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# Microstructure and properties of submicron-scale TiC particle reinforced titanium matrix composites prepared by shock wave consolidation ①

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**Abstract:** Submicron-scale TiC particle reinforced titanium matrix composites (TMCs) were prepared by shock wave consolidation technique at detonation speed of 2 500 - 5 000 m/s. The microstructures were studied by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The compressive strength and hardness values of the composites were also determined. The results show that the composites have higher compressive yield strength and hardness values than hot-rolled pure titanium. Twins in the microstructure of TMCs show that titanium particles undergo plastic deformation during consolidation process. The fine grains with size less than 1 μm often locate in the boundaries among the titanium particles. TiC particles seem to keep unchanged during the consolidation. These bring about the increase in strength and hardness for the composites. The detonation speed of 3 200 m/s is proper parameter for compacting powder in the present work.

**Key words:** titanium matrix composites; mechanical properties; shock wave consolidation
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## 1 INTRODUCTION

Titanium matrix composites have been developed to offer high strength at elevated temperature as well as high specific stiffness and improved abrasion resistance, and have received more and more attention in recent years[1-5]. Furthermore, previous studies show that slower fatigue crack growth rate was observed in titanium matrix composites[5]. Titanium is a chemically active element and trends to react with reinforcements during the traditional fabrication of composites, which often results in thick reaction layer between matrix and reinforcements[6-10], and the mechanical properties are degraded due to the thick brittle reaction layer[9]. Therefore, other fabrication techniques were selected to avoid severe reaction zone, for example, shock wave consolidation[11-13], and the mechanism of the dynamic consolidation is also discussed[14-16]. Shock wave consolidation has the following advantages: 1) extreme short processing time which can prevent reaction layer from forming between matrix and reinforcements; 2) retaining the original condition of powders, such as fine grain size or amorphous state, uniform distribution of dispersoid and supersaturated solid solution; 3) combining the densification with bonding of particles at the same time if enough shock energy is supplied; and 4) very high degree of densification of compacted materials. The reinforcements for titanium composites must be thermodynamically stable and compatible with matrix. In the past, some kinds of ceramic particles, such as TiC, SiC, TiB, $TiB_2$, $B_4C$ and $ZrB_2$ had been used as reinforcements in the composites[17, 18]. Particle cracking was often observed in larger-size reinforcement[1]. In the present paper submicron-scale TiC particles (about 0.1 - 0.2 μm) were selected as the reinforcements in titanium matrix composite, due to their chemical stability. The blended powder of Ti and TiC was consolidated by shock wave. The microstructures of consolidated samples were studied in detail with scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Finally, Vickers hardness and compressive properties were also measured, and the effects of explosive parameters on melting layer were discussed.

## 2 EXPERIMENTAL

Commercially pure titanium powder (< 44 μm) were employed, which was produced by hydride-dehydride (HHDH) method. Table 1 gives the chemical compositions of the titanium powder. In the present work, the size of particles varied from a few microns to the maximum value of 44 μm. The powder with a wide size range is considered to be helpful for consolidation because the small particles can fill the interstices of the larger ones in the process of compaction.

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The appearance of titanium powder is shown in Fig. 1 (a). Fig. 1(b) shows the appearance of TiC particles with the size of 0.1−0.2 μm. Generally, as for titanium powder with size range from a few microns to 44 μm and TiC particle with the size of about 0.1 μm, it is difficult to blend them uniformly by mechanical methods. In the present work, TiC particles were dispersed in acetone using ultrasonic wave techniques firstly, and then the titanium powder was added into the beaker and the mixture was stirred mechanically. Fig. 1(c) exhibits the results of titanium powder blended with TiC particles. The microstructure of commercially pure titanium is given in Fig. 1(d). The mixture consisting of pure titanium powders and 2% (mass fraction) TiC particle was poured into an aluminum tube for shock wave consolidation. The detonation speeds in a range of 2 500 to 5 000 m/s were used to evaluate the effects of detonation speed on consolidation of the powder. The mass ratio of the explosive to the powder was about 10∶1. Fig. 2 shows the schematic set-up of explosive system in present experiment.

