1. INTRODUCTION

Lawrence Livermore National Laboratory (LLNL) manufactures laser targets for experiments on the Omega laser at the University of Rochester and is preparing to build targets for the National Ignition Facility (NIF). These targets serve university collaborations, high energy density physics studies, and inertial confinement fusion (ICF) customers. Of particular interest to ICF studies are high-precision double shell implosion targets for demonstrating thermonuclear ignition without the need for cryogenic preparation. The suite of double shell ignition designs for the NIF [1] consists of a low-Z outer shell that absorbs laser generated x-rays, implodes, and then collides with a smaller high-Z inner shell containing the high-pressure deuterium-tritium fuel. Because the ignition tolerance to interface instabilities is rather low, the manufacturing requirements for smooth surface finishes and shell concentricity are particularly strict.

An exploded view of the double shell target appears in Figure 1a. The design consists of an inner plastic capsule with an outer diameter (OD) of 244 μm and a wall thickness of 15 μm. The inner capsule is suspended in two hemispherical shells (hemis) of low density CRF aerogel with a thickness of 220 μm. The outer ablator hemis have an outer diameter of 550 μm and are 52 μm thick. They are made of an LLNL fabricated 1 at % bromine doped polystyrene and mate at a step joint. A bonded joint secures the two ablator hemis together, Figure 1b.

The following capsule parameters are particularly important to these implosion experiments: concentricity of the two shells, thickness uniformity of the inner and outer shells, roughness of the various spherical surfaces, void volume fraction of the cyanoacrylate in the outer shell bond joint. The overall requirements are to maintain the dimensional tolerance of each component to ±1 μm and all internal flaws to less than ±0.5 μm. The specification on shell concentricity is important for constraining the degree of performance degradation from an asymmetric shell collision. Similarly, any flaws or non-uniformities in the outer shell or bond joint can cause deviations from a spherical implosion, leading to performance degradation.

The objectives of this paper are to show how LLNL’s precision engineering team approached the manufacture of a double shell target with a deterministic manufacturing plan and to discuss process limitations. An error budget was used to quantitatively study the manufacturing process and identify the effects of errors in each step. The manufacturing steps will highlight how each component is built with known datums and reference surfaces, and how the manufacturing plan created a deterministic, repeatable process. By taking this rigorous approach to controlling all error sources during machining and assembly, one can attempt to achieve the requirements of ±1 μm dimensional accuracy, sub-micron surface flaws, and 5 μm concentricity between the two shells. This contrasts with previous literature in the 1980’s and the 1990’s that described the manufacture of double shell targets using methods that introduce uncertainties into the manufacturing process, such as coating mandrels and releasing free-standing components, or backfilling materials to allow machining of components, then extracting the filler material and dealing with part shrinkage [2, 3].

2. MACHINING OF THE COMPONENTS

To fabricate each target, the CRF hemis are machined, the inner contours of the ablator hemis and the step joint are machined, the five components are assembled and bonded, and then the outer contour of the target is machined. The following discussion of the machining processes will follow this sequence. This sequence of manufacturing steps differs from recent efforts at LLNL to manufacture larger double shell targets, in which
freestanding ablator hemis were placed around the CRF hemis and inner capsule and then bonded together [5]. This new manufacturing method has many advantages, including the ease of the bonding process, less precision is required in that an excessive amount of adhesive can be applied since it is machined off anyway, it improves the fit and finish of the outer contours since it is machined after it is bonded, and it improves the precision of design by not having to transfer and handle individual free standing hemis and position them in a vacuum chuck. The design philosophy behind this manufacturing plan is to know the reference position and size of each component throughout the manufacturing process and to minimize points where dimensional uncertainty can affect the quality of the target.  

