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ORIGINAL RESEARCH

Design and Fabrication of a CH/RF/CH Tri-Layer Perturbation Target for Hydrodynamic Instability Experiments in ICF

Jun Tang[1] · Zhiyong Xie[2] · Ai Du[1] · Junjian Ye[2] · Zhihua Zhang[1] · Jun Shen[1] · Bin Zhou[1]

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Abstract A polystyrene (CH)/resorcinol formaldehyde (RF)/CH tri-layer perturbation target for hydrodynamic instability experiments in inertial confinement fusion (ICF) was designed and fabricated and its features were discussed. The target was composed of a perturbed CH layer, a RF aerogel sheet and an unperturbed CH layer. The detailed fabrication method consisted of four steps. An aluminum alloy template with sinusoidal perturbation patterns was prepared by the single-point diamond turning technology; the CH layer was prepared via a simple method which called dip-coating method; the RF aerogel sheet was prepared by sol–gel and supercritical drying process; finally, a CH layer, the RF aerogel sheet and another CH layer were put on the perturbed aluminum alloy template and hot-pressed at 150 °C for 2 h to make these three layers adhered together without the use of adhesive and to transfer the perturbation patterns from the template to the CH layer. A scanning electron microscope (SEM) was used to investigate the microstructure of the RF aerogel sheet. Parameters of the target, such as perturbation wavelength (T) and perturbation amplitude (A), were characterized by QC-5000 tool microscope and alpha-step 500 surface profiler. The results showed that T and A of the target were about 55 and 3.88 μm respectively, the perturbation patterns transferred from the alloy template to the CH layer precisely. Thickness of the perturbed CH layer (H1), RF aerogel sheet (H2) and unperturbed CH layer (H3) and cross-section of the tri-layer target were characterized by QC-5000 tool microscope and SEM. H1, H2 and H3 were about 50, 300 and 20 μm respectively, the cross-sectional photographs of the target showed that the CH layer and the RF aerogel sheet adhered perfectly with each other. As this CH/RF/CH tri-layer target use the RF aerogel to simulate the DT ice of the ignition target capsule, the whole target very close to the actual ignition target capsule.

Keywords Hydrodynamic instability · Tri-layer perturbation target · Single-point diamond turning technology · Inertial confinement fusion

✉ Bin Zhou
zhoubin863@tongji.edu.cn

Jun Tang
charmantang@126.com

1 Shanghai Key Laboratory of Special Artificial Microstructure Materials and Technology, School of Physics Science and Engineering, Tongji University, No. 1239 Siping Road, Yangpu District, Shanghai 200092, China

2 Shanghai Institute of Laser Plasma, Shanghai 201800, China

Introduction

In inertial confinement fusion (ICF) experiments, when the ignition target capsule is directly driven implosion by a high-intensity laser facility, such as NIF, Nova, Omega and LMJ, hydrodynamic instabilities are expected to play a dominant role in determining overall performance of the capsule [1]. Understanding the development of these hydrodynamic instabilities is an important step for successfully achieve fusion ignition. So research of the hydrodynamic instabilities has been focus for years [2–6]. In general, an ignition capsule usually consists of several layers with different density [7, 8]. The outer layer is usually a low-Z ablator material such as CH polymer, and the inner layer is the fusion fuel such as deuterium–tritium (DT) ice, DT gas and so on. When the capsule is driven by high intensity laser for direct-driven or by X-ray for indirect-driven, the outer layer is ablated and the instability seeded by surface roughness of the target and nonuniform irradiation can grow via Rayleigh–Taylor (RT) instability [9, 10]. In recent years, many different kinds of targets had been designed and fabricated for the RT instability experimental in ICF, such as single layer perturbation targets [11, 12], dual-layer perturbation targets [13–17] and multilayer targets [18–21] and so on. In this article, a polystyrene (CH)/resorcinol formaldehyde (RF)/CH tri-layer perturbation target was designed and fabricated to simulate the growth of RT instability occurring at the outer ablator layer of the ignition target capsule. In this tri-layer perturbation target, the RF aerogel sheet "sandwich" held in place by two layers of CH and sinusoidal perturbation patterns introduced on the front layer of CH by a hot-press process. The perturbation patterns on the CH layer were used as the initial seed for RT instability growth and the RF aerogel sheet was used for simulating the DT ice of the ignition target capsule. A scanning electron microscope (SEM) was used to investigate the microstructure of the RF aerogel sheet. Target parameters, such as perturbation wavelength (T) and perturbation amplitude (A), were characterized by QC-5000 tool microscope and alpha-step 500 surface profiler. Thickness of the perturbed CH layer (H1), RF aerogel sheet (H2) and unperturbed CH layer (H3) and cross-section of the tri-layer target were characterized by QC-5000 tool microscope and SEM.

