoxy negligibly affects the transmission of the more energetic x-rays. But the addition of this epoxy layer requires additional steps in the hohlraum fabrication.

For these thinwall hohlraums the copper mandrel material is held in bases as shown in Fig. 1. An indicating surface is machined onto this base during the process of machining the mandrel. This guarantees the indicating surface and the cylindrical hohlraum are concentric. The base is held onto the lathe with a spring-loaded fixture. This fixes the z-position of the base (distance along the lathe axis), but allows adjustment of the transverse x- and y-positions (perpendicular to the lathe axis).

The fabrication of a thinwall hohlraum proceeds as follows. With 1/8" (3.175 mm) 3/4-hard copper rod set in the base the copper mandrel and the indicating surface are machined. A typical mandrel is 1.6 mm in diameter and has a length of 4.0 mm.

Removed from the lathe, the mandrel is first electroplated with the 2 microns of gold. This thickness is controlled by controlling the mandrel area in the plating solution, the current and deposition time, typically about 6 minutes. By inserting the mandrel just below the surface of the plating solution, no plating occurs on the indicating surface of the base. After removal from the plating bath, the mandrel is then dip-coated with epoxy to at least 100 microns thickness. Care is taken to not coat the indicating surface with epoxy. After setting up at room temperature for 3-4 hours the epoxy is cured at 65-70 C, typically overnight.

The parts are then returned to the lathe. At this point the epoxy is not necessarily concentric to the mandrel. But the indicating surface, which was machined concentric to the mandrel, is still accessible, so the part is now adjusted until the total indicator reading (TIR) on the indicating surface is 0.25 micron or less. The spring-loaded fixture holding the base to the lathe spindle also guarantees that the length of the part repeats, so the diameter and length of the epoxy can now be cut to a uniform 100 micron thickness on the diameter and 25 micron thickness on the ends. The mandrel can now be removed with nitric acid. Fig. 2 shows an example of a finished thinwall hohlraum.

Aluminum Witness Plates

The high temperature achieved in hohlraums can be measured in a number of ways. One technique uses an aluminum witness plate placed on the hohlraum as shown in Fig. 3. The quantity determined from this measurement is called the drive temperature.

The aluminum witness plates have lateral dimensions of 800 x 1600 microns, but the thickness can vary from 10-30 microns at the thinner end to 120-200 microns on the thicker end. The material must be full density and of high purity, so we machine these witness plates directly from 99.99% pure vacuum melted aluminum sputter targets.

The technique we use to fabricate these witness plates results in a large number being produced simultaneously. We start with an aluminum disk (75 mm diameter, 4-5 mm thick) and first turn the two sides to be parallel. This is done by using a vacuum chuck which is first "cut in" on the lathe. This ensures that the vacuum chuck face is perpendicular to the lathe axis. The aluminum disk is then turned flat on one side, released, flipped over, and machined again. The disk is then removed and placed on a CNC milling machine where a shallow 250 micron "moat" is machined forming a ring of rectangular islands of aluminum, each 800 x 1600 microns (Fig. 4). The disk is then returned to the lathe and the contour of the wedge is turned onto the tops of the islands (Fig. 5a.). Since the radius of the ring of islands is large compared to the width of a single island the effect of the curvature of the cut can be ignored. (The sagitta for a 0.8 mm chord on a circle of

radius 35 mm is only 2 microns.) At this point the aluminum disk is removed from the lathe and a second aluminum plate is attached using machining wax (Fig. 5b.). After cooling the disk is returned to the lathe and the second plate is turned parallel to the original plate. Now the plate assembly is again removed from the lathe and flipped over. The thickness of the original aluminum disk is now turned down to thickness. (Fig. 5c) Note that at this point the aluminum witness plates are supported only by the wax. The parts are now separated from the wax using hexane. (Fig. 6)

The combination of the lathe precision and the sharpness of the diamond tool makes this technique successful. The minimal tool pressure that results is amply supported by the wax during the final machining step.

Be Hemishells/Quick-flip Locator

Beryllium capsules are candidates for ignition targets to be used on the National Ignition Facility (NIF), now in the design stages. The capsule contains the DT fuel necessary for fusion. Current NIF ignition designs specify a 2.2 mm o.d. spherical shell with a 0.155 mm wall. One way to fabricate such a Be shell is assemble it from directly machined hemishells.

We have developed a technique to machine these beryllium hemishells. A magnetically coupled fixture, called a Quick-flip locator, was developed expressly for this purpose. The Quick-flip locator consists of two parts, a kinematic mount and the Quick-flip, which holds the part being machined. (Fig. 7) The kinematic mount has 3 identical radial v-grooves at 120 degree intervals; between each pair of grooves is a samarium-cobalt magnet. Bolted to the lathe spindle, the kinematic mount is precisely centered to the lathe axis. The Quick-flip consists of a ring with three precision ball bearings held in the ring at the vertices of an equilateral triangle. When coupled to the kinematic mount the 3 ball bearings are held in the grooves by the magnets. The Quick-flip can thus be removed from the kinematic mount and returned with high precision. Moreover, the Quick-flip can be flipped over and re-mated with the kinematic mount, and the axis of the work piece will re-align with the lathe axis.

There are errors encountered with the simple repositioning and flipping of the part holder. The radial reproducibility upon simple repositioning and flipping have been measured at 45nm and 95 nm rms, respectively. The z-position reproducibility measurement is hampered by electrical noise generated by the lathe controller, but the simple z-axis repositioning has been determined to be less than 120 nm rms. The details of these and further measurements on the reproducibility of the Quick-flip locator will be

published in a separate article [3]. These measurements suggest that the wall of the NIF ignition capsule can be machined uniform to within 0.1%.

