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Effect of grain size, notch width, and testing temperature on the fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 using the chevron-notched beam (CNB) method

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Abstract

In this work, the effects of grain size, notch width, and testing temperature on the fracture toughness of two typical MAX phases, $Ti_3Si(Al)C_2$ and Ti_3AlC_2, were investigated using the chevron-notched beam (CNB) method. The high-fracture toughness in the range of 6.43–10.19 MPa $m^{1/2}$ was determined. The critical notch width is about 250 μm for the valid fracture toughness measurements of $Ti_3Si(Al)C_2$ and Ti_3AlC_2. For a fixed notch width and testing temperature, the fracture toughness of coarse-grained (CG) samples is higher than that of fine-grained (FG) samples, and the toughness of Ti_3AlC_2 is higher than that of $Ti_3Si(Al)C_2$. Furthermore, the high-temperature fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 samples show a similar trend that the measured toughness is nearly a constant when the testing temperature is before the ductile–brittle transition temperature (DBTT) and then it declines fast over DBTT. The mechanism for the high-fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 is also discussed.

Keywords: Fracture toughness; $Ti_3Si(Al)C_2$; Ti_3AlC_2; CNB method; Testing

1. Introduction

The fascinating layered ternary ceramics $M_{n+1}AX_n$, where M is a transition metal, A is IIIA or IVA element, X is C or N, have attracted great attentions from material scientists because they combine the merits of both metals and ceramics. Ti_3SiC_2 and Ti_3AlC_2 are two typical MAX phases and have been widely investigated by many research groups.[1–15] They possess many salient properties, such as low density, high elastic modulus and strength, easy machinability, good oxidation resistance, excellent thermal shock resistance, and damage tolerance. Fracture toughness is one of the most important parameters related to the reliability of materials and has received much attention because of their basic role in fracture mechanics. As for Ti_3SiC_2 and Ti_3AlC_2, many works have been carried out to investigate the fracture toughness,[6–15] but the K_{IC} values are reported to be in a large range from 4.52 to 16 MPa $m^{1/2}$ for Ti_3SiC_2,[6–12] and from 4.6 to 9.1 MPa $m^{1/2}$ for Ti_3AlC_2.[13–15] The discrepancies among these reported K_{IC} values mentioned above are probably attributed to the different grain size, the shape and dimension of the sample, sample impurities, different testing methods, and experimental conditions.

Single-edge notched beam (SENB), single-edge pre-cracked beam (SEPB), chevron-notched beam (CNB), indentation strength (IS), indentation fracture (IF), and surface crack in flexure (SCF) testing methods have been developed to determine the fracture toughness of monolithic ceramic.[16–22] Since the indentation crack is hard to induce on the quasi-plastic ceramic,[16] the IS, IF, and SCF methods are unsuitable for K_{IC} measurement of the ceramics like Ti_3SiC_2 and Ti_3AlC_2. Pre-cracked specimens are difficult to prepare in a reproducible manner, and the initial crack front often cannot be seen on the fracture surface after testing, making it nearly impossible to measure the length of the crack for the SEPB method. For the SENB and CNB methods, notch preparation is critical in the determination of the plane strain fracture toughness

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K_{IC}. Many works have shown that the notch should be much small (e.g. less than 66 μm for Al_2O_3)[17] via the SENB method; otherwise, the measured toughness increases with the increment of the notch width.[7,17,18] The fact that a crack develops at the notch tip and extends stably as the load is increased is a unique advantage for the determination of the plane strain fracture toughness by the chevron-notched beam (CNB) method.[19–21] Moreover, the CNB method is an important consideration to evaluate the high-temperature fracture toughness.[17,22] Due to the apparent advantages, the CNB method was widely used[17,19–22] and was recognized as a standard method to measure the fracture toughness of ceramic materials.[23] However, few attempts to determine the fracture toughness of MAX phases using the CNB method can be found in the literature.

It is worth noting that all of the testing specimens of Ti_3SiC_2 mentioned above contain some impurities like TiC and/or $TiSi_2$,[6–12] which will inevitably influence the measured toughness of Ti_3SiC_2. To eliminate the ill effect of the impurities on the toughness of Ti_3SiC_2, TiC-free $Ti_3Si(Al)C_2$ was used as one species of the testing samples. Since $Ti_3Si(Al)C_2$ and Ti_3AlC_2 is a promising structure component at high temperatures,[24–26] understanding the temperature dependence of mechanical properties including fracture toughness is helpful for the design and application of these two ceramics. Hence, it is strongly needed to determine the fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 at both room and high temperatures.