**Table 1** Chemical composition of titanium powder (mass fraction, %)

| O | H | N | C | Si | Fe | Cl | Ti |
|---|---|---|---|---|---|---|---|
| < 0.25 | 0.019 | 0.037 | 0.01 | 0.04 | 0.05 | 0.03 | Bal. |

The consolidated samples were annealed at 1 053 K for 1 h to release the residual stress. The microstructures were examined by a HITACHI S-2700 scanning electron microscope (SEM) and a JEM-200CX transmission electron microscope (TEM). The cylindrical compressive specimens ($d$ 9.5 mm × 10 mm) of both composites and commercially pure titanium (TA2) were machined and the compression tests were performed by means of MTS 880 servohydraulic testing machine. The Vickers hardness of the composites was also measured. The hardness and stress—strain curves of hot-rolled commercially pure titanium were also tested for comparison using the same specimen dimensions.

## 3 RESULTS

### 3.1 Microstructure of titanium matrix composites

Fig. 3 shows the microstructure of the different region (schematically shown in Fig. 3(d)) on the cross-section of a cylindrical sample consolidated at detonation speed of 3 200 m/s. According to Fig. 3 (a)−(b), the powder was compacted by shock wave, especially near the central region.

The microstructures of central zone on the cross-section of cylindrical sample consolidated at different detonation speeds are presented in Fig. (4). Fig. 4(a) shows the microstructure of the

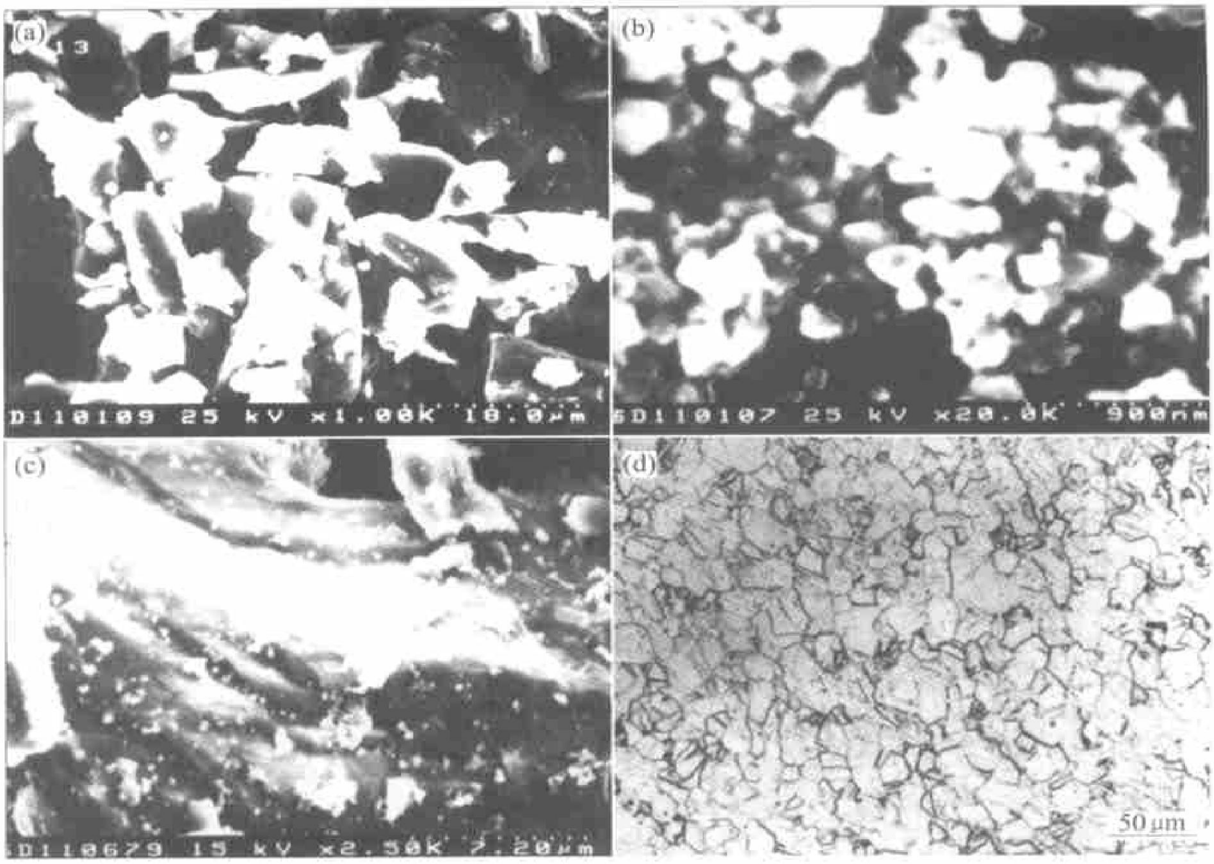


**Fig. 1** SEM images of titanium powder and TiC particles
(a) —Titanium powder; (b) —TiC particles; (c) —Mixture of titanium and TiC; (d) —Pure titanium (TA2)