Experiment

Design of the CH/RF/CH Tri-Layer Perturbation Target

The CH/RF/CH tri-layer perturbation target was designed to simulate the growth of RT instability occurring at the outer surface of the ignition target capsule. Figure 1 shows the schematic of the CH/RF/CH tri-layer perturbation target. The CH polymer, a low-*Z* material composed of C and H elements, with a density of 1.03 g/cm^3, exhibits high energy deposition and good machinability, usually chosen as the preferred outer ablator material [22]. So the perturbed CH layer was used to simulate the unstable outer ablator layer of the ignition target capsule. The RF aerogel sheet due to nano-scale homogeneous microstructure, controllable density (30–1000 mg/cm^3) and low-Z component elements (C, H and O), it was used for simulating the DT ice (250 mg/cm^3) of the ignition target capsule. The unperturbed CH layer was used as rear window of the target. Via a hot-press process, these three layers adhered with each other and the perturbation patterns introduced on the CH layer.

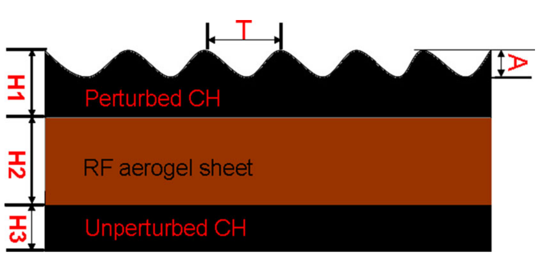

Fig. 1 Schematic of the CH/RF/CH tri-layer perturbation target

Preparation of the Perturbed Aluminum Alloy Template by the SPDT Technology

In order to introduce the perturbation patterns on the CH/RF/CH tri-layer target, an aluminum alloy template with sinusoidal perturbation patterns was prepared by the single-point diamond turning (SPDT) technology [23]. A polished circular aluminum alloy with thickness of 5 mm and diameter of 30 mm was gripped via a vacuum negative pressure, cut by a natural diamond cutter. The whole lathe and spindle use the air-flotation method to reduce the impact of external vibration. Numerical control resolution of the lathe was 1 nm; precision of second grip was controlled under 1 μm. Curvature radius of the diamond cutter was 3 μm. The aluminum alloy was cooled by spray cooling during the cut process. The cuttings were drawn away by an air pump to prevent them from damaging the processed surface of the aluminum alloy or polluting the machining environment. The machining environment was 20 °C, humidity 40 % and ultraclean class of ten thousand.

Preparation of the CH Layer by Dip-Coating Method

The CH layer was prepared by a dip-coating method. Solid CH (purity: 99.9 %) was dissolved in chloroform and stirred with a magnetic bar for 4 h, then vibrated in an ultrasonic bath for 2 h. After this, the CH solution filtered with a qualitative filter paper to obtain a transparent, uniform CH solution. Then the solution was continuing stirred with a magnetic bar as the solvent chloroform gradually volatilized to obtain the CH solution with appropriate concentration. For CH layer preparation, a glass slide dipped into the CH solution, then stably pulled up at a speed of 2 mm/s and a CH film formed on the glass slide in this process, finally, after the solvent chloroform volatilized, took off the CH film from the glass slide, the CH layer was obtained. Thickness of the CH layer was controllable by adjusting the concentration of the CH solution and the pulling speed.

