Dynamic Mechanical Properties of Materials Measured by Plate Impact Experiments* (Si₃N₄, SiC and TiB₂)

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Plate impact experiments with PVDF (PolyVinylidene DiFluoride) stress gauges to determine the dynamic mechanical properties of the ceramics Si₃N₄, SiC and TiB₂ were conducted using a shock gun system. From the experiments, we obtained the Hugoniot curves and the Hugoniot elastic limits of the ceramics.

Key Words: Elasticity, Plasticity, Stress Wave, Plate Impact Experiment, Dynamic Mechanical Properties, Hugoniot Curve, Hugoniot Elastic Limit, PVDF Stress Gauge, Silicon Nitride, Silicon Carbide, Titanium Diboride

1. Introduction

This paper, which follows the two papers^{(1),(2)}, will present the dynamic mechanical properties (Hugoniot curves and Hugoniot elastic limits) of three ceramic materials: silicon nitride Si₃N₄, silicon carbide SiC and titanium diboride TiB₂. These properties were measured by plate impact experiments conducted using a shock gun system. Experiments and data analyses were conducted in the same manner as in the papers^{(1),(2)}, except for the following points: (1) different kinds of specimens, (2) copper and tungsten flyer plates (impactors), (3) minor change to the shapes of specimens and impactors, and (4) PVDF stress gauge measurement only. See the papers^{(1),(2)}

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for details, as necessary.

2. Method of Experiments

We employed three kinds of ceramic materials as specimens (target plates), and copper and tungsten as impactors (flyer plates). Mechanical properties of the specimens and impactors are shown in Table 1. Their sizes and shapes are also shown in Figs. 1 and 2.

Partial-disk-shaped specimens were adopted for the ceramics, whereas disk-shaped specimens for

Table 1 Mechanical Properties of the specimens and impactors

		Specimens			Impactors	
		Si ₃ N ₄	SiC	TiB ₂	Copper	Tungsten
Tensile test	Tensile strength (MPa)	—	—	—	280	255
	Elongation (%)	—	—	—	27	0
Flexural strength (MPa)		1210	698	452	—	—
Vickers hardness		1530HV1	2305HV1	1918HV1	—	>420HV5
Density ρ (g/cm ³)		3.184	3.214	4.463	8.907	18.971
Sound velocities	Longitudinal c_L (m/s)	10959	12265	10968	4725	5188
	Transverse c_T (m/s)	6096	7792	7374	2232	2872
	Bulk c_B (m/s)	8400	8335	6913	3960	3990
Elastic moduli	Bulk modulus K (GPa)	224.7	223.3	213.3	139.7	302.0
	Shear modulus G (GPa)	118.3	195.2	242.7	44.4	156.5
	Young's modulus E (GPa)	302.0	453.4	527.9	120.4	400.3
	Poisson's ratio ν	0.276	0.162	0.088	0.356	0.279

Fig. 1 Sizes and shapes of the specimens

Fig. 2 Sizes and shapes of the impactors

Fig. 3 Schematic of PVDF stress gauge method

metals were used in our previous papers^{(1),(2)}. This was because we were afraid that cracking might occur on the ceramic specimen at the moment of impact if we made a small hole on the specimen and attach a trigger pin. For each experiment, only one trigger pin was used. Tungsten impactors were designed to be thinner than copper in order to reduce weight.

The PVDF stress gauge measurement was employed for the experiments, as in Fig. 3. For each kind of specimen, i.e., silicon nitride Si_3N_4 , silicon carbide SiC and titanium diboride TiB_2 , we established five experimental conditions: at the impact velocities of

Fig. 4 Measured waveforms of Si_3N_4

about 1200 m/s, 1500 m/s and 1900 m/s with the copper impactors, as well as about 1500 m/s and 1900 m/s with the tungsten impactors. Three experiments were conducted under each condition.

3. Results and Discussions

Measured waveforms for the three ceramics are shown in Fig. 4 through 6, respectively. Each figure contains five waveforms measured under the five impact conditions mentioned above. The horizontal axis represents the time after impact. In fact, the arrival time of the elastic wave varies a little from measurement to measurement, but the time is compensated by using the longitudinal wave speed c_L so that each elastic wave can arrive at the same time for each measurement. The vertical axis of each figure represents the voltage generated between the two electrodes of the PVDF stress gauge. The voltage can be converted into the corresponding stress value by using a characteristic equation of gauges.

