Impulsive coupling characteristics of materials irradiated by electron beam

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Abstract. The blow-off impulse is the condition of applied loads of the structural response induced by pulsed beam and the coupling coefficient of impulse is a key parameter to estimate the potential of producing impulse. A new kind of impulse probe was developed and tests were conducted to measure the impulses of several kinds of materials exposed to electron beam on “Flash II” accelerator. Experimental results of these tests show that: (1) when the energy fluxes are in the range of 150 ~ 183 J · cm⁻², the average coupling coefficient of blow-off impulse of the soft graphite is 0.40 Pa · s/(J · cm⁻²), and that of C/E is 0.94 Pa · s/(J · cm⁻²). (2) as a structural material, the C/E composite has better anti-radiation performance than aluminium material because the average coupling coefficient of C/E is less than that of aluminium.

1. Introduction
When intense pulsed beam is absorbed in the surface layer of a solid target, a shock wave may be induced by the vapor blowing off from target surface. The dynamic behavior of materials at high pressure and high temperatures have been of interest for many years [1-3]. Recent studies of materials exposed to pulsed electron beam have focused on attention on the blow-off impulse coupling response of materials generated by pulsed energy deposition [4-6]. The intense impulse load will cause the structure’s spalling and damage, and the coupling coefficient of impulse is a very important parameter to assess the quantities of impulse produced by intense pulsed beam.

The objective of the present program is to study the characteristics of coupling impulse of several kinds of materials. To accomplish this objective, an impulse probe is developed to carry out the impulse experiments of carbon fibre epoxy composite (shorted as C/E), Ta, the soft graphite and aluminium, which are irradiated by electron beam.

2. Measuring Method
There are many methods of measuring the velocities of moving bodies, such as high velocity photography, magnetoelectric transducer, eddy transducer, photoelectric transition. Here, the impulse probe adopted the principles of directly measuring the specific series of time intervals and transducing technique passing infrared ray.

Figure 1 shows the schematic diagram of the probe. The flat target is attached on one end of the translational bar. The other end of the bar is shaped as several rings with a constant spacing. The infrared luminous tubes and photoelectric triodes are installed on the two sides of the bar. When the bar moves forward, the ring blocks the light and the signal is off, after that, the signal is on. The digital oscilloscope records the time interval “Δt” while the bar moves through the spacing “L” between two rings. Thus, the average velocity is obtained by
\[ V = \frac{L}{(1 - \xi) \Delta t} \]  

(1)

Where, \( \xi \) is the friction adjusting factor (less than 4.5%), which is calibrated by light gas gun. According to the law of momentum conservation, the blow-off impulse is

\[ I = \frac{mV}{A} \]  

(2)

Where, \( m \) is the total mass of the target and bar, \( A \) is the irradiated area on the target. The experimental uncertainty of impulse is less than 8%. If the energy flux of electron beam on the target, noted as \( \Phi \), the coupling coefficient of blow-off impulse will be determined:

\[ \beta = \frac{I}{\Phi} \]  

(3)

\( \beta \) represents the potential for generating blow-off impulse with unit energy flux of electron beam.

3. Experiments

Experiments are carried out on the “Flash-II” accelerator to measure the blow-off impulse of materials, which is Ta, aluminium, the soft graphite and the C/E composite respectively. Figure 2 shows that four impulse probes are installed in the drift tube in one shot and four experimental data can be gained at a time. Figure 3 is the typical recording waveforms in experiment. The velocity is determined by the time intervals of the voltage signal waveforms and the distance between two rings on the one end of transmitting bar. The masses of the target and moving bar are quantified by the high-precision electric balance. The radiated area of the target is measured by ruler after experiment. Finally, the impulse of unit area is obtained from equation (2). Figure 4 is the ablation pictures of C/E composite and the soft graphite irradiated by electron beam. The carbon fibre is hard to melt down and the impulse is mainly induced by the melt or boiled base components flying away from the target surface. The soft graphite’s main component is carbon, which is hard to vapor, it’s impulse is also caused by the other components blowing off from the target surface.

The energy flux \( \Phi \) is measured by the graphite calorimeters around the probe. There are three calorimeters around per impulse probe and the energy flux is mean value from the three calorimeters. The uncertainty of the energy flux measurement is less than 5%.
4. Results and Discussion

4.1. Experimental Results

The impulse data of all experimental materials are illustrated with figure 5. The impulse coupling coefficients are illustrated with figure 6.

When the energy fluxes are in the range of 150 ~183 J·cm⁻², the impulses of the soft graphite are in the range of 57.1 ~ 81.4 Pa·s, and its coupling coefficients vary from 0.39 to 0.48 Pa·s/(J·cm⁻²). When the energy flux is 172 and 180 J·cm⁻², the impulse of Ta is 82.5 and 89.4 Pa·s respectively, and the average coupling coefficient is 0.49 Pa·s/(J·cm⁻²).

The impulse of the C/E composite increases from 92 to 154 Pa·s when the energy flux in the range of 97 ~ 162 J·cm⁻², and the average coupling coefficient is 0.94 Pa·s/(J·cm⁻²).
aluminium increases from 168 to 200 Pa·s when the energy flux in the range of 168 ~ 200 J·cm⁻², and the coupling coefficient increases from 0.75 to 1.15 Pa·s/(J·cm⁻²).

4.2. Discussion

The Whitener [1] analytical model has been used to calculate the impulse induced by X rays. The Whitener model requires knowledge of the energy deposition through the thickness of exposed structure with appropriate physical properties. The model can be expressed as

$$ I = \sum_{j=1}^{n} (\rho \Delta x_j) (H - E_s)^{1/2} $$

Where, ρ is the density of zone j, Δx is thickness of zone j, H is total energy deposited in zone j, E_s is the sublimation energy for the material. To implement this model the distribution of the deposited energy through the thickness of the structure must be known.

However, the melt part of the material also has a contribution to the impulse. The Whitener model is revised as

$$ I = \sum_{j=1}^{n} (\rho \Delta x_j) (H - E^*)^{1/2} $$

Where, E* is the blow-off energy, which is less than E_s. It can be determined by the experiments.

The melting point of Al is about 661 °C, the heat of dissolution is 398 J/g. The melting point of Ta is 2997 °C, the heat of dissolution is 433J/g. The blow-off energy of Ta is bigger than that of Al, so the impulse of Ta is less than that of Al in the same energy flux. The experimental results accord with the revised Whitener model.

When the energy flux exceeds about 170 J·cm⁻², the impulse of the C/E composite is less than that of Al, and the coupling coefficient remains almost unchanged. Compared with Al, the C/E composite has better anti-radiation property.

5. Conclusions

Based on the discussions as mentioned above, the following meaningful conclusions can be obtained:

1. when the energy fluxes are in the range of 150 ~ 183 J·cm⁻², the average coupling coefficient of blow-off impulse of the soft graphite is 0.40 Pa·s/(J·cm⁻²), and that of Ta is 0.49 Pa·s/(J·cm⁻²) when the energy fluxes are in the range of 172 ~ 180 J·cm⁻², that of C/E is 0.94 Pa·s/(J·cm⁻²) when the energy fluxes are in the range of 97 ~ 162 J·cm⁻², that of aluminium increases from 0.75 to 1.15 Pa·s/(J·cm⁻²) when the energy fluxes are in the range of 97 ~ 162 J·cm⁻².

2. The C/E composite has better anti-radiation performance than Al.

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