Preparation of RF Aerogel Sheet by Sol–Gel Process

The RF aerogel sheet was prepared via a sol–gel process. Resorcinol, formaldehyde, deionized water and sodium carbonate were mixed at room temperature. After stirring with a magnetic bar for 2 h, two glass slides separated by 0.5 mm were put into the mixture. Then the mixture was sealed and placed in a constant temperature box to carry out the sol–gel polymerization; the treatment temperatures were 30 °C for 24 h, 50 °C for 24 h and 90 °C for 72 h. After gelation, the RF wet gel sheet was taken out from the gap of the two glass slides in acetone solvent and the solvent was substituted with fresh acetone once per day for 3 days to remove the residual solution. After the residual solution was completely removed, the treated RF wet gel sheet was placed into an autoclave for CO_2 supercritical drying. After 3–4 days solvent exchange by liquid CO_2 at 5 °C and 6 MPa, the temperature and pressure were raised to 40 °C and 8.5 MPa for CO_2 supercritical drying. Finally, the RF aerogel sheet was obtained. Figure 2 shows a schematic of this sol–gel and supercritical drying process.

Fabrication of CH/RF/CH Tri-Layer Perturbation Target by Hot-Press Process

For CH/RF/CH tri-layer perturbation target formation, a hot-press process was used to make the three layers adhere to each other without the use of adhesive and to introduce the perturbation patterns on the surface of the CH layer. A CH layer, the RF aerogel sheet and another CH layer were put on the perturbed surface of the aluminum alloy template in sequence and a quartz glass substrate covered on them. Then the whole five parts put into a muffle furnace at 150 °C and a 250 g weight pressed on them for 2 h. As the CH layer been heated and pressed, the CH layer soften, adhered with the RF aerogel sheet and filled the gaps between the CH layer and the valley of the perturbed template. Finally, these five parts were cooled naturally to room temperature, and then the CH/RF/CH tri-layer perturbation target was obtained by manual cuts. Figure 3 shows the schematic of the hot-press process.

Measurement of the Target and Target Parameters

For density measurements of the RF aerogel sheet, its geometrical dimension was measured by QC-5000 tool microscope (Metronics QC-5000, resolution: ±0.001 mm), and its mass was weighed by an electronic balance (resolution: ±0.0001 g) under ambient laboratory conditions. A SEM (Philips-XL30FEG) was used to investigate the microstructure of the RF aerogel sheet. Target parameters, such as T and A were characterized by QC-5000 tool microscope and alpha-step 500 surface profiler (Tencor Corporation, Alpha-step500). H1, H2, H3 and cross-section of the tri-layer target were characterized by QC-5000 tool microscope and SEM as well.

Results and Discussion

Perturbation Patterns of the Aluminum Alloy Template

Figure 4 shows the enlarged view of the template after been perturbed by the STDP technology, (a) was the perturbed surface of the template which shows a uniform T about 50 μm, and (b) was the cross-section of the template which shows not only a uniform T about 50 μm but also a uniform A about 4 μm. In the turning process, as the scale of perturbation patterns was small, a sharp edge cutter with curvature radius of 3 μm was chosen to cut the aluminum alloy. Under this condition, the perturbation patterns with T/A of 10–15 could obtain.

In order to get precise T and A of the perturbation patterns and observe the three-dimensional image of the template's perturbation patterns, a white light interferometer was used to measure the perturbation surface of the template. The template was put on the test platform of the white light interferometer with the perturbed surface up and enlarged 50X. The three-dimensional image of the perturbation patterns was showed in Fig. 5. In this figure, A and T were uniform as well, and were 3.85 and 55 μm respectively. The perturbation patterns were very close to the sinusoidal fluctuation shape of the mold.