From the figures, we see that the level of voltage or stress after the arrival of elastic wave, i.e., at the Hugoniot elastic limit (HEL) is almost the same regardless of impact conditions. As we have already pointed out in the papers^{(1),(2)}, this result is consistent with the reference⁽³⁾, which states that the HEL stress does not depend on the impact velocity. Additionally, we observe from the figures that the maximal stress level attained afterwards by the plastic wave arrival changes according to the type and velocity of the impactor. For the same type of impactors, the higher the impact velocity is, the higher level the stress reaches. For the same impact velocity, the tungsten impactor generates higher stress than the copper impactor. This is because tungsten bears larger shock impedance (product of density and shock wave velocity) more than copper.

We observe some waveform features that would characterize individual ceramics. In Fig. 4 of Si_3N_4 ,

Fig. 5 Measured waveforms of SiC

Fig. 6 Measured waveforms of TiB₂

each stress level is kept almost constant between the arrival times of elastic and plastic waves. In Fig 5 of SiC, however, each stress grows incrementally after the elastic wave arrival. Further, in Fig 6 of TiB₂, each waveform has one inflection point between the elastic wave arrival and the maximal stress attainment. In other words, the plastic wave arrives in two parts, which we hereafter call the first and second plastic waves, respectively. This seems to be the result of a phase transition. Almost the same stress level is observed at the point of first plastic wave arrival (second yield point) regardless of impact conditions, just as at the Hugoniot elastic limit (first yield point). These waveform features of SiC and TiB₂ are in good agreement with those of the reference⁽⁴⁾, where some plate impact measurements by VISAR are described.

Though some signals caused by spall fracture were observed for metals in the preceding papers^{(1),(2)}, no such signals were measured for the ceramics in this series of experiments. Some plate impact experiments were conducted for ceramics similar to our specimens in the paper⁽⁴⁾, but no spall signals were present. We guess that the fragmentation might occur

Fig. 7 The Hugoniot curve of Si₃N₄ in $V/V^0 - \sigma$ Fig. 8 The Hugoniot curve of SiC in $V/V^0 - \sigma$ Fig. 9 The Hugoniot curve of TiB₂ in $V/V^0 - \sigma$

before spalling for brittle specimens such as ceramic materials.

3.1 Hugoniot curves

We calculated some shock parameters after the arrivals of elastic and plastic waves with respect to the ceramic materials Si₃N₄, SiC and TiB₂, and plotted them in Fig. 7 through 18. The Hugoniot curves of the ceramics obtained in a way similar to the papers^{(1),(2)} are also shown in Fig. 7 through 15. As for TiB₂ in Figs. 9, 12 and 15, the second yield point as well as the Hugoniot elastic limit (first yield point) was calculated by averaging the measured values, and

Fig. 10 The Hugoniot curve of Si_3N_4 in $\mu-\sigma$ Fig. 13 The Hugoniot curve of Si_3N_4 in $\mu_p-\sigma$ Fig. 11 The Hugoniot curve of SiC in $\mu-\sigma$ Fig. 14 The Hugoniot curve of SiC in $\mu_p-\sigma$ Fig. 12 The Hugoniot curve of TiB_2 in $\mu-\sigma$ Fig. 15 The Hugoniot curve of TiB_2 in $\mu_p-\sigma$

the two yield points were connected by a line segment in each figure. We ignored a few extraordinary data in deriving the above Hugoniot curves and yield point values. Besides, we shifted the Hugoniot curves in the plastic regions to the initial condition point so as to obtain the hydrostatic pressure curves. Those curves are also shown in the figures.

For SiC and TiB_2 in Figs. 8, 9, 11, 12, 14, 15, 17 and 18, corresponding data in the book⁽⁵⁾ are plotted for reference. It is inappropriate to simply compare the two sets of data because the materials of the specimens are not identical, but it could be pointed out that

the two data sets bear some resemblance.

