Shock compression and equation-of-state measurements of titanium carbide up to 630 GPa

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INTRODUCTION

Titanium carbide (TiC) is a typical transition-metal carbide, attracting wide interest because of its super high hardness, high melting point, thermal stability, high oxidation resistance as well as metallic conductivity. The structure of single crystal TiC is NaCl type (B1) at standard pressure and temperature, and the bulk material is manufactured usually as a nickel-cobalt matrix ceramics, known to be a refractory superhard "cermet" with a hardness of 9-9.5 Mohs. Such cermets are used instead of a typical cemented carbide, tungsten carbide, in cutting tools, and are in the manufacture of resistors, capacitors, and other electronic components experiencing harsh high temperatures too.

The high-pressure and high-temperature equation-of-state (*i.e.*, Hugoniot) of TiC has been so far measured up to ~300 GPa with shock compression technique. Although a large number of studies demonstrate that NaCl type structure generally transforms into CsCl type (B2) under high pressures, the evidence of such transformation has not yet been seen in TiC because of fewer data above 200 GPa. For the same reason, the behavior of the Hugoniot near the shock melting has not been elucidated. Here we report the TiC Hugoniot up to 630 GPa measured in the laser-shock compression experiments on the GEKKO XII laser facility.

EXPERIMENT

The Hugoniot measurements for TiC were performed on the GEKKO XII laser facility at the Institute of Laser Engineering, Osaka University [1, 2]. The experimental setup and target assembly are shown in Fig. 1(a). The wavelength of the shock-driving laser was 527 nm or 351 nm, which is the second or third harmonics of the fundamental wavelength (1053 nm) of the neodymium-doped glass laser, respectively. The experiments used 3 to 6 laser beams of an approximately 2.5 ns square pulse duration with an on-target energy of up to ~680 J. The focal-spot diameter was typically 1000 µm or 600 µm with a flat-top intensity distribution, resulting in a planar shock front of more than 300 µm in the diameter.

Typical targets consist of a 30-µm thick polypropylene (CH_2) ablator, 40-µm aluminum (Al) baseplate, 50-µm *z*-cut α-quartz (SiO_2) EOS reference (*i.e.*, baseplate quartz in Fig. 1), and 10-µm TiC sample. The samples were polished on both sides. The TiC was sintered with Ni binder (matrix) material of 15 wt%. The grains were randomly oriented and the average size of the grains was ~5 µm. The initial mass density ρ_0 was 5.06 g/cm. As shown in Fig. 1(a), the TiC samples were fixed onto the left half of the baseplate quartz. Two quartz witnesses (*i.e.*, the rear and side quartzes) are glued onto the rear of the TiC and the right half of the baseplate quartz, respectively.

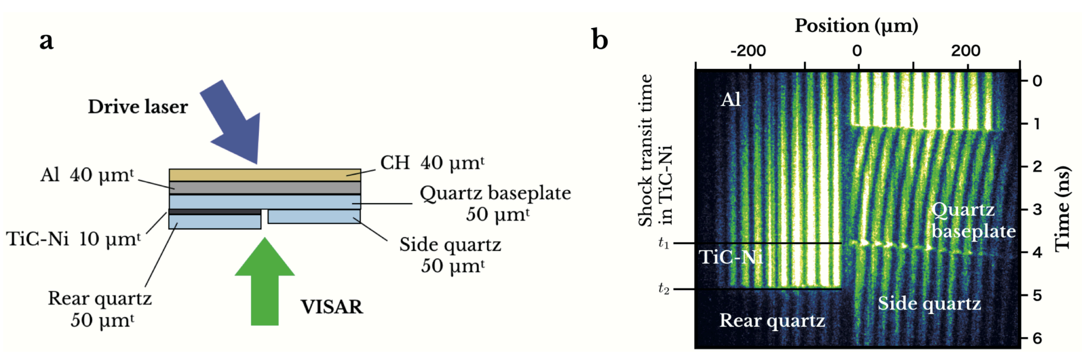

Fig. 1. (a) Target assembly. (b) Typical VISAR image. The time t_1 and t_2 correspond to the baseplate-SiO2/TiC interface and the TiC/witness- SiO_2 interface, respectively. From the shock transit time t_2 - t_1 and the initial sample thickness, the mean shock velocity of TiC was obtained.