The Be hemishells are initially roughed out with a flange. Screws are used to clamp the Be piece securely to the Quick-flip. With the Quick-flip joined to the kinematic mount, the concave surface is first machined to the correct radius. Then the Quick-flip is reversed on the kinematic mount and the convex surface is machined. At this point the flange area of the Be is still intact. The Quick-flip can now be transferred to a second kinematic mount on a separate lapping apparatus, where the inner and outer surfaces can be polished. The surface finish thus obtained has been measured over a $10,000 \mu\text{m}^2$ area to be $< 10 \text{ nm rms}$.

After the lapping is complete the Be shell is ready to be parted from its flange. A small cup containing machining wax is placed over the convex side of the hemishell whereupon the wax is melted and allowed to re-solidify. The Quick-flip is then positioned in the lathe's kinematic mount with the concave side facing the cutting tool. Fine facing cuts then part the hemishell from its flange. As with the aluminum witness plates, the wax provides the necessary support for this operation. Fig. 8 shows a pair of beryllium hemishells thus produced.

Azimuthal Sinusoids/Electronic Tracer Lathe

Cylindrical implosion targets can be used in place of spherical targets to compare experimental results with calculations. The cylindrical targets are much easier to diagnose. One can view down the axis of an imploding hollow cylinder and watch the walls move in. Hydrodynamic effects, such as the growth of instabilities, are much more obvious in this configuration. For such experiments we have fabricated plastic cylinders of $430 \mu\text{m}$ i.d. and $535 \mu\text{m}$ o.d. with azimuthal sinusoidal perturbations; that is, hollow cylinders with outer radii that vary sinusoidally. The amplitudes of these perturbations have varied from 0.25 micron to 1.5 micron in modes 10 and 14. Mode 10 (14) means there are 10 (14) complete sine waves in 360° .

Cutting any azimuthal perturbation, for instance flutes on a rod, is not a task normally expected to be performed using a lathe. To do so requires that the cutting tool move along the length of the rod and simultaneously move perpendicular to the rod and at a specific frequency phase-locked to the rotation of the spindle. We have developed an apparatus that does precisely that. We call this apparatus an electronic tracer lathe.

A schematic of the electronic tracer lathe is shown in Fig. 9. The critical parts are the cam, the capacitance gage and the piezoelectric tool holder with its internal capacitance gage and amplifier (Queensgate Instruments). The cam is a nominal 100 mm diameter disk whose radius varies sinusoidally with the desired modal structure. The amplitude of the

sine wave on the cam is only 75 microns, and cams of both mode 10 and mode 14 have thus far been required. This cam was machined directly with a CNC milling machine. The cam is mounted on the spindle of the precision lathe. The capacitance gage yields a voltage proportional to the gage-cam separation. This voltage is fed into the piezoelectric transducer's amplifier, and this drives the tool in and out, and in phase with the cam., thus cutting the desired sinusoidal perturbation in the 0.5 mm diameter surface. The amplitude of the perturbation is controlled by adjusting the gain of the amplifier.

The internal capacitance gage of the piezoelectric toolholder is necessary because the piezoelectric transducer itself is quite non-linear with applied voltage. But this internal capacitance gage provides feedback of the actual motion to the amplifier, thus ensuring an overall linear response of the system. The variations in the cam are de-magnified and reproduced on the tiny part with high fidelity.

Fig. 10 is a photo of the tracer lathe with on machine metrology provided by a LVDT (linear variable differential transformer). When machining is completed, the LVDT probe is moved to the cylinder surface. Its gage force is low enough that on even polystyrene cylinders the sinusoidal figure of the surface can be measured without damaging the surface.

Conclusion

We have discussed four different applications of the precision lathes to ICF target fabrication. The demands of the National Ignition Facility will surely provide fertile ground for future applications.

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Figure Captions

Fig. 1. Schematic of re-centering bases. Used when fabrication procedure requires two or more precision lathe operations with intervening coating operation. A threaded hole on the bottom of the base provides a means for holding the base to the lathe.

Fig. 2. A completed thinwall hohlraum. The opening on the end has a diameter of 1.2 mm.

Fig. 3. Schematic for drive temperature measurement. The high temperature launches a shock into the aluminum wedge. The shock breakout along the exterior aluminum surface is clearly visible due to the high temperature of the shock. Following this breakout with a streak camera allows the shock velocity to be determined. Knowledge of the aluminum equation of state then allows the drive temperature to be calculated.

Fig. 4. Beginning wedge fabrication. The shallow moat is created around each small rectangle with a CNC milling machine.

Fig. 5. Schematic of lathe operations in aluminum wedge fabrication. a) Aluminum Ramp, b) Addition of wax and additional aluminum plate, and c) Machining of opposite to expose individual wedges.

Fig. 6. Photo of finished aluminum wedges.

Fig. 7. Quick-flip locator. a) Kinematic Mounts and b) Quick-flip part holder.

Fig. 8. 2.2 mm o.d. beryllium hemishells fabricated using the Quick-flip locator.

Fig. 9. Schematic of the electronic tracer lathe.

Fig. 10. Electronic tracer lathe with LVDT. The LVDT allows on machine characterization of the sinusoidal perturbations.

Fig. 1.

Fig 20

Fig 3

Fig 4

Fig 5 a

b)

Fig 5 c)

Fig 8

Fig 6

0P2 2PUC

Fig 7a)

Fig 7b)

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Fig 9

Fig 10