euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
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Precision manufacture in support of experiments at the National Ignition Facility

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Abstract
Successful science experiments at the National Ignition Facility (NIF) require that millimetre-scale targets are fabricated, aligned, and measured with micrometre-scale tolerances, and surface roughness in the nanometre regime, spanning over six orders of magnitude in scale. Development of the novel materials required for targets including shaping and assembly into specific geometries related to the type of experiment required in these complex targets present challenges for manufacturing and metrology and require focused research and development. The completed assemblies must accommodate features required to field the targets on the facility such as shields, coatings and alignment fiducials. Finally, as shot rate increases on NIF, there is a need to utilize more efficient fabrication techniques to ensure targets do not become the bottleneck while retaining precision. This presentation will describe how the US target development and fabrication at Lawrence Livermore National Laboratory in cooperation with private industry utilizes advances in precision micro-manufacturing techniques including single point diamond turning (SPDT), micro-milling, robotics, vapor deposition, optical and x-ray metrology and precision fixturing to allow for in-situ assembly and characterization of these complex assemblies. In addition, a look forward at the future challenges in manufacturing and metrology will be presented.
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-744402

Precision manufacturing, metrology, diamond turning, x-ray, optical

1. Experiments on the NIF

The National Ignition Facility is the most energetic laser in the world consisting of 192 beams capable of delivering 1.8 MJ of energy to the centre of the target chamber measuring 10 m in diameter. In the case of inertial confinement fusion (ICF) [1] experiments the 192 beams are used to heat a gold cylinder (Hohlraum) creating an intense x-ray oven where a capsule filled with fuel ablates causing rapid compression of the fuel inside.

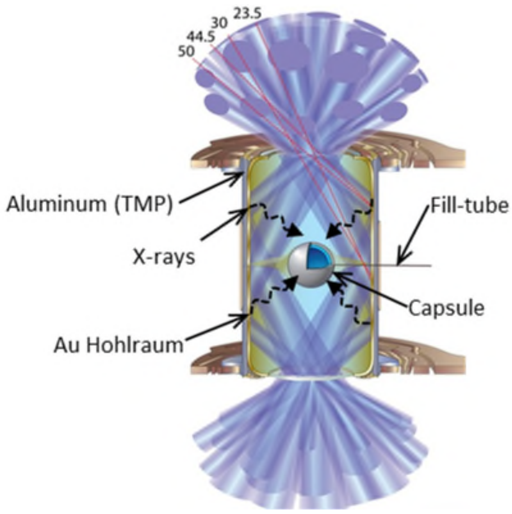

Figure 1. Ignition target showing NIF beams, Aluminium thermal mechanical package (TMP), Au hohlraum and fuel capsule with fill-tube.

The fuel is compressed to over 100 times the density of lead and ignites at a temperature of approximately 100,000,000 °C. This generates thermonuclear burn and represents 10-100 times gain in energy out versus energy applied to the system, see Figure 1. In addition to ignition experiment the NIF is used to study high energy density science (HEDS) where the facility is being used to study phenomenon at high pressures and temperatures as seen at the centre of a star [2].

2. Target fabrication at NIF

Target fabrication at Lawrence Livermore National Laboratory (LLNL) uses a combination of strategic partnerships with industry and academia leveraging core capabilities to manufacture and assemble targets. Tolerances required for most of the experiments on NIF require nanometre level surface finish and micrometre form where the specifications are highest at the interface of the capsule. Adding to complexity of the experiment is the cryogenic environment needed to create solid fuel used during the experiment. These types of features and critical requirements rely on precision manufacturing and metrology techniques to characterize and quantify key parameters important to the output of the experiment.

3. Core manufacturing technologies

There are many core precision technologies used in the manufacture of NIF targets including single point diamond turning (SPDT), micro milling, physical vapor deposition (PVD), microfabrication and electroplating as examples. These core technologies are used by LLNL and its industrial partners to manufacture a wide range of parts ranging from hohlraums to TMPs shown in Figure 1. These technologies and processes are well understood for most common materials and can produce nanometre level surface roughness and micrometre or better shape. SPDT has been used to manufacture stepped samples with better than 100 nanometres parallelism and less than 20 nanometres surface roughness.

4. Metrology

Metrology is critical part of target fabrication manufacturing. Experiments rely on characterization as the means of verifying experimental results. Optical coordinate measuring machines (OCMMs) and optical surface profilometers are standard metrology tools used for assembly and final metrology of targets for NIF experiments. Understanding the task specific uncertainty is critical to acquiring the highest quality information and is commonly at the 1-2 micrometre level. Computed tomography (CT) has become a regular characterization tool for looking at structures within materials such low density foams and additively manufactured structures as shown below in Figure 2. Quantifying these systems for dimensional metrology at the micrometre level and physical properties such as density is a focus area for target characterization.