Figures 7, 8 and 9 show the relations between the relative volume V/V^0 and the stress σ . The expressions of the Hugoniot curve and hydrostatic pressure curve are

$$\sigma = \begin{cases} 382 - 382(V/V^0) \text{ (GPa)} & \text{if } 0.964 \leq V/V^0 \leq 1 \\ 27.0 + 229(V/V^0) - 251(V/V^0)^2 \text{ (GPa)} & \text{if } V/V^0 < 0.964 \end{cases}$$

$$p = 22.8 + 229(V/V^0) - 251(V/V^0)^2 \text{ (GPa)}$$

for Si_3N_4 ,

Fig. 16 The u_p - u_s relation of Si_3N_4 Fig. 17 The u_p - u_s relation of SiC Fig. 18 The u_p - u_s relation of TiB_2

$$\sigma = \begin{cases} 484 - 484(V/V^0) \text{ (GPa)} & \text{if } 0.970 \leq V/V^0 \leq 1 \\ 599 - 948(V/V^0) + 357(V/V^0)^2 \text{ (GPa)} & \text{if } V/V^0 < 0.970 \end{cases}$$

$$p = 591 - 948(V/V^0) + 357(V/V^0)^2 \text{ (GPa)}$$

for SiC and

$$\sigma = \begin{cases} 537 - 537(V/V^0) \text{ (GPa)} & \text{if } 0.983 < V/V^0 \leq 1 \\ 409 - 407(V/V^0) \text{ (GPa)} & \text{if } 0.956 \leq V/V^0 < 0.983 \\ 698 - 1107(V/V^0) + 416(V/V^0)^2 \text{ (GPa)} & \text{if } V/V^0 < 0.956 \end{cases}$$

$$p = \begin{cases} 407 - 407(V/V^0) \text{ (GPa)} & \text{if } 0.956 \leq V/V^0 \leq 1 \\ 696 - 1107(V/V^0) + 416(V/V^0)^2 \text{ (GPa)} & \text{if } V/V^0 < 0.956 \end{cases}$$

for TiB_2 , respectively. Using the equation $\epsilon = 1 - V/V^0$ and converting the expressions above into the stress σ -strain ϵ relations, we obtain

$$\sigma = \begin{cases} 382\epsilon \text{ (GPa)} & \text{if } 0 \leq \epsilon \leq 0.036 \\ 4.27 + 274\epsilon - 251\epsilon^2 \text{ (GPa)} & \text{if } \epsilon > 0.036 \end{cases}$$

$$p = 274\epsilon - 251\epsilon^2 \text{ (GPa)}$$

for Si_3N_4 ,

$$\sigma = \begin{cases} 484\epsilon \text{ (GPa)} & \text{if } 0 \leq \epsilon \leq 0.030 \\ 7.22 + 235\epsilon + 357\epsilon^2 \text{ (GPa)} & \text{if } \epsilon > 0.030 \end{cases}$$

$$p = 235\epsilon + 357\epsilon^2 \text{ (GPa)}$$

for SiC and

$$\sigma = \begin{cases} 537\epsilon \text{ (GPa)} & \text{if } 0 \leq \epsilon \leq 0.017 \\ 2.18 + 407\epsilon \text{ (GPa)} & \text{if } 0.017 < \epsilon \leq 0.044 \\ 7.21 + 275\epsilon + 416\epsilon^2 \text{ (GPa)} & \text{if } \epsilon > 0.044 \end{cases}$$

$$p = \begin{cases} 407\epsilon \text{ (GPa)} & \text{if } 0 \leq \epsilon \leq 0.044 \\ 5.03 + 275\epsilon + 416\epsilon^2 \text{ (GPa)} & \text{if } \epsilon > 0.044 \end{cases}$$

for TiB_2 , respectively.

The relations between the compression $\mu (= \rho/\rho^0 - 1)$ and the stress σ in Figs. 10, 11 and 12 are expressed as

$$\sigma = \begin{cases} 368\mu \text{ (GPa)} & \text{if } 0 \leq \mu \leq 0.0378 \\ 4.74 + 255\mu - 318\mu^2 \text{ (GPa)} & \text{if } \mu > 0.0378 \end{cases}$$

$$p = 255\mu - 318\mu^2 \text{ (GPa)} \quad (1)$$

for Si_3N_4 ,

$$\sigma = \begin{cases} 468\mu \text{ (GPa)} & \text{if } 0 \leq \mu \leq 0.0313 \\ 7.01 + 244\mu + 12.3\mu^2 \text{ (GPa)} & \text{if } \mu > 0.0313 \end{cases}$$

$$p = 244\mu + 12.3\mu^2 \text{ (GPa)} \quad (2)$$

for SiC and

$$\sigma = \begin{cases} 528\mu \text{ (GPa)} & \text{if } 0 \leq \mu \leq 0.0170 \\ 2.49 + 382\mu \text{ (GPa)} & \text{if } 0.0170 < \mu \leq 0.0463 \\ 6.86 + 287\mu + 6.86\mu^2 \text{ (GPa)} & \text{if } \mu > 0.0463 \end{cases}$$

