Experimental measurement of thermal shock wave in C/Ph induced by electron beam radiation

Yan-Jia Lin[1]**, Peng Lin**[2]
[1]School of Physical Science and Technology, Southwest University, Chongqing, China
[2]Xi Jing University, Xi'an, China
[2]Corresponding author
E-mail: [1]*yjlin2002@163.com*, [2]*linpa11@sina.com*

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Abstract. The attenuation characteristic of thermal shock wave in a new type of carbon phenolic (C/Ph) radiated by pulsed electron beam were studied experimentally on "FLASH II" accelerator with PVDF transducer. The attenuation trend of thermal shock wave produced by electron beam radiation in the material is calculated by means of numerical simulation. Experimental results show that: when electron beam energy fluxes are in the range of 169-531 $J\cdot cm^{-2}$ and the electron's mean energy is about 0.6 MeV, stress at 4 mm from the irradiation surface of C/PH are in the range of 0.12-2.22GPa. The experimental results of the attenuation trend of thermal shock waves are in good agreement with the simulation results.

Keywords: thermal shock wave, electron beam, energy flux, C/Ph, PVDF.

1. Introduction

Carbon fiber reinforced phenolic resin composite, namely carbon phenolic resin, has been widely used in aviation, aerospace, transportation, weapon components and other high-tech fields because of its high specific strength and specific stiffness, high temperature resistance, ablation resistance and other excellent properties [1, 2]. In recent years, with the development of material science and the demand of application field, new carbon phenolic materials based on modified high performance phenolic resin have been paid more and more attention. The studies are mainly focused on the fabrication, ablation mechanism and thermodynamic parameters of the C/Ph composite [3-9]. The physical and mechanical properties of this new material, especially the characteristics of thermal shock wave produced by pulse radiation, is one of the hot issues that people pay close attention to. It is of great significance for related fields to study the radiative thermal shock wave and its propagation and attenuation process of this material.

This paper mainly studies the propagation law of thermal shock wave produced by pulsed electron beam radiation in a new type of C/Ph material. The attenuation process of thermal shock wave in the target is measured by PVDF piezoelectric technique, and the results are compared with the results of numerical simulation.

2. Measuring method

Polyvinylidene fluoride (PVDF) is the principal commercially available polymer that exhibits strong piezoelectric properties. Since the discovery of piezoelectric effects in PVDF by Kawai [10], it has been widely using in the areas of impact dynamics to measure the dynamic pressure [11].

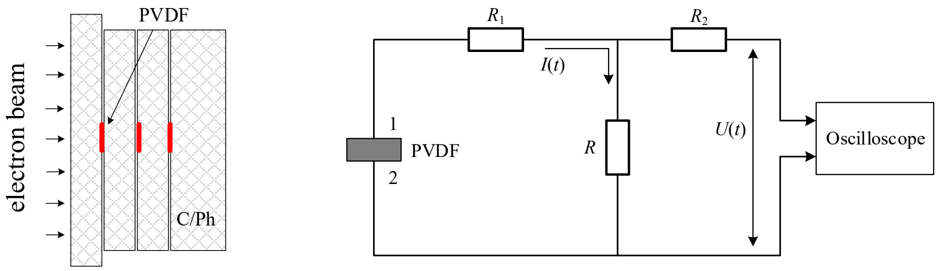
The PVDF is placed into the target assembly to directly measure the evolution of the thermal shock wave, as shown in Fig. 1. Because the self-made PVDF meter is very thin (about 40 μm), the effect on the propagation behavior of thermal shock wave can be ignored.

A resistor R of 50 Ω was connected between two electrodes of the sensor. As shown in Fig. 1, the output voltage corresponding to shock pressure was recorded by the oscilloscope. The shock-induced current can be expressed as Eq. (1):

$$I(t) \approx \frac{U(t)}{R}. \tag{1}$$

The output electric charge $Q(t)$ of a PVDF sensor was then related to the recorded voltage $U(t)$ by the following equation:

$$Q(t) \approx \int_0^t I(t)dt = \int_0^t \frac{U(t)}{R}dt. \tag{2}$$



a) Target assembly b) The measurement circuit of PVDF sensor

Fig. 1. A schematic diagram of PVDF instrument

Calibration of the sensor usually showed a linear relationship between the electric charge and applied pressure. It is:

$$Q(t) = AKP(t), \tag{3}$$

where $P(t)$ is the longitudinal pressure applied on the sensor, $Q(t)$ is the electrical charge delivered by the PVDF. A is the active area of PVDF film, $A = 9$ mm^2. K is the sensitivity constant of the PVDF sensor and its value is 33.5 pc/N.