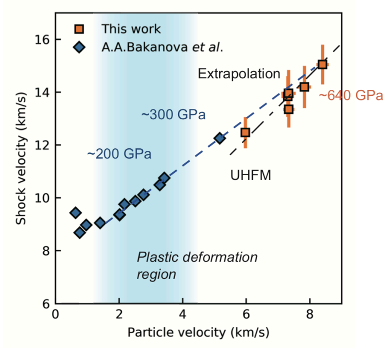

Fig. 2. Shock velocity vs. particle velocity.

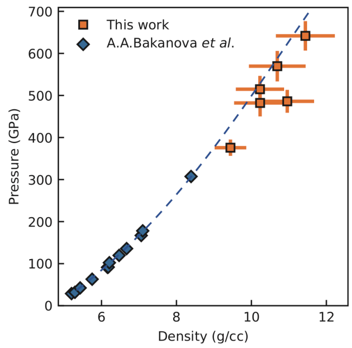

Fig. 3. Pressure vs. density.

We measured the shock velocities of TiC and quartz and performed the impedance matching analysis (IMA) [3] to determine a TiC Hugoniot point using the measured velocities and the known Hugoniot curves of quartz as reference material [4, 5]. The velocity measurements were made using two line-imaging velocity interferometers (VISARs) [6]. The VISAR probe, an injection-seeded Q-switched YAG laser, operated at 532 nm was irradiated onto the target from the rear side. The two line-VISARs allow us to resolve 2π-phase shift ambiguities in the interferometry image. The velocity sensitivities of the line-VISARs were 5.518 and 3.439 km/s/fringe under vacuum, respectively. Figure 1(b) shows a typical raw image of the VISAR measurement. The time resolution of the whole system that combined the streak cameras and the VISAR interferometer was around 50 ps. The time-resolved shock velocity of quartz was obtained from the interference fringe pattern of the line-VISARs, because quartz was transparent to the VISAR probe light (532 nm) at ambient pressure but shocked quartz became reflective at pressures of interest in this work; *i.e.*, above 100 GPa [7]. The measurement uncertainty of the time-resolved velocity was 1.5-3.0%. The time-integrated (mean) shock velocity of TiC was measured, because the TiC samples were not transparent. The mean velocity was obtained from the measurements of initial sample thickness and shock transit time. The right half of the target shown in Fig. 1(a) provided the arrival time (t_1) of shock wave to the SiO_2/TiC interface and the time-resolved quartz shock velocity. The left half of the target provided the arrival time (t_2) to the TiC/(rear-)SiO_2 interface. The shock transit time of TiC was obtained from the t_1 and t_2.

RESULTS AND DISCUSSION

A total of six laser shots were conducted and the shock Hugoniot data for TiC were obtained in the pressure range between 380 GPa and 650 GPa. The shock velocity (U_s) – particle velocity (u_p) relationship is shown in Fig. 2 along with the previous low-pressure data by using a gas gun [8]. The laser experiment data agree with the extrapolation of the linear approximation of the gas-gun data within the uncertainty. The approximation line is $U_s = 7.622 + 0.8956\ u_p$ (dashed). The laser data also agree with a shifted "universal Hugoniot of fluid metal" (UHFM) line [9]. This is reasonable because the states of the shocked TiC could be high pressure and temperature liquid metal.

Figure 3 shows the Hugoniot relationship between pressure (P) and density (ρ). The symbols used in this figure are the same as in Fig. 2. Our experiments suggest that the TiC Hugoniot above ~350 GPa in the liquid range becomes systematically softer than that in the solid range.

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