Void Free Fuel Solidification in a Foam Shell FIERX Target*)

Akifumi IWAMOTO, Takeshi FUJIMURA[1] and Takayoshi NORIMATSU[1]

National Institute for Fusion Science, National Institutes of Natural Sciences, Toki 509-5292, Japan
[1] *Institute of Laser Engineering, Osaka University, Suita 565-0871, Japan*

(Received 29 November 2019 / Accepted 3 February 2020)

We study fuel layering for the Fast Ignition Realization EXperiment (FIREX) cryogenic target with a foam shell. A void free solid fuel layer within a porous foam material must be formed ideally. We have demonstrated the residual void fraction of ~1% in a foam wedge with temperature controlled solidification. ANSYS simulations have shown that the residual void reduction technique will be applicable to the FIREX target. We examined each step in the simulated solidification process using a dummy foam shell target. In several attempts, solid fuel formation with a reduced void fraction in the foam shell succeeded.

Keywords: fast ignition laser fusion, cryogenic target, foam shell, void free solid fuel layering

DOI: 10.1585/pfr.15.2404006

1. Introduction

FIREX targets have been developed under the collaboration research between the Institute of Laser Engineering (ILE), Osaka University and the National Institute for Fusion Science (NIFS), the National Institutes of Natural Sciences (NINS). The targets are a unique design with a cone guide for the ignition laser. One of the targets is shown in Fig. 1. The shell is hollow with a ~20 µm foam layer. The porous foam material is impregnated with a void free solid fuel. This form shell method has been proposed for Inertial Confinement Fusion (ICF) by direct drive central ignition [1]. Foam shells have been developed for laser fusion experiments [2–4].

To date, the beta layering technique [5] realizes solid DT targets for the National Ignition Facility (NIF) and OMEGA for central ignition experiments. The spherical symmetry temperature profile makes the solid layer uniform. However, the layering technique is not applicable for the FIREX target with axial symmetry just as they are. The cone becomes a heat exchanger, and therefore, the temperature profile in the shell is naturally not spherical but axial symmetry. Thus, uniform solid fuel layer formation is a key technology. The foam shell method which utilizes the capillarity of a porous foam material would have the potential to create a uniform solid fuel layer in axisymmetric targets.

We study the layering technique on a foam shell target [6], which has an essential challenge. Residual voids in a formed solid fuel within the porous foam must be reduced by less than 1%. We have studied the reduction technique of residual voids within ~1% in principle, and ANSYS simulation has shown its applicability to the FIREX foam shell target [7]. A remaining issue is that the simulation process is experimentally demonstrated.

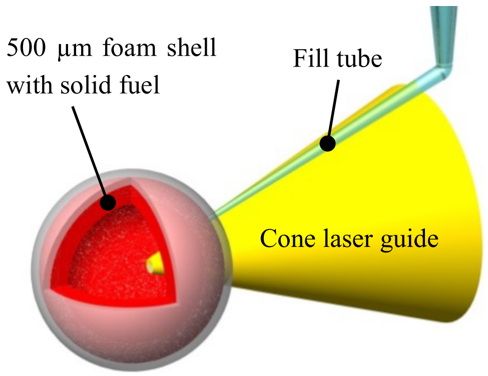

Fig. 1 Typical appearance of FIREX foam shell target. A cone guide and a fill tube are attached to a foam shell. The shell diameter is 500 µm. A uniform solid fuel has to be formed within the foam layer of a ~20 µm thickness. The sphericity is required to be more than 99%.

2. Foam Shell Method – Residual Void Reduction in a Foam Shell

Foam is a porous material consisting of ~100 nm cells. A liquid fuel is soaked up in the foam uniformly by capillary action and then is solidified. Spherical symmetry is not required to make a solid layer uniform, and therefore, it would be possible to apply the foam shell method to the FIREX target without spherical symmetry. However, because of the density difference between the liquid and solid phases on H_2, D_2 and DT, voids with a fraction of more than 10% would be developed in the formed solid under random solidifications without any countermeasures.

A residual void reduction procedure has been already demonstrated using H_2 as a surrogate fuel as shown in Fig. 2 [7]. The temperature controlled solidification essen-

author's e-mail: iwamoto.akifumi@nifs.ac.jp
*) This article is based on the presentation at the 28th International Toki Conference on Plasma and Fusion Research (ITC28).