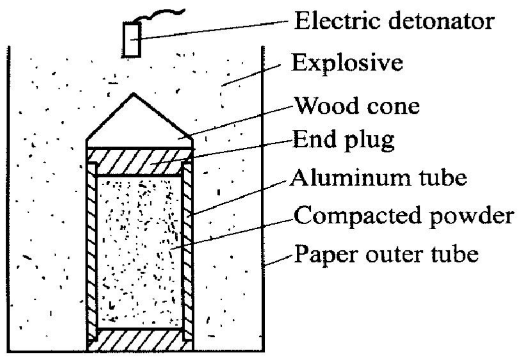


**Fig. 2** Schematic set-up of shock wave consolidation in present work

sample consolidated at 2 500 m/s. Obviously, the particle boundaries can be seen even in the center of the sample, which means that the detonation speed of 2 500 m/s is too low to supply enough energy for compacting powder. With increasing the speed to 3 200 m/s, the powder is compacted effectively, as shown in Fig. 4(b), where particle boundaries can not been observed. However, detonation speed of 5 000 m/s is so high that it can produce a central hole with about 2 mm in diameter which is called Mach Stem[19, 20], and Fig. 4(c) shows the microstructure near Mach Stem.

During explosive consolidation, the titanium granules are subjected to plastic deformation. Some lath in Fig. 4(a) (at lower speed, 2 500 m/s) and fine acicular plates in Fig. 4(b)−(c) (at high speed, 3 200 and 5 000 m/s) are commonly observed in the consolidated specimens. This is considered to result from the plastic deformation or adiabatic shear during shock wave consolidation. In the microstructure with low magnification, the TiC particles are difficult to the resolved, while in Fig. 4(c) magnifying by 4 000 times, the TiC particles can be seen.

The microstructures of explosively consolidated samples are also studied by TEM. The results are present in Figs. 5(a)−(c). Twins are commonly observed in the microstructure, as seen in Fig. 5(a). This gives direct evidence that titanium granules undergo plastic deformation during shock wave consolidation. Fig. 5(b) also shows some fine grains, which locate in the interface among titanium particles. The fine grains are considered to come from melted titanium in the surface of the titanium particles or from recrystallization. Fig. 5(c) gives appearance of TiC particles in microstructure of consolidated samples. TiC particles keep the original appearance and reaction layer between titanium and TiC particle can not be seen clearly.

### 3.2 Mechanical properties of composites

The cylindrical specimens were machined for compressive tests. All the specimens were com-

