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Measurement of Young's modulus and damping of fibers at cryogenic temperatures

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ABSTRACT

High-yield inertial confinement fusion targets are at cryogenic temperatures and must remain stable to within 10 μm during the implosion. Young's modulus and damping properties of fibers used to mount cryogenic targets are needed to design stable targets, but these property values do not exist in literature. A novel experimental method that tracks how target vibrations respond to an impulse is used to quantitatively measure these properties from 295 to 20 K. Young's modulus and the critical damping ratio are measured for Nicalon™ ceramic grade [silicon carbide (SiC)], Zylon®HM {poly[p-phenlyne-2,6-benzobisoxazole] (PBO)}, M5 {dimidazo-pyridinylene [dihydroxy] phenylene (PIPD)}, and polyimide fibers. This method allows one to accurately measure the properties of interest for fiber diameters as small as 12 μm at ~20 K. Significant changes are seen in Young's modulus for the three polymeric fibers with respect to temperature; while Young's modulus is relatively invariant to temperature for the ceramic fiber.

1. Introduction

The direct-drive laser approach to inertial confinement fusion (ICF) at the University of Rochester's Laboratory for Laser Energetics involves the use of high-power laser beams to uniformly compress a target capsule filled with hydrogen isotopes in a spherically symmetric implosion. The use of cryogenic (cryo) targets, filled with fuel and cooled to form an ice layer at ~20 K on the capsule's inner surface, results in higher fuel densities and therefore higher yields [1].

A typical production cryogenic target assembly is shown in Fig. 1. The target shell's outer diameter is ~875 μm and, depending on ice thickness, has a filled mass of ~55 μg. The shell is attached to a 17-μm silicon carbide fiber with a small spot of adhesive. Adhesive lap joints are used to attach the silicon carbide fiber to the polyimide fiber, and the polyimide fiber to the stainless steel tube. The design of cryogenic targets must meet the stringent stability requirement of remaining within 10 μm of target chamber center (TCC) during the implosion. Target position is a superposition of static alignment and vibration caused by the retraction of the thermal shrouds that maintain the temperature of the target prior to implosion. When the target offset with respect to TCC is increased, a compression asymmetry is introduced, resulting in a reduction of observed [2] neutron yield.

Target mount assemblies must be designed with a fundamental mode of >300 Hz at ~20 K so that the capsule is minimally excited by the impulse created by the aforementioned shroud retraction. Designing a target mount with a specific natural frequency and transmissibility requires accurate values for Young's modulus and critical damping ratio at cryogenic temperatures. Data for these material properties at cryogenic temperatures is not available in literature for the materials of choice in target mount design. The materials of interest for this study are Nicalon™ ceramic grade [silicon carbide (SiC)] [3], Zylon®HM {poly[p-phenlyne-2,6-benzobisoxazole](PBO)} [4], M5 {diimidazo-pyridinylene [dihydroxy] phenylene (PIPD)} [5], and polyimide [6]. Table 1 lists the room-temperature (RT) values of Young's modulus taken from literature for these materials of interest.

The method used in this study involves exciting a target mounted on a fiber of each of these materials over a range of temperatures from ~295 K to ~20 K. A SiC test target assembly is shown in Fig. 2. The shell is attached to a 17-μm SiC fiber with a small spot of adhesive. An adhesive lap joint is used to attach the SiC fiber to the stainless steel tube. The experimental setup records the displacement of the target capsule's centroid, caused by an impulse load, with respect to time. From this data, the modulus and damping ratio can be calculated over a range of temperatures.

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Nomenclature

Abbreviations and acronyms

1-D	one dimensional
3-D	three dimensional
cryo	cryogenic
DMA	dynamic mechanical analysis
FE	finite element
FFT	fast Fourier transform
ICF	inertial confinement fusion
ID	inner diameter
OD	outer diameter
PBO	poly[p-phenlyne-2,6-benzobisoxazole]
PIPD	dimidazo-pyridinylene [dihydroxy] phenylene
rms	root mean square
RT	room temperature
SiC	silicon carbide
TCC	target chamber center

Physical variables

E	Young's modulus
E^{RT}	estimated Young's modulus at room temperature
E^{T}	estimated Young's modulus
f_n	natural frequency
f_n^{RT}	measured fundamental frequency at room temperature
f_n^{T}	measured fundamental frequency at temperature of interest
I	beam's second area moment of inertia
L	length of the cantilever beam
M	point of mass supported by the free end of the beam
M_b	fiber mass
N	number of cycles between peaks in
x_1 and x_2	magnitudes of two peaks in the time domain
ζ	logarithmic decrement