In this work, specimens of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 with two different grain sizes, named fine-grained (FG) and coarse-grained (CG) samples, were prepared by hot pressing (HP) method and used to measure the fracture toughness using the CNB method. The effects of notch width and testing temperature were also investigated. The results will be beneficial for the promotion of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 as candidates for structural materials and for the understanding of the intrinsic fracture resistance of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 materials.

2. Experimental procedure

Bulk $Ti_3Si(Al)C_2$ and Ti_3AlC_2 materials with different grain sizes were fabricated by the in situ hot pressing/solid–liquid reaction synthesis, which was also described elsewhere.[14,27] The true phase composition of $Ti_3Si(Al)C_2$ is $Ti_3Si_{0.95}Al_{0.05}C_2$. Briefly, the elemental powders of Ti (99%, −300 mesh), Si (99.5%, −300 mesh), Al (99%, −200 mesh), and graphite (98%, −200 mesh) were used as the initial materials and precisely weighed according to the target composition, and then mixed in an agate mill for 15 h in a wet medium. After milling and drying, the mixtures were screened through a 60-mesh sieve and cold compacted into a Ø 50 mm graphite mold coated with boron nitride (BN). To obtain the FG samples, the green compacts were hot-pressed at 30 MPa under a flowing Ar atmosphere at 1550 °C for 60 min, and subsequently annealed at 1400 °C for 30 min for FG $Ti_3Si(Al)C_2$, and at 1520 °C for 30 min for FG Ti_3AlC_2. To get the CG specimens, the green compacts were hot-pressed at 30 MPa under a flowing Ar atmosphere at 1620 °C for 60 min and subsequently annealed at 1470 °C for 30 min for CG $Ti_3Si(Al)C_2$, and at 1520 °C for 30 min and further annealed at 1580 °C for 120 min for CG Ti_3AlC_2.

The densities of the as-prepared materials were determined by Archimedes's method. The phase compositions were identified by X-ray diffraction (XRD) using powders drilled from the bulk samples. The XRD data were collected by a step-scanning diffractometer with Cu Kα radiation (Rigaku D/max-2400, Tokyo, Japan). The microstructure of the materials was examined in a SUPRA 35 scanning electron microscope (SEM) (LEO, Oberkochen, Germany) equipped with an energy-dispersive spectroscopy (EDS) system. To expose the $Ti_3Si(Al)C_2$ and Ti_3AlC_2 grain, samples were mechanically polished up to 1200# SiC paper and etched by a HNO_3:HF:H_2O (1:1:2) solution before SEM observation. The Vickers hardness was tested on the polished surfaces at 9.80 N with a dwell time of 15 s. The dynamic elastic moduli of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 samples at room temperature were measured in a RFDA-HTVP1750-C testing machine (IMCE, Diepenbeek, Belgium).[26] The specimens for flexural strength were rectangular bars of 3 mm × 4 mm × 36 mm in size. Three-point bending tests with a crosshead speed of 0.5 mm/min were performed to measure the flexural strength of $Ti_3Si(Al)C_2$ and Ti_3AlC_2.

Specimens with dimensions of 3 mm × 4 mm × 36 mm were electrical-discharge machined from the as-prepared bulk $Ti_3Si(Al)C_2$ and Ti_3AlC_2. Chevron notches were introduced by diamond-coated wheel slotting. To study the effect of the notch width on the fracture toughness, four types of blade with the thickness of 0.054, 0.117, 0.169, and 0.365 mm, respectively, were used to introduce the chevron notches. After that, the true notch width was measured by optical microscope (OM). Four-point bending tests with a crosshead speed of 0.05 mm/min were performed for fracture toughness measurements and then the fractured surfaces were examined by means of SEM and OM. To investigate the effect of testing temperature, the fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 was measured at various temperatures from room temperature up to 1200 °C. The fixtures for high-temperature tests were made of α-SiC. The testing specimens were heated to the target temperatures with a heating rate of 10 °C/min. Prior to the tests, all the samples were held for 20 min to make sure the temperature equilibrium. No attempt was made to avoid the oxidation of the samples during the tests at high temperatures. For each condition, three to five specimens were tested to ensure the veracity. The fracture toughness measured with the four-point bending tests using CNB specimens was calculated using the equation,[21,23]

$$K_{IC} = \frac{P(S_o - S_i)}{BW^{3/2}} \times Y^*_{min} \quad (1)$$

where P is the critical load, S_o the outer span (30 mm), S_i the inner span (10 mm), B the width of sample, W the thickness of the sample, Y^*_{min} the stress intensity factor coefficient for the