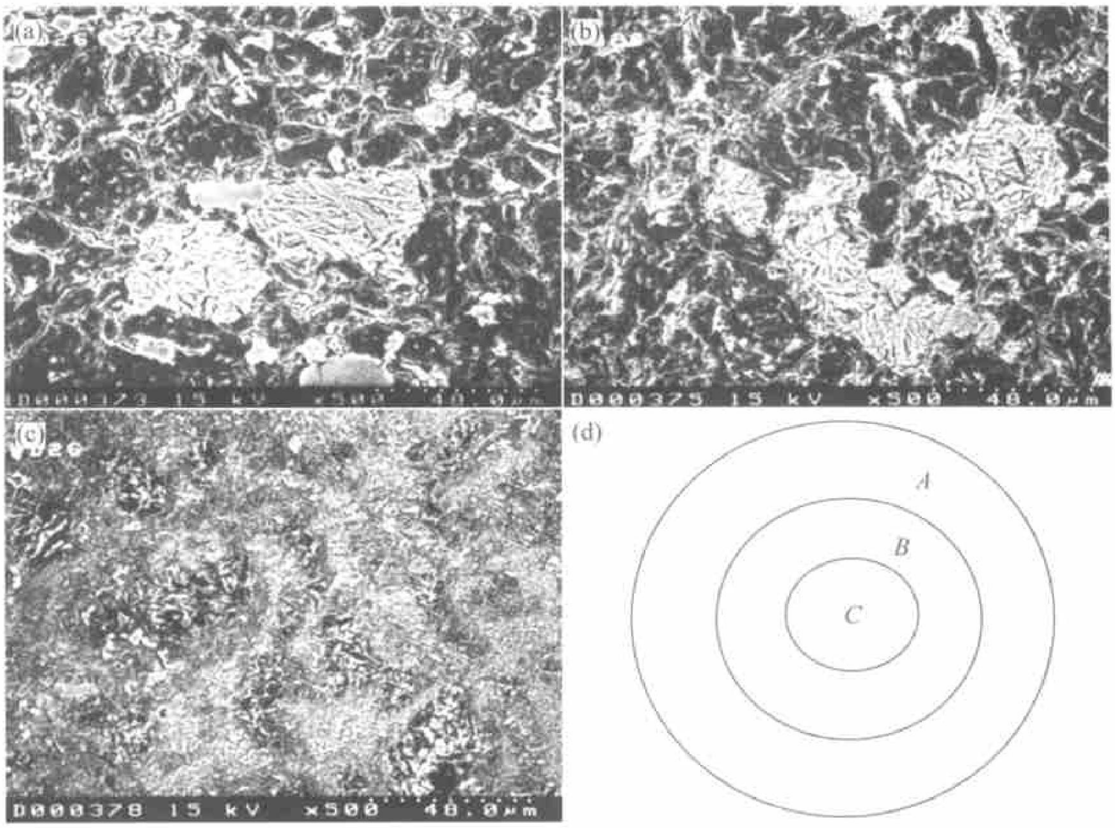


**Fig. 3** Microstructures (SEM) of cylindrical sample consolidated at detonation speed of 3 200 m/s
(a) —*A* region; (b) —*B* region ; (c) —*C* region; (d) —Schematic regions for (a)−(c) on cross-section

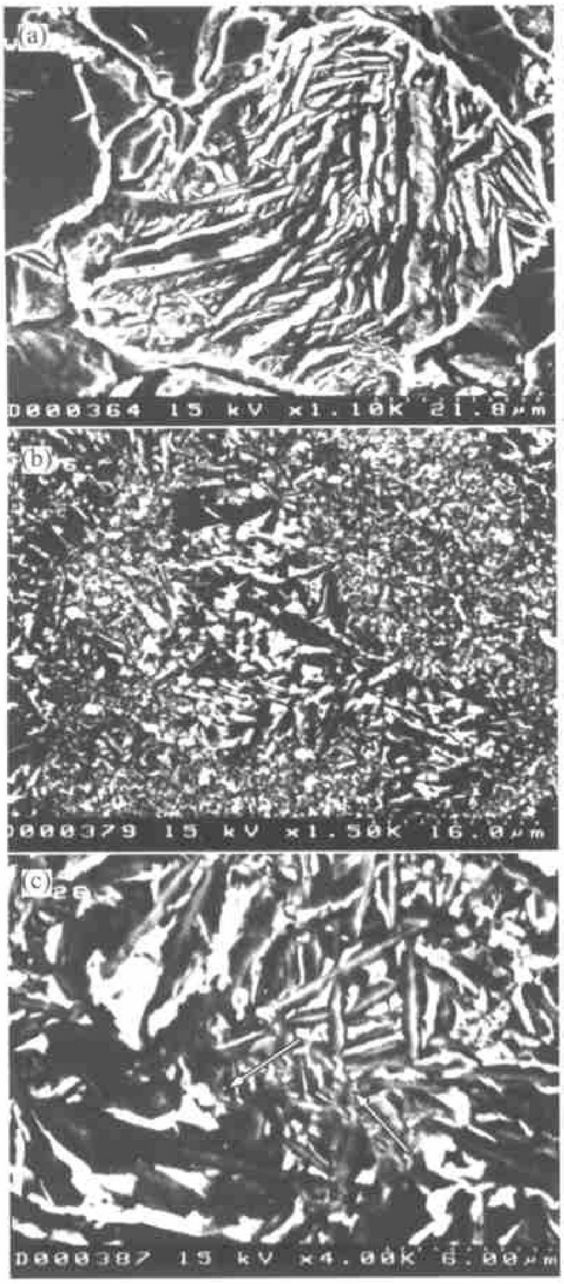


**Fig. 4** SEM images in center of samples consolidated at different detonation speeds
(a) —2 500 m/s; (b) —3 200 m/s;
(c) —5 000 m/s (TiC particle marked by arrows)