5. Areas of research

There are several precision manufacturing strategic research areas being undertaken at LLNL that can have direct impact on experimental performance. Two-photon lithography is being used to create uniform lattice structures [3] as shown in Figure 2. These types of structures allow for very reproducible structures that can be designed based on spacing and geometry to engineer features into the material. An important feature of this technique is the ability to create a material with an inherent density gradient by modifying the spacing and size of the structure being printed. The graded density product can be used to regulate the pressure drive profile of the experiment allowing for varying the fidelity of the pressure over a wider range.

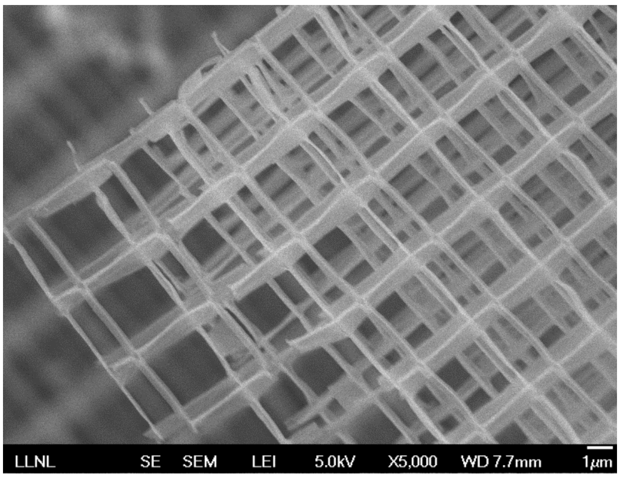

Figure 2. Scanning electron microscope (SEM) image of two-photon lithography printed structure with sub-micrometre feature size.

Inertial confinement fusion experiments are very sensitive to mass at the surface of the capsule during the experiment where nanograms or smaller discrete masses can cause a perturbation of the shape of the implosion as it compresses. As shown in Figure 1, thin films (45 nm thick) are used to suspend the capsule in the hohlraum during the experiment [4]. It has been shown that the mass of films over the contact area of the capsule cause shape changes [5] having a negative impact on the experiments results. To address these concerns LLNL has been working alternative capsule support techniques to reduce the impact of the added mass to the experiment. One possible technique is to use micrometre scale fibres, two parallel fibres across the bottom and an orthogonal pair of fibres across the top of the capsule, creating a set of four line-contact regions oriented to hold the capsule/fill-tube assembly in the required location. To accomplish this, micrometre scaled fibres that can withstand large tensile forces need to be manufactured. Figure 3 shows a 2.5 micrometre diameter fibre woven from carbon nanotubes. A 3 micrometre diameter carbon nanotube yarn can hold up to nearly 2 grams before failure. The goal is to bring the diameter down to 1 micrometre or smaller as an option for ICF experiments.

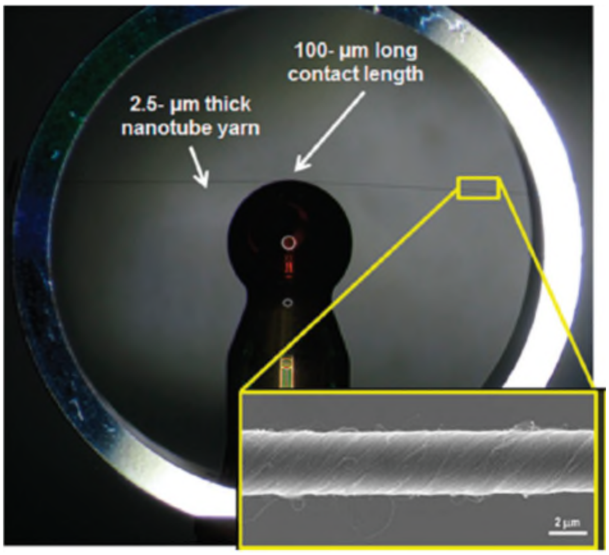

Figure 3. Carbon nanotube yarn used as alternate capsule support in ICF experiments.

6. Conclusion

Precision engineering and manufacturing is a core competency of target fabrication supporting NIF and other experimental facilities. Understanding the fundamental processes with uncertainties associated with these processes is critical to understanding the experimental results. This presentation will highlight some of the core capabilities and look at current and future research opportunities as discussed briefly above.

References

The work presented in this paper is the combination of efforts of a multidisciplinary team of Scientists, Engineers, Technicians and Machinists to maintain and advance key technologies supporting LLNL's efforts towards science experiments on NIF and other experimental facilities.

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