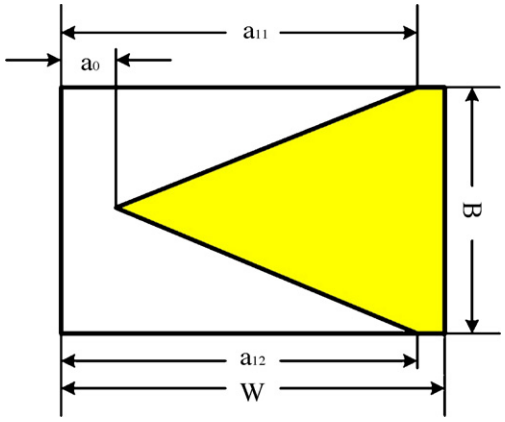

Fig. 1. Schematic illustration of the model for the chevron notch beam (CBN) method.

CNB method and given in,[21,23]

$$Y^*_{\min} = \left[2.92 + 4.52\left(\frac{a_0}{W}\right) + 10.14\left(\frac{a_0}{W}\right)^2\right] \times \sqrt{\frac{(a_1/W) - (a_0/W)}{1.0 - (a_0/W)}} \quad (2)$$

where a_0 is the distance from the chevron tip to the specimen surface at the notch mouth (the tensile surface), a_1 the average notched depths on the two side surfaces ($a_1 = (a_{11} + a_{12})/2$), as shown in Fig. 1.

3. Results

3.1. Phase composition, microstructure, and mechanical properties

The samples prepared by the in situ hot pressing method were fully dense (98–99% of the theoretical density). The XRD analysis shown in Fig. 2 reveals that no impurities like TiC or $TiSi_2$ are detected in $Ti_3Si(Al)C_2$ and no TiC is found in FG Ti_3AlC_2, while a small amount of TiC (about 7 vol.%) is found in the CG Ti_3AlC_2. Fig. 3 compares the etched surface of FG $Ti_3Si(Al)C_2$ (Fig. 2(a)), CG $Ti_3Si(Al)C_2$ (Fig. 2(b)), FG Ti_3AlC_2 (Fig. 2(c)), and CG Ti_3AlC_2 (Fig. 2(d)) samples. The large elongated $Ti_3Si(Al)C_2$ grains show layered characteristics and their longitudinal edges are parallel to (0 0 0 1) planes of Ti_3SiC_2.[28] It can be found that the grain length and grain width of the CG samples are 48.7 ± 41.2 and 15.4 ± 11.7 μm for $Ti_3Si(Al)C_2$, respectively, which is about three times higher than those of the FG $Ti_3Si(Al)C_2$ samples. For Ti_3AlC_2, the grain length and grain width of the CG samples are 74.9 ± 23.4 and 19.1 ± 8.1 μm, which is in excess four times than those of the FG Ti_3AlC_2 specimens.

The physical and mechanical properties of the $Ti_3Si(Al)C_2$ and Ti_3AlC_2 were summarized in Table 1. It can be seen that