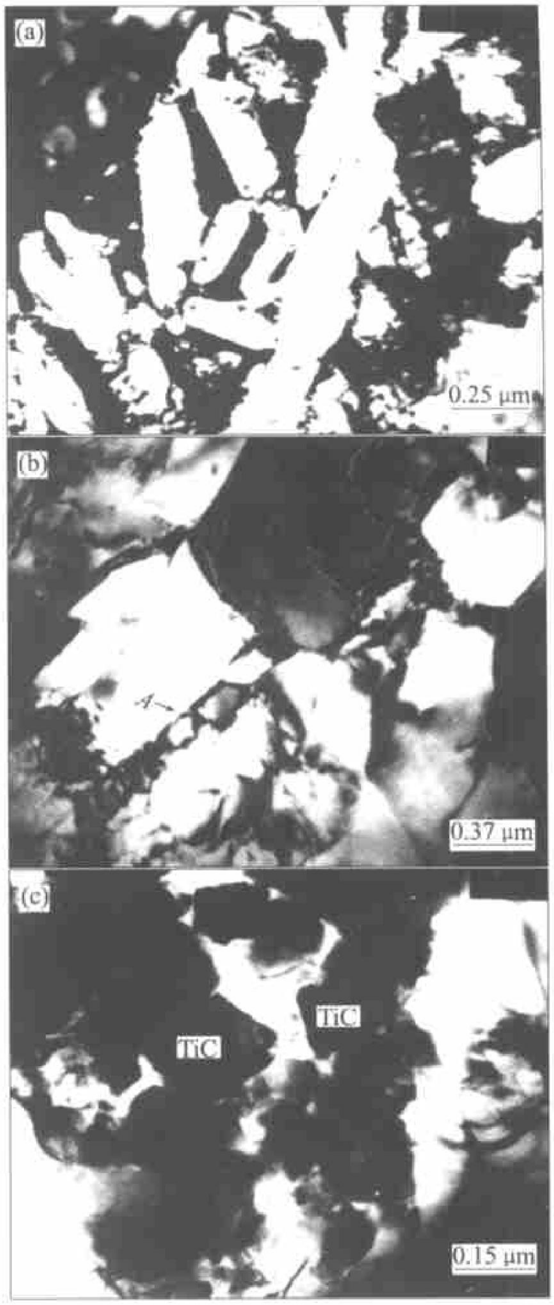


**Fig. 5** Microstructures (TEM) of samples consolidated by shock wave
(a) —Twins; (b) —Fine grains;
(c) —TiC particles in composite

pressed to fracture except the pure titanium specimen. The results are listed in Table 2. According to data in Table 2, the compressive strength increases with increasing detonation speed from 2 500 to 5 000 m/s. Fig. 6 shows the compressive stress—strain curves of specimens consolidated at different detonation speeds. For comparison the compressive stress—strain curves of hot-rolled titanium are also presented in Fig. 6. The composite shows higher compressive yield strength than hot-rolled pure titanium. As for pure titanium, the cylindrical specimen becomes drum shape and does not fracture, consequently, the compressive stress continues rising with increasing strain.

**Table 2** Compressive strength and hardness(HV) of composites consolidated by shock wave

| Specimens No. | Detonation speed/ $(m\cdot s^{-1})$ | Yield stress/ MPa | Compressive strength$^{2)}$/ MPa | HV |
|---|---|---|---|---|
| 1 | 2 500 | 940 | 1 248 | 220 |
| 2 | 3 200 | 1 045 | 1 508 | 286 |
| 3 | 5 000 | 1 053 | 1 532 | 291 |
| 4$^{1)}$ | – | 386 | 1 252 | 155 |

1) —Specimen No. 4 is hot-rolled titanium, and it does not fracture under compressive loading. The test stopps at strain of 42%.
2) —Compressive strength is stress at fracture