$$p = \begin{cases} 382\mu \text{ (GPa)} & \text{if } 0 \leq \mu \leq 0.0463 \\ 4.37 + 287\mu + 6.86\mu^2 \text{ (GPa)} & \text{if } \mu > 0.0463 \end{cases} \quad (3)$$

for TiB_2 , respectively. The expressions (1), (2) and (3) of the ceramics serve as "equations of state" that are necessary for numerical simulation of impact phenomena.

Further, the relations between the particle velocity u_p and the stress σ are shown in Figs. 13, 14 and 15. The expressions we obtained are

$$\sigma = \begin{cases} 0.0349u_p \text{ (GPa)} & \text{if } 0 \leq u_p \leq 398 \text{ (m/s)} \\ 2.47 + 0.0292u_p - 1.26 \times 10^{-6}u_p^2 \text{ (GPa)} & \text{if } u_p > 398 \text{ (m/s)} \end{cases}$$

$$p = 0.0292u_p - 1.26 \times 10^{-6}u_p^2 \text{ (GPa)} \quad u_p: \text{ (m/s)}$$

for Si_3N_4 ,

$$\sigma = \begin{cases} 0.0394u_p \text{ (GPa)} & \text{if } 0 \leq u_p \leq 372 \text{ (m/s)} \\ 4.17 + 0.0275u_p + 1.86 \times 10^{-6}u_p^2 \text{ (GPa)} & \text{if } u_p > 372 \text{ (m/s)} \end{cases}$$

$$p = 0.0275u_p + 1.86 \times 10^{-6}u_p^2 \text{ (GPa)} \quad u_p: \text{ (m/s)}$$

for SiC and

$$\sigma = \begin{cases} 0.0490u_p \text{ (GPa)} & \text{if } 0 \leq u_p \leq 183 \text{ (m/s)} \\ 1.16 + 0.0426u_p \text{ (GPa)} & \text{if } 183 < u_p \leq 446 \text{ (m/s)} \\ 4.15 + 0.0347u_p + 2.82 \times 10^{-6}u_p^2 \text{ (GPa)} & \text{if } u_p > 446 \text{ (m/s)} \end{cases}$$

$$p = \begin{cases} 0.0426u_p \text{ (GPa)} & \text{if } 0 \leq u_p \leq 446 \text{ (m/s)} \\ 2.99 + 0.0347u_p + 2.82 \times 10^{-6}u_p^2 \text{ (GPa)} & \text{if } u_p > 446 \text{ (m/s)} \end{cases}$$

for TiB₂, respectively.

Finally, Figs. 16, 17 and 18 represent the relations between the particle velocity u_p and shock wave velocity u_s . For Si₃N₄, there doesn't seem to be a definite tendency. For SiC, the shock wave velocity u_s decreases till the particle velocity u_p reaches about 1000 m/s and then stops decreasing. For TiB₂, the shock wave velocity u_s rises almost linearly in the second plastic region where the particle velocity u_p is greater than about 600 m/s. The tendencies of the same kind are found in the reference⁽⁵⁾ regarding SiC and TiB₂, as is shown in the figure.

In fact, the data of the book⁽⁵⁾ cover particle velocities u_p up to about 3000 m/s. According to them, u_s begins increasing when u_p reaches about 1500 m/s as to SiC, and u_s rises almost linearly as u_p increases from about 800 m/s to about 3000 m/s as to TiB₂. In the data book⁽⁵⁾, we can find out some ceramics of the SiC type for which u_s decreases as u_p increases when u_p is under 1000 or 1500 m/s and u_s increases as u_p increases when u_p is over 1000 or 1500 m/s. On the other hand, we can also find some other ceramics of the metal type where u_p and u_s vary with a linear correlation in the plastic region. Since our experimental measurement covers just the region in which the particle velocity u_p is less than about 1500 m/s, we cannot judge how u_s would behave if u_p were larger. That is why no approximate curves are drawn in the figures.

The Hugoniot curves of the three ceramics as well as the three metals in the previous papers^{(1),(2)} are given for comparison in Fig. 19. We see from the figure that ceramic materials require larger change in stress or pressure than metals in order to induce a change in volume.

