Compressive tests were conducted in vacuum at temperatures up to 1203 K, on the Ti₃SiC₂ samples synthesized from 2Ti/2Si/3TiC powder mixture through pulse discharge sintering technique. The compressive strength of Ti₃SiC₂ compound showed a monotonic decrease with increasing testing temperature. The Ti₃SiC₂ samples displayed obvious brittle fracture behavior at temperatures below 1073 K. When the testing temperature was above 1123 K, obvious pseudo-plastic deformation behavior was observed in the stress-strain curves. At these temperatures, after an initial pseudo-strain-hardening, a decrease in stress follows with further increasing strain. The pseudo-plastic behavior of Ti₃SiC₂ at temperature above 1123 K could be attributed to the basal plane slip, kink-band formation, delamination of layers at local sites, and intergranular cracking. Further increase in strain causes the growth and linkage of microcracks, which gives rise to the reduction of the real area of the cross section of specimen and hence lead to the “strain-softening” phenomenon.

Keywords: titanium silicon carbide, pulse discharge sintering, compressive deformation, strength, fracture, microcrack
Ternary Compound Ti$_3$SiC$_2$: Part II. Deformation and Fracture Behavior at Different Temperatures

Fig. 1 Stress-strain curves of Ti$_3$SiC$_2$ in compression at various temperatures.

![Stress-strain curves](image)

**Fig. 1** Stress-strain curves of Ti$_3$SiC$_2$ in compression at various temperatures.

![Engineering Strain vs. Engineering Stress](image)

**Fig. 2** Variation of compressive strength of Ti$_3$SiC$_2$ with testing temperature. Some literature data also plotted, in open symbols and broken lines.

![Compressive Strength vs. Testing Temperature](image)

**Fig. 2** Variation of compressive strength of Ti$_3$SiC$_2$ with testing temperature. Some literature data also plotted, in open symbols and broken lines.

referred to as the inelastic deformation stress or IDS. Since yielding occurred only when at least five independent slip systems are available, while in Ti$_3$SiC$_2$ slip has so far not been observed except on the basal plane.\(^\text{12,13}\) Besides, there are quite a few experimental phenomena which could not be explained when the IDS is a yield point: (1) Large asymmetry exists in the IDS under compression and tension;\(^\text{3,14}\) (2) Extremely high “strain-hardening” rate was observed after IDS;\(^\text{3}\) as can also be seen in Fig. 1; (3) The IDS point and the stress-strain shape are highly strain rate-dependent;\(^\text{13}\) and (4) The mechanical properties of Ti$_3$SiC$_2$ are identical to those of ice.\(^\text{15}\) The pseudo-strain-hardening and softening observed in Fig. 1 at elevated temperatures higher than 1123 K is then attributed to, rather than yielding, the formation of shear bands along the basal planes, kink-band-formation, microcrack formation and so forth, as discussed in the following sections.

The compressive strength is plotted in Fig. 2 as a function of testing temperature, which shows a monotonic decrease with increasing testing temperature below the transition temperature for the compound from brittle to ductile deformation, and a drastic decrease in strength with temperature was observed when tested at a temperature higher than this transition temperature. Except the data of the present investigation, some literature data were also plotted in the figure for comparison. The data marked with FG (FG: a few microns) and CG (CG: 100–200 µm) are the materials fabricated by reactive HIPing titanium, SiC and graphite powders at temperatures of higher than 1700 K for a few hours.\(^\text{2,3}\) It can be seen that the strength of the Ti$_3$SiC$_2$ compound fabricated using the present process is located between the strength values of coarse and fine grain compounds. The microstructure used in the present study is a duplex structure consisting of coarse plate shaped grains and fine equiaxed grains. It is in good consistent that the strength of the compound, fabricated with this pulse discharge sintering technique at a lower temperature and for a shorter sintering time, demonstrates comparable values in the testing temperature range. Also plotted in the figure are data marked with TSC$^{2510}$ and TSC$^{2510}$, fabricated by in-situ solid-liquid reaction process\(^\text{16}\) with Ti$_3$SiC$_2$ content of 93 mass% and 87%, respectively. Compared with the data of the literature, it has been found that the ductile-brittle transition temperature for the compound obtained in this study is about 200–300 K lower than that of the samples sintered from Ti/Si/C and Ti/SiC/C powders. This could be due to the low content of the second phase of TiC in the material used in this study.