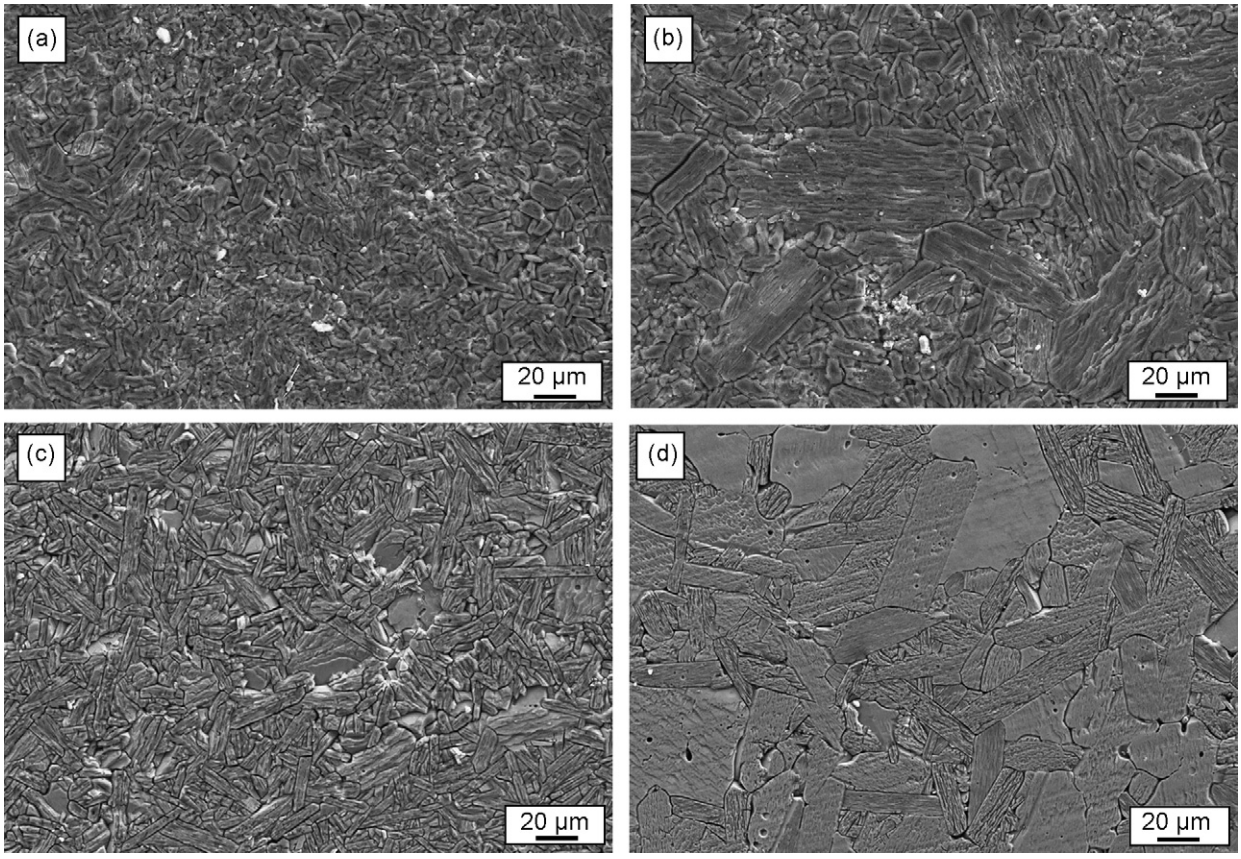

Fig. 2. Typical micrographs of the etched fracture surface for FG $Ti_3Si(Al)C_2$ (a), CG $Ti_3Si(Al)C_2$ (b), FG Ti_3AlC_2 (c), and CG Ti_3AlC_2 (d) samples.

Table 1
Physical and mechanical properties of FG $Ti_3Si(Al)C_2$, CG $Ti_3Si(Al)C_2$, FG Ti_3AlC_2, and CG Ti_3AlC_2 samples

Properties	FG $Ti_3Si(Al)C_2$	CG $Ti_3Si(Al)C_2$	FG Ti_3AlC_2	CG Ti_3AlC_2
Density (g/cm^3)	4.47 (98.9%)	4.46 (98.7%)	4.20 (98.9%)	4.19 (98.6%)
Grain width (μm)	4.2 ± 1.4	16.1 ± 9.3	6.5 ± 2.1	19.1 ± 8.1
Grain length (μm)	15.4 ± 11.7	48.7 ± 41.2	28.4 ± 9.5	74.9 ± 23.4
Elastic modulus (GPa)	336	335	304	301
Vickers hardness (GPa)	4.02 ± 0.12	3.28 ± 0.17	3.46 ± 0.16	2.22 ± 0.22
Flexural strength (MPa)	458.5 ± 25.8	306.4 ± 13.6	320.3 ± 11.2	169.2 ± 12.9

the grain size has little effect on the dynamic elastic modulus, but has great influence on the measured flexural strength and Vickers hardness. For $Ti_3Si(Al)C_2$, the flexural strength and Vickers hardness of CG samples are 306.4 ± 13.6 MPa and 3.28 ± 0.17 GPa, respectively. Compared with that of the FG samples, the strength and hardness decrease by about 33.2 and 18.4%. For Ti_3AlC_2, the strength and hardness of CG specimens are 169.2 ± 12.9 MPa and 2.22 ± 0.22 GPa. Compared with that of the FG samples, the strength and hardness decrease by about 47.2 and 35.8%, respectively.