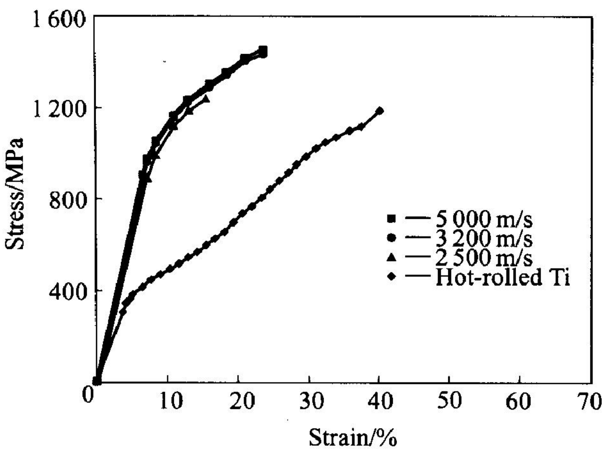


**Fig. 6** Compressive stress—strain curves of composites and hot-rolled pure titanium

The Vickers hardness of consolidated composites is also given in Table 2. The results indicate that hardness also increases with increasing detonation speeds, showing the same trends as the compressive yield strength. All the shock-wave consolidated samples have much higher hardness values than hot-rolled titanium. It suggests that they may possess better wear-resistance than pure titanium. According to microstructure of the consolidated samples, the high compressive strength and hardness of the composites are considered to arise from the following aspects: reinforcement of TiC particles, work hardening of pure titanium matrix during the consolidation, and fine grains in the microstructure.

## 4 DISCUSSION

Apparently, the volume of porous samples is subjected to great change during the explosive consolidation, which means that a large amount of work is done irreversibly on the porous samples. The irreversible work ($W_t$) can be calculated as[15]

$$W_t = p(V_0 - V_1)/2$$

where $p$ is the compaction pressure of shock wave, $V_0$ is the initial volume of porous samples, and $V_1$ the volume of compacted samples.

If $f = V_1/V_0$, then Eqn. (1) can be rewritten as

$$W_t = pV_0(1-f)/2$$

where $f$ can also be regarded as $\rho_0/\rho_1$ according to the fact that the mass of powders keeps constant during consolidation process ($\rho_0$ is the density of porous sample before consolidation, and $\rho_1$ is the density of compacted samples).

During the explosive consolidation the granules of powder could slide by each other, and the surface of the particle can be heated by friction. The previous investigation pointed out that a large of $W_t$ is dissipated near the particle boundary[15]. Consequently, the energy spent in heating the interior of the particle becomes negligible when being compared with the total energy ($W_t$), and the total energy can be considered to utilize to heat and melt the surface of the titanium particles. The melted mass($m$) can be calculated approximately by the following equation according to the energy conservation law[21]:

$$m[\bar{c}_p(T_m - T_0) + H_m + H_t] = pV_0(1-f)/2 \quad (3)$$

where $\bar{c}_p$ is specific heat capacity, $T_m$ is the melting temperature of titanium, and $T_0$ the initial temperature of powder before consolidation, $H_m$ and $H_t$ stand for fusion heat and transformation heat($\alpha \rightarrow \beta$), respectively. The melted mass was calculated and results are listed in Table 3. The homogeneous melted layer in the surface of titanium particle and the aspect ratio of 1∶1 for the titanium particles are assumed. The thickness of melted layer for different detonation speeds were calculated and the value are also given in Table 3. It's obvious that melted mass increases with increasing detonation speed because high detonation speed often leads to high compaction pressure and total energy[16]. The melted layer on the surface of titanium particles is 0.8, 1.3, 2.9 μm for detonation speed of 2 500, 3 200, and 5 000 m/s, respectively. The present results indicate that detonation speed of 3 200 m/s compacts the powder effectively, and brings about satisfied properties (compressive strength and hardness). This is in accordance with the results by Meyers et al, who suggest that melted layer with thickness of 1−2 μm is suitable for powder compaction[22].

**Table 3** Explosive parameters, melted mass and melted layer thickness during shock wave consolidation

| Specimen No. | Detonation speed/($m \cdot s^{-1}$) | Melted mass/g | Melted layer thickness/μm |
|---|---|---|---|
| 1 | 2 500 | 0.90 | 0.8 |
| 2 | 3 200 | 1.43 | 1.3 |
| 3 | 5 000 | 2.88 | 2.9 |

## 5 CONCLUSIONS

1) The submicron-scale TiC particles reinforced titanium matrix composites are prepared by shock wave consolidation. The composites have higher compressive yield strength and hardness values than hot-rolled pure titanium.

2) Twins are commonly observed in the samples compacted by shock wave consolidation technique. Fine grains are formed in the interfaces among the titanium granules, and submicron-scale TiC particles seem to keep unchanged during the consolidation. These bring about increase in strengthening and hardness for the composites.

3) The melted mass increases with increasing detonation speed. The detonation speed of 3 200 m/s is demonstrated to be suitable for compacting powder in the present work.

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