Adjust Thickness of the CH Layer

Thickness of the CH layer was controllable by adjusting the concentration of the CH solution and the pulling speed of the glass slide. When deposition a polymer film by dip-coating method at slow speeds, thickness of the polymer film will depend on square root of pulling speed and linear with polymer concentration times square root of solution viscosity [24]. So increasing the concentration of the CH

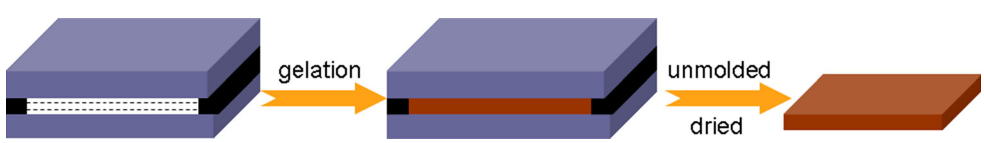

Fig. 2 Schematic of sol–gel and supercritical drying process

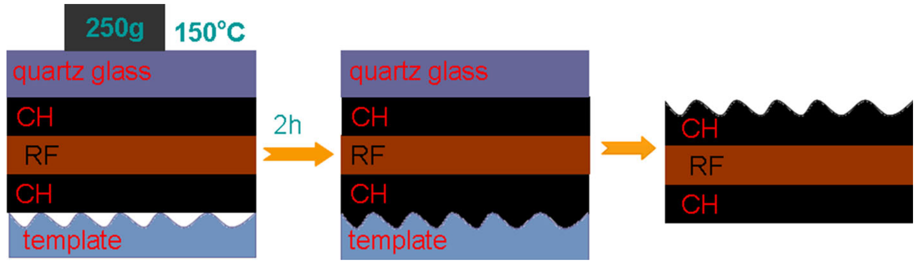

Fig. 3 Schematic of the hot-press process

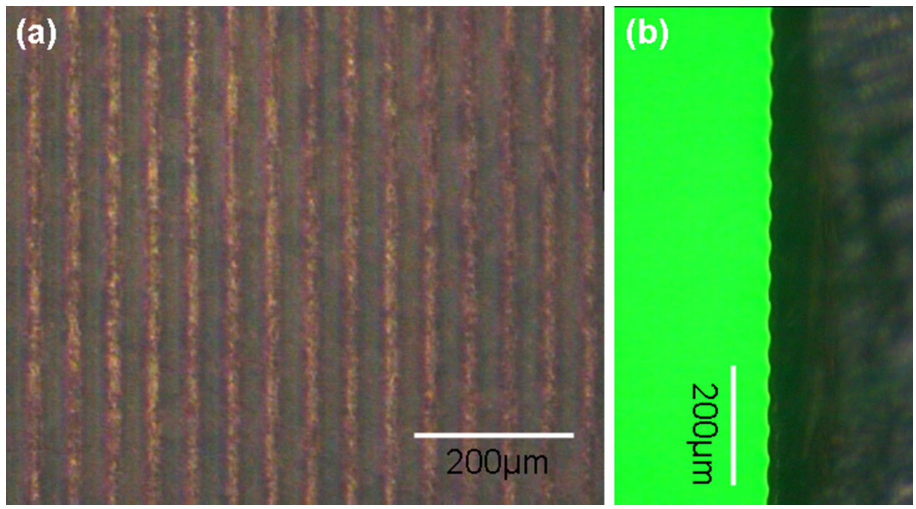

Fig. 4 Enlarged view of the aluminum alloy template **a** surface on view, **b** cross-section