3.2. Fracture toughness determined by CNB method

Fig. 3 shows the typical optical micrograph of the testing specimen with the chevron notch prepared by the diamond-coated blade with the thickness of 0.054 mm, which indicates that a successful chevron notch is introduced. Fig. 4 represents the measured fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 as a function of the true notch width. High fracture toughness of 6.4–9.5 MPa m$^{1/2}$ for this kind of ceramics (MAX phases) is found. It can also be seen that the fracture toughness of Ti_3AlC_2 is higher than that of $Ti_3Si(Al)C_2$, and the toughness of CG samples is slightly higher than those of FG samples for both $Ti_3Si(Al)C_2$ and Ti_3AlC_2. For the FG and CG samples, the scatter of the standard deviation is rather limited when the notch width is less than 250 μm, whereas it becomes quite large when the notch width is 383 μm. To check the stability of crack propagation, the typical curves of the force as a function of testing time for different notch width is shown in Fig. 5. For CG and

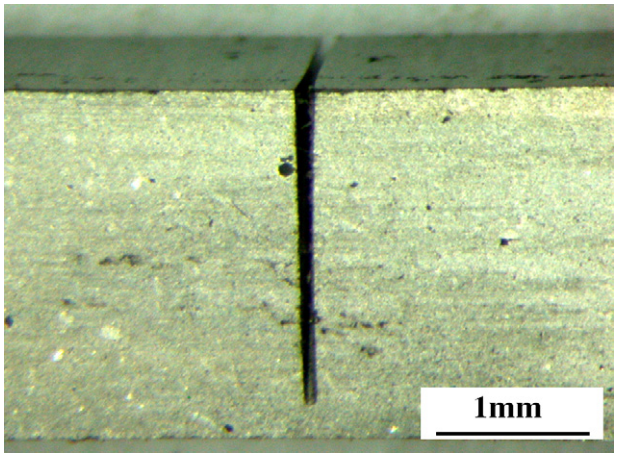

Fig. 3. Optical micrograph of the typical testing samples for CNB method. The notch was introduced by a 0.057 mm blade diamond saw.

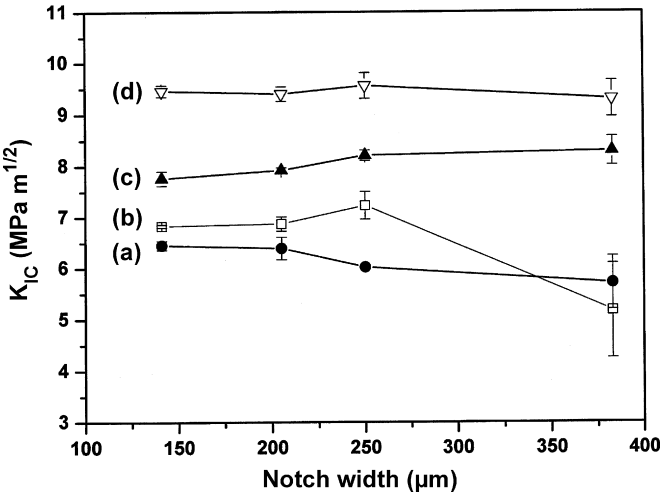

Fig. 4. The measured fracture toughness of FG $Ti_3Si(Al)C_2$ (a), CG $Ti_3Si(Al)C_2$ (b), FG Ti_3AlC_2 (c), and CG Ti_3AlC_2 (d) samples as a function of the true notch width.