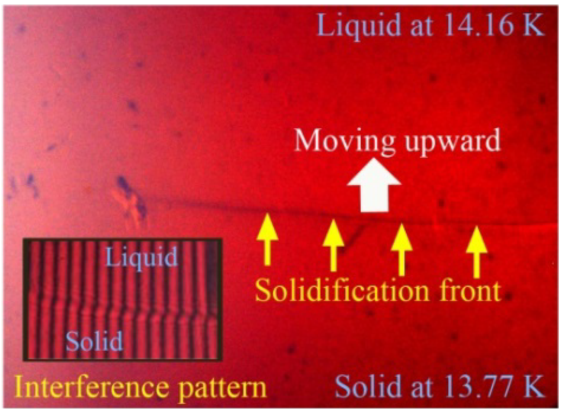

Fig. 2 Solidification process established using a foam wedge. The temperature gradient between the top and the bottom makes the solidification front systematic. Solidification was started from the bottom, and then its front moved upward [7].

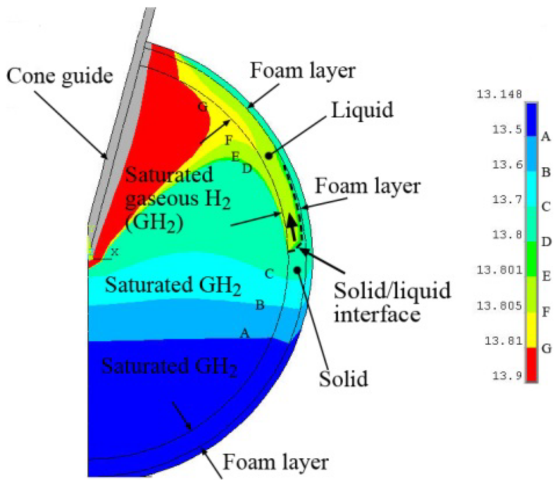

Fig. 3 Successful simulation of solidification control in the 500 μm FIREX target [7]. The figure represents temperature distribution in the foam shell 8800 sec after the start of the calculation. The solid/liquid interface is moving upward in the foam layer.

tially creates void free solid within the foam wedge. The residual void fraction was confirmed to reach to ∼1%. We have established the technique to reduce residual voids in principle. Then we speculate regarding its applicability to the FIREX target using ANSYS simulation as shown in Fig. 3 [7]. The simulation starts from the condition that the foam layer is filled with liquid H_2 (LH_2). The target is cooled by the ambient gaseous He (GHe) at the temperature of 14.0 K, and the cone temperature rises by an induced heat input of ∼10 μW. As the cone is heated, the ambient GHe temperature is lowered to 10 K. Solidification starts from the shell bottom, and then, the solid/liquid interface is moving upward in the foam layer. The interface must be the same condition which occurred in the foam wedge experiment. It takes more than 2300 sec to complete

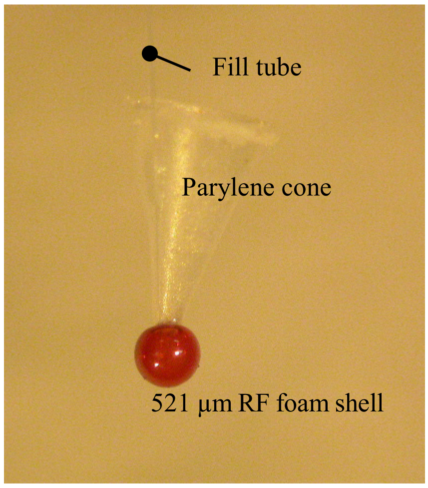

Fig. 4 Prototype RF foam target with a parylene cone.

the solidification of the whole LH_2. We have succeeded in reproducing the experimental condition to demonstrate the residual void reduction using the foam wedge in the foam shell FIREX target model. This simulation is tested using a ∼500 μm prototype foam shell target.

3. Prototype RF Foam Target

A 521 μm Resorcinol-Formaldehyde (RF) foam shell with a parylene cone was prepared as shown in Fig. 4. The foam shell was produced at ILE. The diameter of the RF foam shell was 521 μm. The foam layer thickness was 18 μm, and its density was ∼90 mg/cm^3. Parylene was coated on the shell with a 5.3 μm thickness, and it works as not only a gas barrier but also as an adhesive to attach the cone and the shell to each other. The thickness of the cone was 20 μm. A fill tube of an 8 μm diameter was inserted into the shell. After no leak was detected at room temperature, the target was installed in a NIFS apparatus [8].