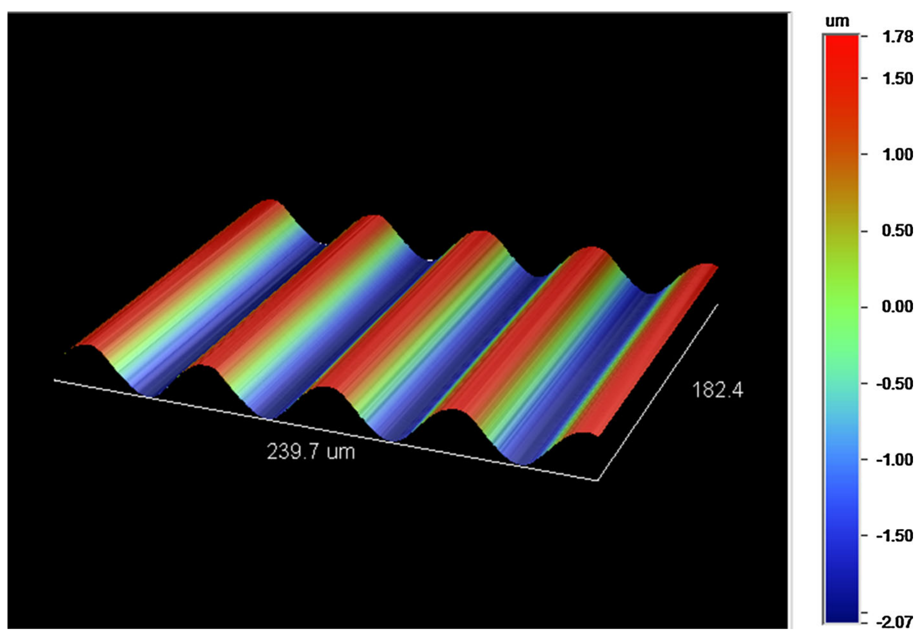

Fig. 5 Three-dimensional image of the perturbation patterns on template

solution or the pulling speed of the glass slide, it results in a thicker CH layer. Based on large amounts of experimentations, as the concentration of the CH solution 8–24 % and pulling speed 1–6 mm/s, the CH layer could obtain was about 5–70 μm.

Density and Microstructure of the RF Aerogel Sheet

In the preparation procedure of the RF aerogel sheet, RF gel were synthesized by the polycondensation of resorcinol (R) and formaldehyde (F), using sodium carbonate (C) as the catalyst and deionized water as the solvent. Density and microstructure of the RF aerogel sheet were controlled by the resorcinol–catalyst ratio (R/C) and the mass ratio of R and F in the reactant (*W* %). Reaction rate, gelation temperature and time were determined by the molar rate of R and F. As the R/C increased and *W* % decreased, density of the RF aerogel sheet decreased. By preparing a series of RF aerogel sheet samples, it was found that density of the RF aerogel sheet could be controlled at 30–1000 mg/cm^3. In order to match the density of DT ice (about 250 mg/cm^3), the parameters R/C and *W* % were set to be 1500 and 30 % respectively. Photos of the RF aerogel sheet are shown in Fig. 6a, The calculated density of the RF aerogel sheet was about 230 mg/cm^3, close to that of DT ice. Microstructure of the RF aerogel sheet was shown in Fig. 6b measured by SEM, the whole aerogel has a nano-porous microstructure and with a uniform cell size about 200 nm.