2.1 Vacuum chucks  
Vacuum chucks are used in three places during this target build. The manufacturing method is similar for each of the three chucks and is illustrated in Figure 2. To create the vacuum chuck that holds the CRF, a hole is drilled in a brass rod with a polystyrene disk on the end, which is mounted on a precision holder that allows vacuum to be pulled through the spindle of the machine, (Figure 2a). Then a hemispherical contour with a diameter slightly smaller than the OD of the CRF hemis is machined into the polystyrene disk, and a set of concentric channels 97 µm wide and 15 µm deep is cut into the inner contour (Figure 2c). The part is subsequently placed back in the DTM, and the contour is machined to its final diameter of 446 µm to match the OD of the CRF hemis (Figure 2d).

2.2 CRF hemispheres  
Figure 3 illustrates the process for machining each CRF hemi. First, a large piece of the CRF is glued to an arbor mounted to a precision holding fixture. The CRF is then turned down to create a partial sphere of diameter 446 µm, supported by a neck of material, which will be the outer contour of the hemi (Figure 3a). The sphere is manually broken off at the neck using a surgical blade, and placed into the vacuum chuck (Figure 3b). Throughout the machining of the CRF, its position is deterministically known with respect to the DTM by orienting the hemis using vacuum chucks with reference surfaces. The only occasion in which the orientation of the part is not controlled with respect to a reference datum is when it is transferred to the vacuum chuck. To relocate the part once it is in the vacuum chuck, the tool is touched off on the face of the vacuum chuck, which is a known reference. This touch-off process allows the position of the part to be reestablished. The sphere is then faced off to create a solid hemisphere, and the internal contour is machined into the CRF to complete the hemi (Figure 3c). Each internal contour is custom fit to a particular capsule size. The length of the excess neck material is minimized to reduce the torsional moment on the vacuum chuck imposed by the tool cutting forces. When complete, the parts are inspected under a microscope to measure the ID. The uncertainty in this measurement is ±1 µm.

2.3 Polystyrene ablator components  
The ablator hemis are machined in two different stages. First, the inner contour, a reference surface and corresponding step joint are machined, as shown in 4a. The second stage is the machining of the outer contour of the ablators, but this is performed after the target has been assembled and bonded and is discussed in Section 4. This sequence for building the targets has simplified the manufacturing and improved the quality of the target, compared to LLNL’s previous double shell target design [5].

3. ASSEMBLY AND BONDING  
An assembly fixture that uses the same workpiece holders that are used on the diamond turning machines is used for assembly. The assembly fixture is on a clean de-ionized bench and provides force control to 1 gram resolution. The assembly process is illustrated in Figure 4. Initially, the lower ablator component is inserted into the lower actuator of the assembly station (Figure 4a). Then one of the CRF hemis is placed into the lower ablator component (Figure 4b). Because the equator of the hemi is flush with the surface of the vacuum chuck, the part can be located axially by bottoming out the face of the vacuum chuck on the inner step of the joint on the lower ablator component. The inner capsule is then inserted into the inner contour of the CRF hemi (Figure 4c). The inner
capsules of the target are composed of plastic and are supplied by General Atomics (GA). The designed diameter of the capsules is \(240 \pm 0.5 \, \mu m\) and varies from 239 to 247 \(\mu m\). The capsules are measured by GA by taking three equatorial traces around the sphere using an spheremapper [4]. The upper CRF hemi is then taken directly from the vacuum chuck in which it was machined and placed on top of the inner capsule (Figure 4d). The inner contours of each CRF hemi are machined to match the outer diameter of the corresponding capsule, but due to the uncertainty in the OD of the capsule, the potential exists for concentricity errors at this step. In the final assembly step, the upper ablator component is placed over the CRF (Figure 4e) and mated with the joint in the lower component. The two ablator components are pressed together with a force of 10 grams, and the seating of the joint is visually inspected to ensure it has a uniform gap around the perimeter.

The bonding of the ablator components is done on two steps. First, cyanoacrylate is applied around the perimeter of the joint by placing a droplet on the end of a camel hair and running it around the perimeter. The volume of cyanoacrylate applied is sufficient to fill the 2 \(\mu m\) gap and wick into the joint, but it fills only the apex of the tapered sections. The joint has a straight step, and the inside surfaces of the joint are flush to prevent the adhesive from wicking into the CRF. Then the tapered sections of the components are filled with epoxy (Figure 4f), which is allowed to cure for 24 hours. This epoxy supports the joint during machining and is fully machined away in subsequent steps. By machining the external surface after bonding the components, any crazing that occurs upon application of the cyanoacrylate is removed in subsequent machining, leaving a diamond turned quality surface.