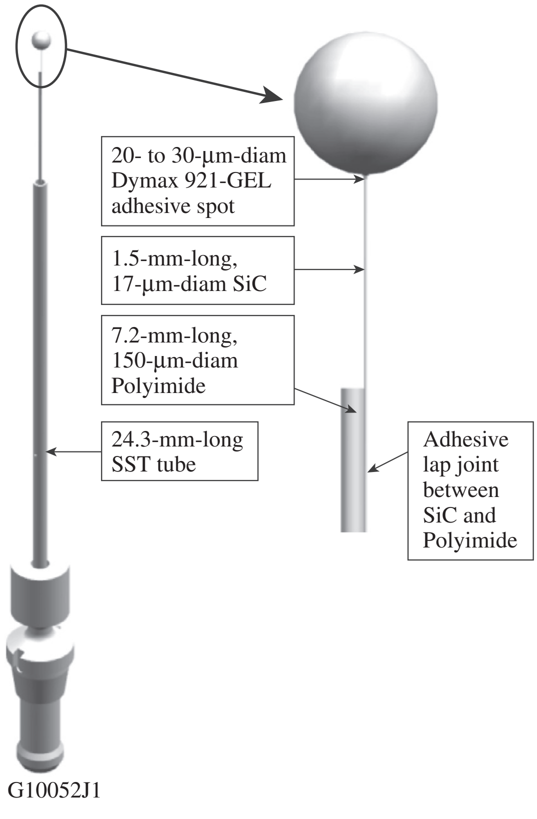

Fig. 1. A typical production cryogenic target mount assembly. SST: stainless steel; SiC: silicon carbide; PI: polyimide.

Similar methods have been used to measure Young's modulus in other studies; however, these tests have not included fiber sample shapes or the materials of interest in this study [7].

Dynamic mechanical analysis (DMA) is another viable method to find these parameters; however, the results are extremely sensitive to the setup and test procedures when measuring fibers <20 µm in diameter. In addition, it is not possible to reach temperatures below ~100 K [13] with the currently available equipment. The method used in this paper demonstrates that these properties can be accurately measured for fiber diameters as small as 12 µm at ~20 K. Targets have been manufactured at LLE with ~5 µm diameter carbon fibers. Extension of this method to these fibers should not present any unique challenges.

2. Experimental methods

A Montana Instruments Cryostation [8] provides a selectable isothermal environment, from ~295 K down to ~20 K, to conduct vibration tests on (fiber) test target assemblies. The test setup is shown in Fig. 3. A target capsule without fuel is supported by a fiber of the material of interest and cooled in a helium environment to the desired test temperatures. Fig. 4 shows a test target mounted to the internal Cryostation support structure. The support structure and target assembly is mounted inside the Cryostation and is shrouded in helium to maintain an isothermal environment between the support structure, target assembly, and temperature sensor. The Montana Instruments Cryostation is designed to minimize steady-state target vibrations caused by the presence of its coldhead (<25-nm rms (root-mean-square) background vibration) [8]. The test target is excited by an impulse from a modal hammer hit on the body of the cyrostation at a given temperature set point. The Cryostation's low background vibration contributes to a high signal-to-noise ratio of the target's response to the applied impulse.

Two high-speed cameras with perpendicular viewing angles capture video of target vibrations at a sampling rate of 2000 frames per second. Image-processing software is used to record the displacement of the centroid of the target capsule in each frame, resulting in a displacement (along the x- and y-axes) versus time data set. To prevent aliasing, test targets were designed to a have a fundamental frequency at room temperature of ~3× lower than the Nyquist frequency of the measurement system. The modulus of the fiber is calculated from the fundamental frequency of the target assembly, and damping is calculated from the logarithmic decay of the waveform in the time domain.

Modal hammer hits are aligned with the y-axis, and target vibration data are recorded along the x- and y-axes by using both cameras. A typical vibration response to an impulse aligned with the y-axis is shown in Fig. 5 for a Nicalon™ fiber test target at 20 K. Fig. 5(a) shows target vibration with respect to time and Fig. 5(b) shows the fast Fourier transform (FFT) of target vibration. Damping is measured by the rate of vibration decay in the time domain (Fig. 5(a)). The modulus of the fiber is calculated based on the fundamental vibration mode along the y-axis (Fig. 5(b)).