FG samples of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 with the notch width less than 250 μm, the test force–time records exhibit a smooth, nonlinear transition to the maximum force prior to final fracture, which confirms that the test is stable.[29] When the notch width is about 383 μm, the test is becoming unstable. For $Ti_3Si(Al)C_2$ and Ti_3AlC_2, the crack propagation will convert from stable to unstable, which agrees well with the results in Fig. 4. Hence, the critical notch width of 250 μm is recommended for K_{IC}

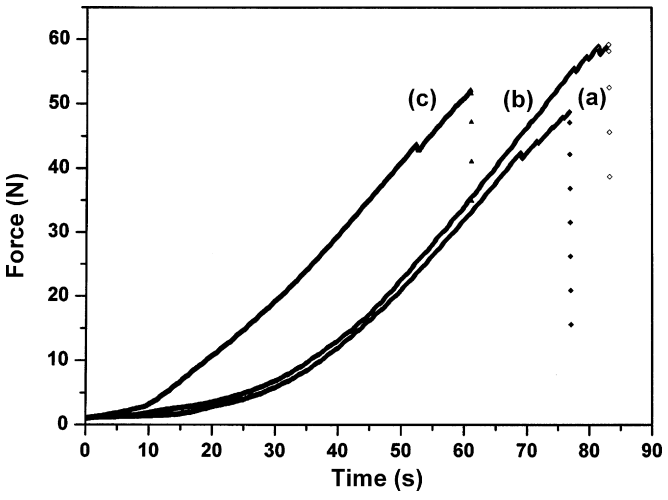

Fig. 5. The force as a function of testing time during the loading for $Ti_3Si(Al)C_2$ with the notch width of 141 (a), 250 (b), and 383 μm (c).

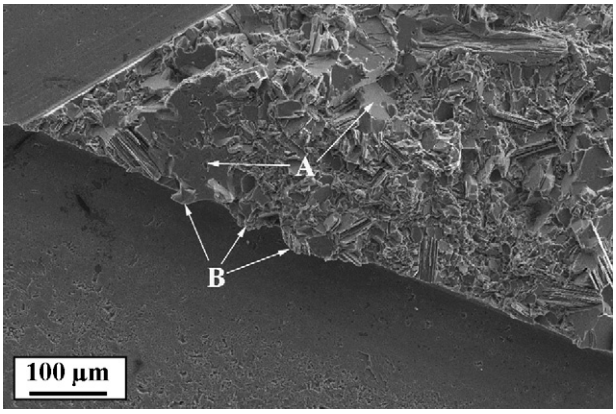

Fig. 6. Typical fracture surface of $Ti_3Si(Al)C_2$ with the notch less than 250 μm, showing the intrinsic fracture resistance. "A" showing basal plane slip; "B" showing pull-out of the grains.

calculation of $Ti_3Si(Al)C_2$ and Ti_3AlC_2. Fig. 6 displays the typical fracture surface of the testing specimens with the notch width less than 250 μm after bending. It can be found that intergranular fracture is dominant at the apex of the triangular ligament and that transgranular fracture occurs frequently in the latter part near to the tail of the chevron notch. The delamination and pull-out of the laminated grains are also found in Fig. 6, which may be dominant in the energy absorbing mechanism.

To investigate the effect of testing temperature on the fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2, the notch width was chosen to be a fixed value of 141 μm. Fig. 7 shows the fracture toughness of the CG and FG samples of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 as a function of the testing temperature. For all the testing temperatures, the fracture toughness of CG specimens is higher than that of FG samples. The fracture toughness of the FG and CG samples show a similar trend that the toughness is nearly a constant in the range of 25–1100 °C, but it declines fast over 1100 °C.

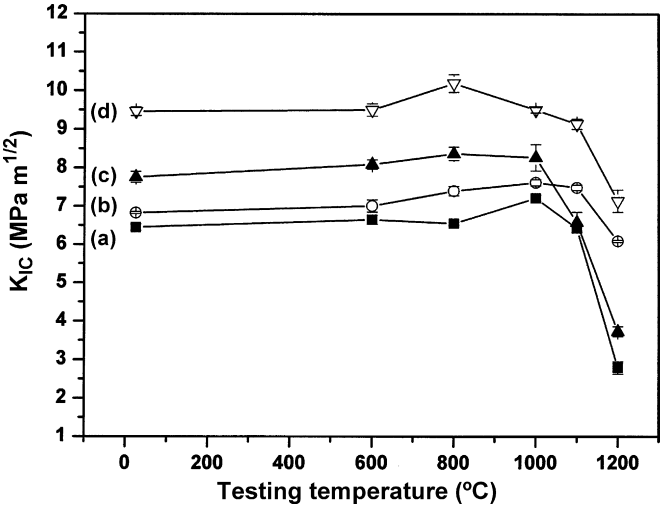

Fig. 7. The fracture toughness of FG $Ti_3Si(Al)C_2$ (a), CG $Ti_3Si(Al)C_2$ (b), FG Ti_3AlC_2 (c), and CG Ti_3AlC_2 (d) samples as a function of the testing temperatures.