Parameters of the CH/RF/CH Tri-Layer Perturbation Target

The tri-layer perturbation target was fabricated by a hot-press process after its three component layers all prepared. Figure 7 shows the picture of CH/RF/CH dual-layer perturbation target, (a) is the face-on view. In this figure, the perturbation patterns with a uniform T about 50 μm on the surface of the CH can be seen clearly. Figure 7b–d are the cross-section view of the CH/RF/CH tri-layer perturbation target; (b) is the cross-section image measured by the QC-5000 tool microscope. In this picture, the perturbed CH layer, the RF aerogel sheet and the unperturbed CH layer adhered with each other. The perturbation patterns were transferred from the template to the surface of CH layer successfully. Parameters of the target, such as H1, H2 and H3 were 50, 300 and 20 μm respectively. More detailed cross-section images were measured by SEM and showed in Fig. 7c, d. These two pictures also indicate that the CH layers and the RF aerogel sheet combined well after being hot-pressed. There was no bleed-through of the outside surface perturbation during the hot-press step. As Fig. 7d shows, interface of the CH and RF was clear and intermediate layer between them was quite small which appeared to be <1 μm. During the hot pressing, as the temperature was low and the hot-press time was short, there was almost no densification of the RF. In order to verify this conclusion, another 300 μm RF sheet was hot-pressed between two quartz glasses for 2 h under the same condition. After hot-pressed, its density was calculated to be 236 mg/cm^3, very little change compared to before hot-pressed (230 mg/cm^3), which indicated that the RF aerogel sheet almost no densification during the hot pressing.

Perturbation Patterns of the CH/RF/CH Tri-Layer Target

In order to get precise perturbation patterns of the tri-layer target and compare it with the template, a surface profiler was used to characterize the perturbed surface of the tri-layer target and the template. The template and the target were fixed on the test platform of the profiler, probe of the profiler scanning over the perturbation surface of them with a scanning speed of 50 μm s^{-1}. Figure 8 shows the profile curve of their perturbation patterns, (a) was the template and (b) was the tri-layer target. T and A of the profile curve were 55 and 3.89 μm respectively in Fig. 8a and 55 and 3.88 μm respectively in Fig. 8b. T and A of these two profile curves were almost exactly the same, which indicated that the perturbation patterns transferred from the template to the CH layer precisely. The perturbation patterns of the tri-layer target were controllable by controls the template's perturbation patterns. Both of these two profile curves were very similar to the sinusoidal fluctuate, which meet the requirements of the hydrodynamic instability experiments in ICF well.