4. Experiments

The system to examine the condition of the simulation is shown in Fig. 5. The target was set in the thermal shield which was cooled by a 4 K Gifford-McMahon (GM) cryocooler (RDK-415D, Sumitomo Heavy Industries, Ltd.) with temperature control. The shield also worked as a heat exchanger to control ambient GHe temperature for the target cooling. The details of the cooling system are described in reference 8. Two laser systems, a 594.1 nm He-Ne laser with 2 mW (HYP020, Tholabs Inc.) and a 632.8 nm He-Ne laser (05-LHP-151, Melles Griot Inc.) were prepared for cone heating and for a Michelson interferometer, respectively. Neutral Density (ND) filters were applied to control laser energies. A CCD camera with a macro lens (DS-5 M with AF Micro-Nikkor 200 mm, Nikon) was used as a microscope. It was possible to observe the target with several μm resolution.

The process in the simulation was not fully repro-

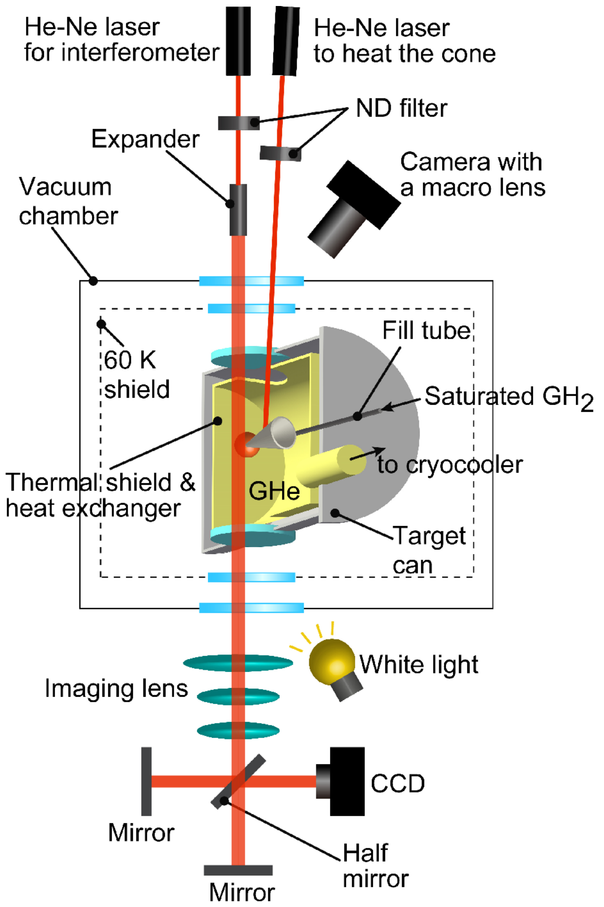

Fig. 5 System for solidification control with laser heating. A microscope and a Michelson interferometer were used to observe liquefaction and solidification in the foam shell.

duced because of the limitation of temperature control. The experimental procedure is as follows. The thermal shield temperature was set at 13.5 K, where the shell inside stayed at liquid temperature because heat transfer and thermal conduction of the ambient GHe cause a temperature gap. Then gaseous H_2 (GH_2), as a surrogate fuel, was filled in the shell at the pressure of ~8 kPa. Liquefaction follows. LH_2 was soaked in the foam layer. The development of liquefaction was confirmed by concentric fringe pattern formation following deformation with the interferometer. The liquid quantity was controlled by the GH_2 supply pressure. We could maintain the liquid quantity overfilling the foam layer by the state of the meniscus around the cone. The 594.1 nm He-Ne laser was irradiated to the cone as a heat source to make the cone temperature higher than other parts of the target. Its power was adjusted through an ND400 filter. The absorbed power on the cone was estimated to be ~20 μW. This value is comparable to that of the simulation. We confirmed that LH_2 remained in the foam layer after the cone heating. Then the shield temperature was lowered step-by-step at an interval of several mK. Eventually, solidification was observed by a gradually altered fringe pattern. Several attempts of the layering sequence were made to maintain a clear fringe pattern after solidification. By comparison, solidification without laser heating was conducted.