4. Discussion

Many works have been carried on to investigate the fracture toughness of Ti_3SiC_2 and Ti_3AlC_2 using different methods. The measured toughness of Ti_3SiC_2 and Ti_3AlC_2 with different impurity and/or sample size was summarized in Table 2. The measured K_{IC} of Ti_3AlC_2 by Peng[13] is only 4.6 MPa m$^{1/2}$, which is ascribed to the effect of residual pores. Zhou et al.[15] found that the fracture toughness of Ti_3AlC_2, prepared by two different synthesized methods, was ranged from 5.7 to 9.1 MPa m$^{1/2}$. For full dense Ti_3AlC_2 with different grain size in this work, the valid fracture toughness is about 7.76–9.46 MPa m$^{1/2}$, which is close to the reported K_{IC} value by Wang and Zhou.[14]

For Ti_3SiC_2, most of the reported K_{IC} values are within 6–8 MPa m$^{1/2}$. The measured toughness of Ti_3SiC_2 by SEPB[11] and R-curve[10,12] may be overestimated due to the effect of sample size, the impurities, and a material's R-curve behavior.[10,12,30] Li et al.[6] reported that the K_{IC} of Ti_3SiC_2 with the average grain length of 11.3 μm and grain width of 2.3 μm was only 4.52 MPa m$^{1/2}$, which might be the lowest reported toughness, but the reported flexural strength was also very low (about 300 MPa). Recently, Bao and Zhou [7] have evaluated the fracture toughness of Ti_3SiC_2 containing 7 wt.% TiC using three different methods and the reported values are 6.2–6.6 MPa m$^{1/2}$. The fracture toughness measured by SEPB was the lowest due to the narrowest crack width, and the K_{IC} value of 6.2 MPa m$^{1/2}$ could be considered as the reference toughness. In this work, the fracture toughness of $Ti_3Si(Al)C_2$ with similar grain sizes (FG samples) is 6.45 MPa m$^{1/2}$, which confirms the convenience and validity of the CNB method. It can also be found that the measured toughness by SENB is slightly higher than that by CNB or SEPB, as shown in Table 2. If the notch width is less than 200 μm, the measured toughness of $Ti_3Si(Al)C_2$ via the SENB method[26] is slightly higher than the reference toughness (6.2 MPa m$^{1/2}$). These results suggest that the measured toughness of Ti_3SiC_2 by the traditional fracture toughness testing method, i.e. the SENB method, is reliable when the notch width is less than 200 μm. Gilbert et al.[10,12] investigated the effect of grain size on the fracture toughness of Ti_3SiC_2 and found that the toughness of the CG samples was higher than that of the FG specimens, which was in good agreement with our results. In addition, these results indicate that the SENB, CNB, and SEPB methods are all suitable to determine the fracture toughness of MAX phases when an appropriate notch width (below a critical notch width) is introduced. Considering the scatter of the measured toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 showing in Table 2, the SEPB and CNB methods seem to be more reliable.

Our results demonstrate that $Ti_3Si(Al)C_2$ and Ti_3AlC_2 have a relatively high fracture toughness (>6.4 MPa m$^{1/2}$). This phenomenon can be explained according to the following facts. (1) The fracture toughness is a property related to energy absorption. The energy absorbing mechanism has been widely investigated for Ti_3SiC_2 and Ti_3AlC_2 including basal plane slip, grain buckling, crack deflection, crack branching, pull-out, and delamination of the laminated grains.[1,4,5,31] (2) The

Table 2
Summary of the measured fracture toughness of Ti_3SiC_2 and Ti_3AlC_2 at room temperature using different methods