The surface morphologies of the specimens after compressive deformation at temperatures below 1073 K are shown in Fig. 3 (Fig. 3(a): 298 K, Fig. 3(b): 873 K, and Fig. 3(c): 1073 K). Except some basal plane slip traces in isolated grains as shown in Fig. 3(a), generally a main crack, as can be seen in Fig. 3(b), can be found in the deformed surface and the prop-
agation of the main crack will finally lead to a catastrophic failure of the specimen. Figure 3(c) shows the main crack propagating across a plate-shaped grain, causing the breakage of the grain and giving rise to the pullout of the grains. The formation of cracks and their propagation of a main crack accounts for the brittle fracture of the material when compressed at a temperature lower than 1073 K.

When tested at higher testing temperatures, at which plastic deformation was observed on the stress-strain curves, the surface morphology is quite different as shown in Fig. 4. The most prominent difference in the surface morphology from that tested at low temperature is that large amount of microcracks were observed. As can be seen in the low magnification micrographs of Figs. 4(a) and (b), the microcracks are mainly formed at the grain boundaries. Beside basal plane slipping or interlayer sliding, intergranular cracking, grain buckling, and kink band formation was found to be common deformation phenomena.

The fracture surfaces of the specimens after compression tests at 298 K and 1173 K are shown in Figs. 5(a) and (b), respectively. On the room temperature fracture surface, the cleavage facets and the fractured layer structure can be clearly seen, indicating typical brittle fracture characteristics. On the other hand, when tested at high temperature the fracture surface is considerably different (Fig. 5(b)), where the buckled layered-grain is clearly shown, likely caused by kink-band formation. In this photograph, microcracks can also be found in between the layers and also on the grain boundaries, consistent with the surface observation result as shown in Fig. 4. In the buckled grain, the delamination of the layered grains can also be clearly seen.

The experimental results in this study suggest that Ti$_3$SiC$_2$ deforms in a multiple mechanism as illustrated schematically in Fig. 6. Figure 6(a) shows the basal-plane slipping in one grain and the formation of a microcrack at the grain boundary, due to the difficulty in accommodating the deformation because of the lack of slip system in the crystal structure (Cf. Fig. 3(a)). Figure 6(b) shows a grain buckling or bending under compression and the formation of microcracks at the grain boundaries. This also gives rise to the formation of kink
band when further deformation is undergone, as can be seen in Fig. 6(c). Kinking is predicted in hexagonal metals and alloys having an axial $c/a$ ratio greater than 1.732. With a $c/a$ ratio of 5.76, it is not surprising that Ti$_3$SiC$_2$ is susceptible to kinking.\(^{17}\) Especially when tested at high testing temperatures, kink band formation is a common deformation mechanism and gives rise to microcracks in the adjacent boundaries as indicated in Fig. 6(c). While the micro-deformation and microcracks give rise to a pseudo-plastic deformation and pseudo-strain-hardening after the linear deformation, further increase in strain causes the linkage of microcracks and void formation, and the specimen softens due to the decrease in the real cross section. As illustrated in Fig. 6(d), when a propagating crack encounters a grain with the basal plane perpendicular to the crack, usually a grain pullout, and also lamella pullout will be resulted after the grain fracture.

4. Summary

The fracture and deformation behavior of a Ti$_3$SiC$_2$ compound synthesized with pulse discharge sintering technique from 2Ti/2Si/3TiC powders was investigated by compression test and the main results can be summarized as follows.

1. The fracture stress of Ti$_3$SiC$_2$ decreases monotonically with increasing testing temperature.
2. Under compressive loading, Ti$_3$SiC$_2$ exhibits brittle fracture at the testing temperature below 1073 K. However, obvious plastic deformation was observed in the stress-strain curves at the temperature above 1123 K, where a pseudo-strain-hardening was observed followed by a strain softening.
3. At temperature below 1073 K, fracture of Ti$_3$SiC$_2$ mainly originates from one main crack and its propagation, resulting in catastrophic failure. When tested at temperature above 1123 K, many microcracks forms homogenously on the sample surfaces during compression.
4. The micro-deformation mechanisms of Ti$_3$SiC$_2$ subjected to compressive deformation at different temperatures consist of basal plane slipping, kink band formation, grain buckling, fracture of layers and delamination of the layered structure. It was observed that kink band formation is a common deformation mode of Ti$_3$SiC$_2$, especially at high temperatures.

REFERENCES