3.2 Hugoniot elastic limits

As already noted, the stresses attained after elastic wave arrivals (corresponding to the Hugoniot elastic limit) and after first plastic wave arrivals as to TiB₂ turned out to be almost at the same level irrespective of impactor types or impact velocities in our experiments. The aim of Figs. 20, 21 and 22 is to exhibit this observation. Removing apparently eccentric data and averaging measured stress values after

Fig. 19 Hugoniot curves of some ceramics and metals

Fig. 20 The relation of elastic wave stress of Si₃N₄ with impact velocity

elastic wave arrivals, we obtained the stresses σ_{HEL} at the Hugoniot elastic limit (first yield point). As for TiB₂, we calculated the stress at the second yield point similarly by taking an average of measured stress values after first elastic wave arrivals. Shock parameters such as the relative volume V/V^0 , the compression μ , the particle velocity u_p , the shock wave velocity u_s hardly depend on experimental conditions, either. So we took the averaged data for their values at the Hugoniot elastic limit or second yield point. In addition, we derived the values of dynamic yield stress Y_D in the single-axis stress condition in the manner of our previous papers^{(1),(2)} by using

$$Y_D = \frac{1-2\nu}{1-\nu} \sigma_{HEL}$$

where ν denotes Poisson's ratio. Those calculated values are summarized in Table 2. The values of stress σ for the same kind of ceramics in the papers^{(4),(6)} at the Hugoniot elastic limit (and second yield point) are also shown for reference in the table. Both of their methods to measure are different from ours; The VISAR was employed in the paper⁽⁴⁾ and the inclined mirror method in the paper⁽⁶⁾. Since the

Fig. 21 The relation of elastic wave stress of SiC with impact velocity

Fig. 22 The relation of elastic/first plastic wave stress of TiB₂ with impact velocity

paper⁽⁶⁾ states that stress values of Si₃N₄ at the Hugoniot elastic limit could be variant in the range of 10 to 20 GPa by grain size control, we should not make a simple comparison between two materials that are not exactly identical. However, it is noticeable that the values of our result and the references are of the same order.

The Hugoniot elastic limit (and second yield point) stress values of the three ceramics, along with the three metals in the papers^{(1),(2)}, are presented in Table 3. The stress values of ceramics are 10 to 100 times larger than those of metals.

4. Concluding Remarks

Employing specimens of three ceramic materials, silicon nitride Si₃N₄, silicon carbide SiC and titanium diboride TiB₂, we conducted plate impact experiments using a shock gun system and measurements with PVDF stress gauges. From the measurement results, we obtained the Hugoniot curves and the Hugoniot elastic limit (HEL) as dynamic mechanical properties of the ceramics. Those curves and properties are precious data of materials under hyper-

Table 2 Shock parameters at the Hugoniot elastic limit (HEL) and the second yield point

	Si ₃ N ₄	SiC	TiB ₂	
	HEL	HEL	HEL	Second yield point
Relative volume V/V_0	0.964	0.970	0.983	0.956
Compression μ	0.0378	0.0313	0.0170	0.0463
Stress σ (GPa)	13.9	14.7	8.65	20.1
Particle velocity u_p (m/s)	398	372	183	446
Shock wave velocity u_s (m/s)	10959	12265	10968	9605
Dynamic yield stress Y_D (GPa)	8.60	11.9	7.82	—
Stress σ (GPa) in References	10-12.5, 14-16.5, 17-20 ⁽⁶⁾	14.8-15.3 ⁽⁴⁾	4.7-5.2 ⁽⁴⁾	13.1-13.7 ⁽⁴⁾

Table 3 Hugoniot elastic limit (HEL)/second yield point stresses of some ceramics and materials

	HEL stress (GPa)
Si ₃ N ₄	13.9
SiC	14.7
TiB ₂	8.65 [second yield point: 20.1]
Ti-6Al-4V	2.42
Al6061-T4	0.463
Al7075-T6	0.774

velocity impact, and are of great importance as input data for numerical simulations of impact and fracture phenomena.

The outcome of our experiments is positive because it satisfies enough recurrence property and is consistent with some references' results obtained in different measurements. Measuring dynamic mechanical properties of ceramics with a PVDF stress gauge is our original idea. This series of experiments is also meaningful in the sense that a measurement was established. We would like to continue acquiring more dynamic mechanical properties of a broader variety of materials.

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