Samples	Sample size (mm^3)	Testing method	Fracture toughness ($MPa{\cdot}m^{1/2}$)	Ref.
Ti_3SiC_2 (<3 vol.% TiC)	2 × 3 × 24	SENB[a]	4.52 ± 0.15	6
Ti_3SiC_2 (7 wt.% TiC)	4 × 8 × 36	SEPB[b] CNB[a] SENB[b]	6.2 ± 0.32 6.6 ± 0.15 6.62 ± 0.12	7
Ti_3SiC_2 (TiC)	2 × 4 × 24	SENB[b]	7.20	8
Ti_3SiC_2 (7 wt.% TiC)	3 × 6 × 36	SENB[b]	7.88	9
Ti_3SiC_2 (3 vol.% TiC)	3 × 4 × 18	SEPB[b]	11.2	11
Ti_3SiC_2 (2 vol.% SiC)	2.9 mm thick × 19 mm wide compact-tension specimens	R-curve	9.5 (FG) 16 (CG)	10,12
$Ti_3Si(Al)C_2$	4 × 8 × 36	SENB[b]	6.80	26
$Ti_3Si(Al)C_2$	3 × 4 × 36	CNB[a]	6.45 ± 0.09 (FG) 6.83 ± 0.03 (CG)	This work
Ti_3AlC_2 (TiC)	3 × 6 × 36	SENB[b]	4.6 ± 0.3	13
Ti_3AlC_2	4 × 8 × 36	SENB[b]	7.2	14
Ti_3AlC_2 (Ti_2AlC, TiC)	4 × 6 × 35	SENB[b]	$5.7 \pm 0.3^{(HPed)}$ $9.1 \pm 0.3^{(SHS\text{-}SPSed)}$	15
Ti_3AlC_2	3 × 4 × 36	CNB[a]	7.76 ± 0.14 (FG) 9.46 ± 0.11 (CG)	This work

HPed = hot-pressed and SHS-SPSed = self propagating high-temperature synthesis-spark plasma sintered.
[a] Four-point bending tests.
[b] Three-point bending tests.

capacity of absorbing energy will become stronger for CG samples because of the larger grain size. Thus, $Ti_3Si(Al)C_2$ and Ti_3AlC_2 have a relatively high fracture toughness (above 6.4 MPa $m^{1/2}$) and the measured toughness of the CG specimens are higher than that of the FG samples at all testing temperatures.

The high-temperature fracture toughness of Ti_3SiC_2 has been reported to be practically constant when the testing temperature is before the ductile–brittle transition temperature (DBTT) and then decreases rapidly.[6,26] In this work, a similar trend was found for $Ti_3Si(Al)C_2$ and Ti_3AlC_2. It should be pointed out that the measured fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 above DBTT will lose its validity because the stress distribution is no longer elastic during the testing. Since $Ti_3Si(Al)C_2$ and Ti_3AlC_2 are promising structural components, it is necessary and helpful to investigate the fracture toughness above DBTT for the design and application of these two ceramics. The mechanism for the degradation of the fracture toughness is mainly ascribed to the decline of elastic modulus at temperatures above DBTT.[6,7,26] Careful analysis of the change of the fracture toughness from room temperature to 1100 °C (Fig. 6), it can be found that the measured toughness is slightly increased with increasing temperature. This phenomenon has been found in measuring the toughness by the SENB method in our previous work.[26] The reason for the increment of the toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 should be related to the closing up of flaws at the tip of the notch at high temperatures. This effect seems to be more obvious for measuring the toughness of $Ti_3Si(Al)C_2$, which is imputed to the poor oxidation resistance of $Ti_3Si(Al)C_2$ compared with Ti_3AlC_2. Further work is needed to show light on it.

5. Conclusions

The effects of grain size, notch width, and testing temperature on the fracture toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2, were investigated using the chevron-notched beam (CNB) method. The measured toughness was ranged from 6.4 to 7.2 MPa $m^{1/2}$ for $Ti_3Si(Al)C_2$ and 7.6 to 10.2 MPa $m^{1/2}$ for Ti_3AlC_2 with limited standard deviation scatters. For a fixed notch width and testing temperature, the fracture toughness of coarse-grained (CG) samples is higher than that of fined-grained (FG) samples.

Notch width has great effect on the measured toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 using the CNB method. The critical notch width for valid K_{IC} measurements of this kind of quasi-plastic ceramic is about 250 μm.

The high-temperature toughness of $Ti_3Si(Al)C_2$ and Ti_3AlC_2 with different grain sizes are insensitive to the testing temperatures before the brittle–ductile transition temperature (DBTT) (about 1100 °C), but it declines fast over 1100 °C. The degradation of the fracture toughness is mainly imputed to the decline of elastic modulus at temperatures above DBTT.

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