So that combining Eqs. (2) and (3) gives:

$$P(t) = \frac{Q(t)}{AK} \approx \frac{1}{K}\frac{\int_0^t U(t)dt}{RA}. \tag{4}$$

3. Experiment and analysis

3.1. Experiment

The experiment was carried out on the “Flash II” pulsed electron beam accelerator, and each shot was equipped with a PVDF thermal shock probe. The PVDF piezoelectric probe gives signals from two to three positions each shot. Fig. 2 shows the thermal shock wave probe installed in the drift tube.

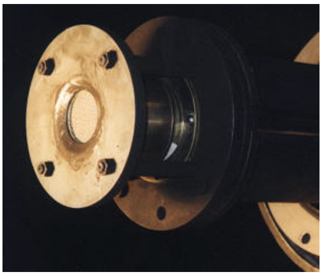
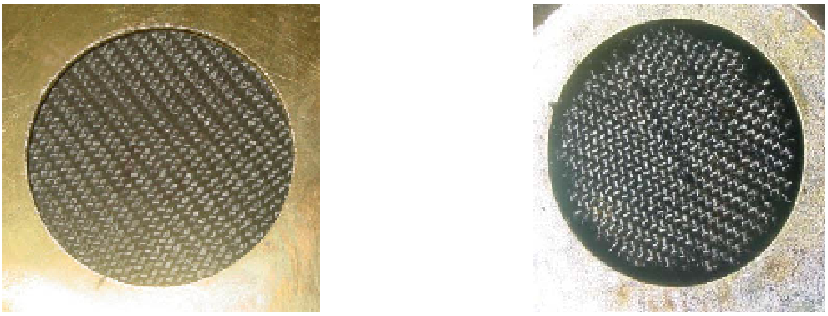


Fig. 2. The thermal shock probe installed in drift tube

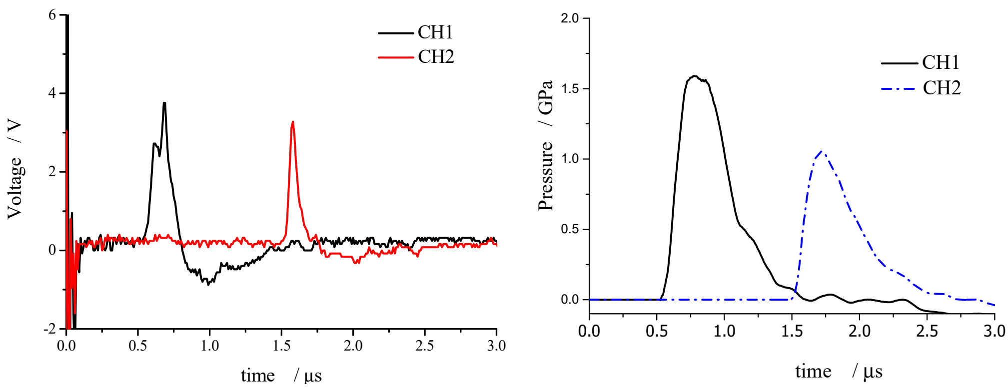
Fig. 3 shows the ablation of the material surface before and after irradiation. After the front surface of the material is irradiated by electron beam, a large amount of energy is deposited on the thin surface layer, the phenolic resin melts or vaporizes, and the carbon fiber does not melt. The vaporization of carbon fiber occurs only when its specific energy reaches sublimation energy.



a) Target before irradiation b) Target after irradiation

Fig. 3. Target before and after irradiation

Fig. 4 shows the typical waveform recorded by PVDF and the stress waveform integrated by Eq. (4).



a) The recorded piezoelectric signal b) The integral waves

Fig. 4. The recorded and integral waves (No. 1)

3.2. Measurement results

The experimental results are shown in Table 1. E_{av} is the average energy of electron beam. Φ is the energy flux of electron beam. The uncertainty of Φ is about 25 %.

Table 1. Experimental results of thermal shock waves

No.	E_{av} / MeV	Φ / J·cm^{-2}	Pressure / GPa		
			x = 4 mm	x = 8 mm	x = 12 mm
1	0.59	410	1.59	1.21	–
2	0.50	383	1.43	1.11	0.90
3	0.70	531	2.22	1.53	1.06
4	0.55	358	0.88	0.67	0.51
5	0.51	312	0.81	0.70	0.47
6	0.58	429	1.82	1.35	1.01
7	0.61	181	0.15	–	–
8	0.65	169	0.12	–	–
9	0.55	217	0.31	–	–

It can be seen from Table 1 that the peak intensity of thermal shock waves attenuates with the propagation distance. The higher the energy flux of the electron beam is, the greater the intensity of the thermal shock wave produced in the target is, and the relationship between them is approximately linear. As shown in Fig. 5, when electron beam energy fluxes are in the range of 169-531 J/cm^2 and the electron's mean energy is about 0.6 MeV, stress at 4 mm from the irradiation surface of C/PH are in the range of 0.12-2.22 GPa.

Taking several shots with same pulse width as an example, the data are normalized. As shown in Fig. 6, the higher the peak intensity of the thermal shock wave is, the faster the peak attenuation is.