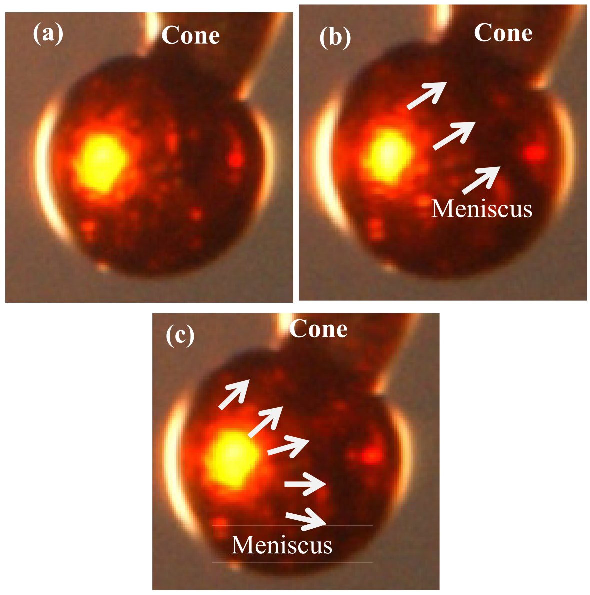

Fig. 6 Observation of LH_2 meniscus. (a) vacant shell. (b) visible meniscus around the cone. (c) LH_2 was added from (b). The meniscus stays in an eccentric position because the cone was not inserted into the shell at a correct angle.

5. Results

Figure 6 represents the meniscus around the cone compared to the shell without LH_2. The meniscus of LH_2 could be observed by the microscope. We could control the quantity of LH_2 by the meniscus position. The visible meniscus made it possible for us to fully fill the foam layer with LH_2.

Figure 7 represents four interference patterns. These are (a) the shell itself, (b) solidification without laser irradiation, (c) solidification in success, and (d) solidification in failure. Fringes clearly appeared through the shell itself as shown in Fig. 7 (a). Solidification without laser heating makes fringes disappear as represented in Fig. 7 (b). The liquid-solid transition might start at random, and the residual void spaces should be developed within solid H_2 (SH_2) formed in cells of the foam material. The photograph of Fig. 7 (c) was quickly taken without the ND filter because the fringes were obscure in reduced laser illumination. Controlled solidification with laser heating resulted in concentric fringe patterns. Experiments successfully reproduced the simulation in several attempts. In the case of failure in solidification with laser heating, fringes could not be observed as represented in Fig. 7 (d).

6. Summary

The independent foam shell method has been developed for the FIREX target. Cone temperature control is a

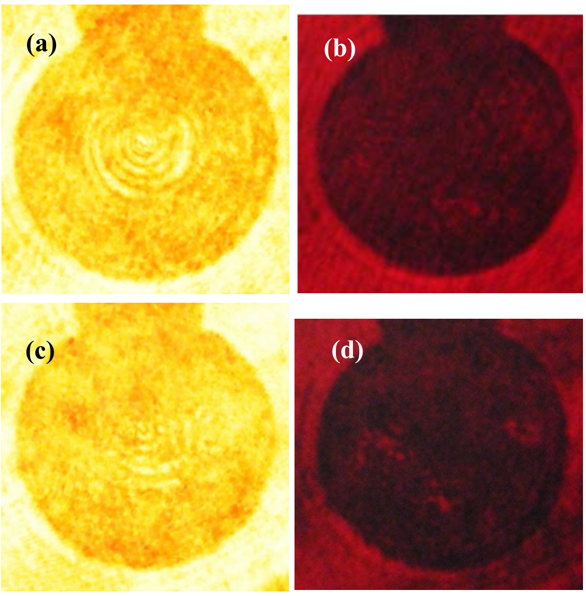

Fig. 7 Interference patterns of the foam shell. (a) the shell itself, (b) solidification without the laser irradiation, and no pattern appeared, (c) concentric fringe patterns are observed in the case of success, and (d) no pattern appeared in the case of failure. Images (a) and (c) were taken without the ND filter.

key technology. The solidification process to reduce residual voids was examined according to the ANSYS simulation. LH_2 within the foam layer can be solidified in order, as we expected. Experiments successfully reproduced the simulation in several attempts.

Acknowledgments

We would like to thank Y. Fujimoto, Y. Kaneyasu, S. Machi, H. Hosokawa, M. Nagata, H. Kadota and Y. Suzuki from ILE, Osaka University for supplying targets.

[1] R.A. Sacks and D.H. Darling, Nucl. Fusion **27**, 447 (1987).
[2] M. Takagi *et al.*, J. Vac. Sci. Technol. A **11**, 2837 (1993).
[3] A. Nikroo *et al.*, Fusion Sci. Technol. **45**, 84 (2004).
[4] K. Nagai *et al.*, Nucl. Fusion **49**, 095028 (2009).
[5] J.K. Hoffer and L.R. Foreman, Phys. Rev. Lett. **60**, 1310 (1988).
[6] A. Iwamoto *et al.*, Fusion Sci. Technol. **51**, 753 (2007).
[7] A. Iwamoto *et al.*, Nucl. Fusion **53**, 083009 (2013).
[8] A. Iwamoto *et al.*, Fusion Eng. Des. **81**, 1647 (2006).