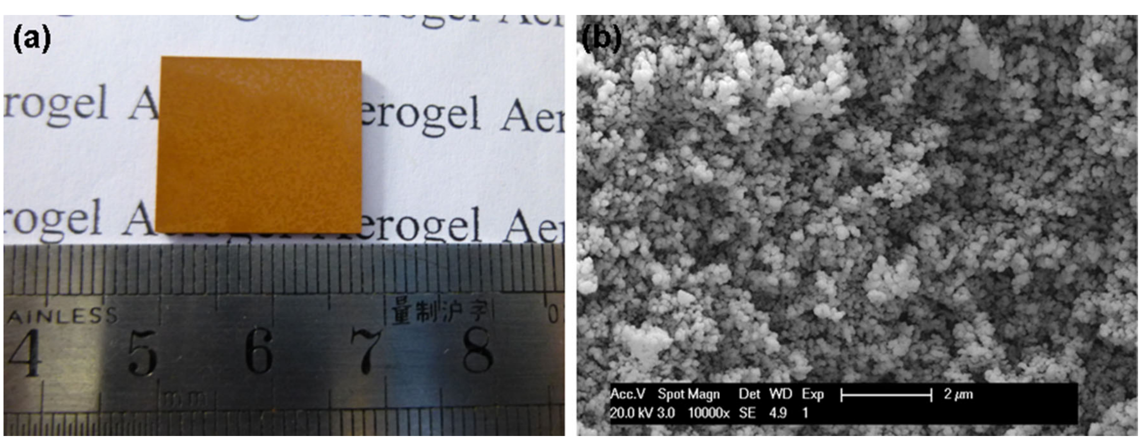

Fig. 6 **a** Photograph of RF aerogel sheet, **b** SEM image of RF aerogel

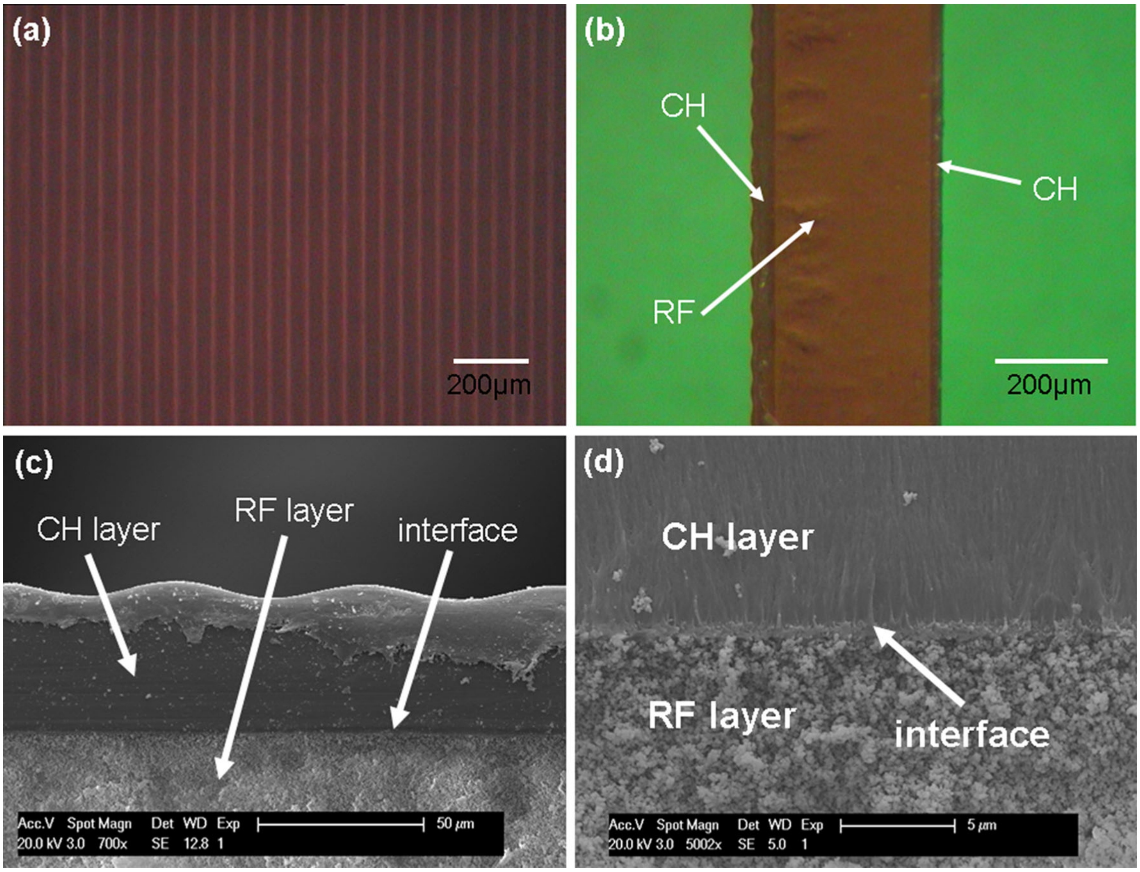

Fig. 7 CH/RF/CH tri-layer perturbation target. **a** Face-on view; **b–d** cross-section