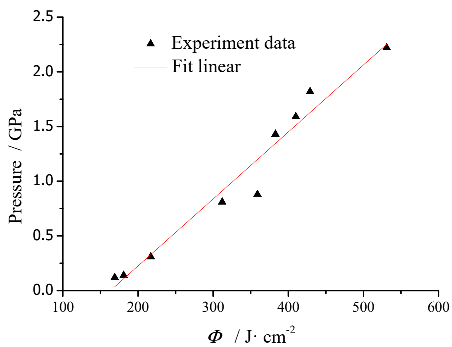


Fig. 5. The pressure vs. Φ curve at the position of $x = 4$ mm

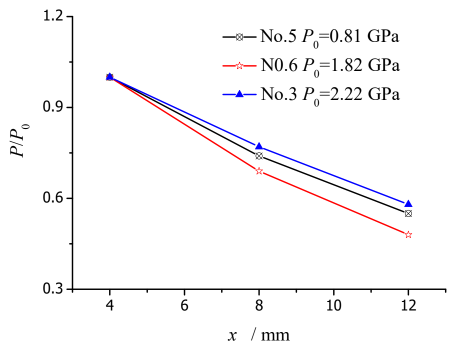


Fig. 6. Wave attenuation with different peak intensities

3.3. Analysis

Electron beams irradiate the target to deposit energy in a thin layer on the surface of the material. The higher the electron energy, the deeper the deposition depth. For the electrons of 0.6 MeV energy, the maximum depth of deposition in carbon phenolic is about 2.5 mm. Fig. 7 shows the energy deposition profiles of the electrons with different energies.

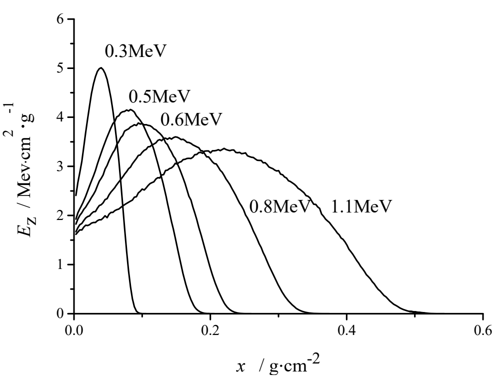


Fig. 7. Energy deposition profile of electrons in C/Ph

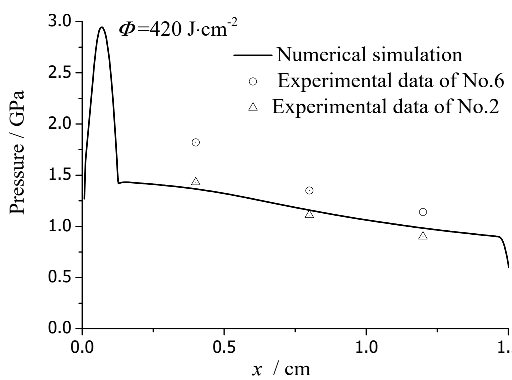


Fig. 8. The attenuation curve of thermal shock

The initial stress curve caused by energy deposition is expressed by the following formula:

$$P(x) = \Gamma_0 \rho E_Z(x). \tag{5}$$

The compressive stress occurs at the same time as the energy deposition and is transferred from the high pressure area to the low pressure area. Non-uniform energy deposition causes compressive stress waves propagating in the material. The propagation characteristics of thermal shock waves in the target are numerically simulated by using an one-dimensional plane fluid elastoplastic model [12, 13].

Fig. 8 shows the attenuation of the thermal shock waves induced by the electron beam with average energy ($E_{av} = 0.6$ MeV). The data of No. 2 and No. 6 are listed in the figure, for their energy Fluence is close to the same. It can be found that the simulation results are in good agreement with the experimental results.

4. Conclusions

Different from the most studies, we pay attention to the study of thermal shock wave propagation caused by intense pulse electron beam irradiation in C/Ph. Through experimental research and analysis, the following conclusions can be drawn:

(1) When electron beam energy fluxes are in the range of 169-531 J/cm^2 and the electron's mean energy is about 0.6 MeV, stress at 4 mm from the irradiation surface of C/PH are in the range of 0.12-2.22 GPa.

(2) At the given location in the target, the peak intensity of thermal shock wave increases linearly with the increase of electron beam energy flux.

(3) For the thermal shock wave with the same pulse width, the higher the peak intensity of the thermal shock wave is, the faster the peak value of the thermal shock wave attenuates.

(4) According to the material parameters, the peak attenuation characteristics of thermal shock waves are numerically simulated, and the simulation results are basically consistent with the experimental results. The compression wave propagates in the composite, and will be reflected from the inner free surface or adhesive layer. When the tensile wave strength exceeds the threshold of the composite, it may cause spallation failure and bond surface degumming of the material.

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