4. FINAL MACHINING

There are three steps to the final machining: setting the tool, machining the first half of the outer contour and then transferring the target to a vacuum chuck, and machining the second half of the outer contour. The tool setting is critical for this operation, because any error in its position will cause wall thickness errors in the target. Therefore, before machining the outer contours of the ablators, the tool is reset.

Figure 5 illustrates the procedure for machining the outer contour of the target. The tool is touched to the previously machined reference surface on the lower ablator component to establish a workpiece coordinate system. Then the bonded assembly is machined from the form shown in Figure 4f to the form shown in Figure 5a. In this machining process, the tool also machines the OD of the shank near the reference surface. This machined OD serves as a reference diameter that can be measured with an uncertainty of \(\pm 1 \, \mu m\). Thus, by measuring this reference diameter, the OD at the equator of the machined target can be inferred. Note that at this stage, the support shank diameter and length have been maintained to provide support, so the part will not deflect under the cutting forces. The epoxy inside the taper provides support to the bonded joint during machining. The free end is then machined to its final spherical form, and it includes another reference surface near the stem, as illustrated in Figure 5b. The stem holding the partially machined sphere is then reduced in size to a thin neck (Figure 5c), which is then broken off with a surgical blade. The free spherical end of the target is then gripped by the specially crafted vacuum chuck (Figure 5d), which holds the part while the remainder of the outer ablator surface is machined. To augment the grip of the vacuum chuck, a bead of urethane adhesive is applied to bond the part to the chuck (Figure 5d). The remainder of the outer surface of the target is then machined (Figure 5e), and the final finishing pass blends together the surfaces on the outer contour.

5. CHARACTERIZATION

A completed target is shown in Figure 6. Once the target is completed, only external dimensional metrology and characterization can be performed. Visual inspection of the joint using an optical microscope...
indicates that the cyanoacrylate has fully wicked around the joint, and there are no visible voids or bubbles in the 2 µm gap. The seating of the two hemispheres appears uniform on all targets. The area in which the two outer ablator surfaces were blended together is inspected with a WYKO NT8000 scanning white light interferometer. It is to quantify the characteristics of the blend line, but the blended area appears to contain a surface flaw in the form of a step estimated at less than 0.3 µm on all targets (radial perturbation < 0.1%).

One of the most important characteristics of the targets is the concentricity between the ablator shells and the inner capsules, which is determined from contact radiographs of the completed targets, (estimated resolution of approximately 1 µm.) Two orthogonal radiographs are taken of each target. Example radiographs for one of the targets appear in Figure 6. For each target, two different fitting routines are used to calculate the concentricity errors in the plane of the joint and in the pole-to-pole direction. The six targets have concentricity errors of 1, 3, 4, 4, 5, and 6 µm, which represent a ∆r/r of between 0.4% and 2%. Only one of the six targets does not meet the specified concentricity of 5 µm.

6. SUMMARY

By taking a rigorous approach to controlling the manufacturing process, double shell targets have been manufactured to meet the specifications of ±1 µm dimensional accuracy and 5 µm concentricity. These targets provide physicists with an experimental target that may yield improved performance. This approach of using known manufacturing methods and pushing the limits of conventional processes can achieve high quality parts, because the manufacturing process has minimized the introduction of geometrical/dimensional uncertainties in each component. The reality is that process control and development are the major tasks in executing a job like this. Most of the effort involves paying extreme care to the minute details at each step.

Throughout this process, we have identified areas where improvements can take place, and the preliminary error budget has been refined to identify the most important sources of error and uncertainty in the manufacturing process and to reveal their impacts on the quality of the completed targets. The error budget reveals that the key areas are developing a better assembly station, reducing the uncertainty in the measured diameters of the inner capsules, obtaining better metrology tools, and obtaining a better tool set station.

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