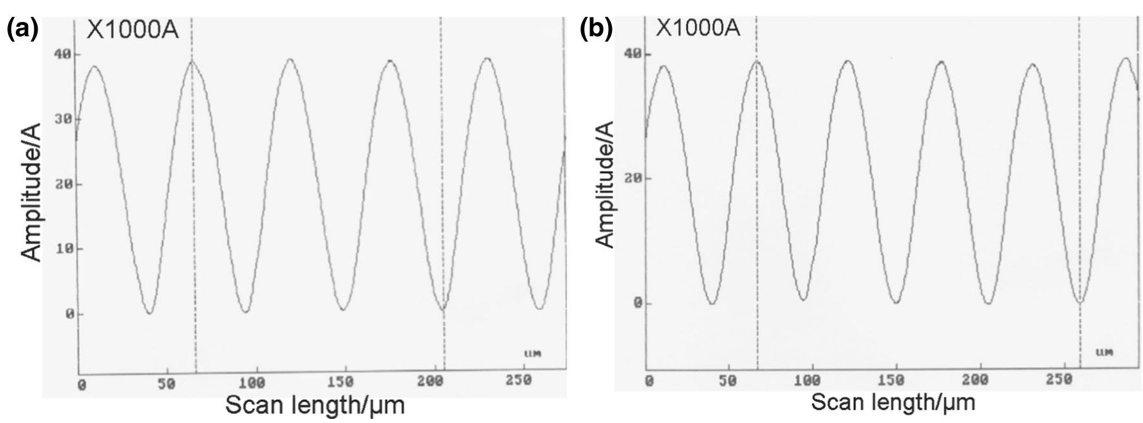

Fig. 8 Perturbation patterns of the template and tri-layer target **a** template; **b** tri-layer target

New Features of the CH/RF/CH Tri-Layer Target

In previous work of Refs. [15, 16], CH/CRF and plastic-foam dual-layer perturbation target was fabricated for the similar purpose. While compared to these dual-layer targets, this tri-layer target has some new features in design and application. Firstly, as the perturbation patterns of this CH/RF/CH target were introduced by the SPDT technology and hot-press process, the perturbation patterns were more precise and controllable than the CH/CRF target, and there were no influence to the RF aerogel sheet like the CH/CRF target which caused by laser ablative in the laser micro-machining process. Secondly, these dual-layer targets only composed of two layers while the CH/RF/CH target composed of three layers, the whole target have one more interface compared to these dual-layer targets, which was closer to the actual hydrodynamic instability experiments in ICF. Thirdly, the perturbation patterns of these dual-layer targets were at the interface of the two dielectric layer, it was used to simulate the RT instability occurred at the interface of the ignition target capsule's two different density layers. While in this CH/RF/CH target, the perturbation patterns were on the first CH layer, it was used to simulate the RT instability occurred at the unstable outer ablator layer of the ignition target capsule. Fourthly, in this CH/RF/CH target, the RF aerogel was "sandwich" held in place by two layers of CH to simulate the DT ice of the ignition target capsule. The whole target was closer to the actual ignition target capsule. However, as the CH/RF/CH target has one more layer compared to these dual-layer targets and has the perturbation patterns on the outer surface, there were some new challenges for the target fabrication. Such as make these three layers adhered together without the use of adhesive, transfer the perturbation patterns from the aluminum alloy template to the CH layer and so on. In this article, with the hot-press process, these three layers adhered together without the use of adhesive and the perturbation patterns transferred from the template to the CH layer precisely. The whole target meets the requirements of the hydrodynamic instability experiments in ICF well and very close to the actual ignition target capsule.

Conclusions

A CH/RF/CH tri-layer perturbation target was designed and fabricated for the hydrodynamic instability experiments in ICF and its features were discussed. The target was composed of a perturbed CH layer, a RF aerogel sheet and an unperturbed CH layer. First a perturbed aluminum alloy template was prepared by SPDT technology. And then via a hot-press process three layers of the target adhered together and the perturbation patterns transferred from the template to the CH layer. T, A, H1, H2 and H3 of the CH/RF/CH tri-layer perturbation target were 55, 3.88, 50, 300 and 20 μm respectively. The cross-section images of the target showed that the CH layer and the RF aerogel sheet combined well. Perturbation patterns transferred from the template to the CH layer precisely, which meets the requirements of the hydrodynamic instability experiments well. The tri-layer target used the RF aerogel to simulate the DT ice of the ignition target capsule, so the whole target very close to the actual ignition target capsule. As the hot-press process not only made the CH layer and the RF aerogel sheet adhered together without the use of adhesive but also transferred the perturbation patterns from the template to the CH layer, it proved to be a simple and useful technique for fabricating structured target foils and maybe much broader application in the future.

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