Original Article

Phase transformation and mechanical properties of B4C/Al composites

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\textbf{A B S T R A C T}

Lamellar constituted with 5, 15, 25 vol.% B\textsubscript{4}C/Al composites and homogeneous (namely 5, 15, 25 vol.% B\textsubscript{4}C/Al) composites were fabricated at sintering temperature 680 °C, sintering pressure 30 MPa, and heat preservation period 90 min via vacuum hot-pressing sintering. Another sample constituted with the raw materials of Al sheet and B\textsubscript{4}C powders has been prepared by the same sintering process to discuss the interface reaction of Al and B\textsubscript{4}C. In-situ XRD of B\textsubscript{4}C/Al mixed powders illustrated that the reaction products between Al and B\textsubscript{4}C were AlB\textsubscript{2}, AlB\textsubscript{12}, Al\textsubscript{3}BC. EDS and EPMA tests have proved that there was an element diffusion existing at the interface of B\textsubscript{4}C and Al. After sintering, new generation phases AlB\textsubscript{12}, Al\textsubscript{3}BC have been detected by SAED analysis of TEM, additionally, the inner microstructure of the lamellar B\textsubscript{4}C/Al composites was also observed. The results of mechanical properties showed that the lamellar B\textsubscript{4}C/Al composites possessed the optimal performance of Vicker hardness 116.23 ± 5.25 Hv, bending strength 780.45 ± 12.35 MPa and fracture toughness 12.21 ± 0.23 MPa m\textsuperscript{1/2}, which was better than these of homogeneous B\textsubscript{4}C/Al composites.

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1. Introduction

B\textsubscript{4}C/Al composites have been the potential candidate materials used in electronic packaging materials, sport equipment, and military protection materials\cite{1-7}. Nevertheless, because of the prodigious physical performance of Al and B\textsubscript{4}C, the bonding and molding of both becomes difficult\cite{8-10}. On the other hand, the combination between Al and B\textsubscript{4}C depends on their reaction\cite{11}. Therefore, it is significant to clarify the reaction mechanism and reaction product in this system.

In the last decades, the phase reaction and mechanical property of B\textsubscript{4}C/Al composites have been reported in part of the literatures. According to the research of Pyzil\cite{12}, the reaction between Al and B\textsubscript{4}C can be classified in several stages at different temperatures, while the reaction products were different at each heat treatment period. Pyzil had reported that the reaction product of B\textsubscript{4}C-Al began to appear at 450 °C, and...
the initial product was AlB₂C (a variant of Al₃B₂C [13]). AlB₂ started to form at 600 °C, AlB₂ and B₄C are the main phases between 600 °C and 700 °C. When the heat treatment temperature exceeded 700 °C, the content of AlB₂C (variant of Al₃B₂C) increased with the increase of temperature, and AlB₂C (Al₃B₂C) became the main reaction product at 900–1000 °C. At about 1000 °C, AlB₂ would decompose to produce Al and AlB₂, the new phase AlB₂C₄ appeared as the main reaction product if the heat treatment temperature further raised, meanwhile a small amount of AlC₁ was detected in the stage. Therefore, AlB₂ and AlB₂C were detected out at 600–700 °C, meanwhile the decomposition of AlB₂ was a longer process, AlB₂ would be generated largely beyond 1000 °C; however, it can be found out at low temperature region (about 700 °C). Viala [14] has used the method of powder metallurgy, controlling the sintering time of 450 h in argon. The results illustrated that, there were only two phases AlB₂C and AlB₂C₄ created at 950–1100 K, the temperature raised further to 1150–1273 K, the products of the reaction converted to AlB₂C and Al₂B₄C₄. Halverson [15] found that when the sintering temperature over 800 °C, if the insulation time was too long, more than 95% of B₄C/Al would converted into ceramic phase of Al-B-C ternary system. The appearance of such structure will have a positive effect on the hardness of the system, but will have a certain harm to the fracture toughness of the materials. Wang [13] has listed the potential reaction products and their physical properties between Al and B₄C that was exhibited in Table 1.

It was clear to see that the hardness of each reactant was between B₄C and Al, and much higher than Al. Among them, the production of AlB₂C₄ would significantly reduce the mechanical properties of B₄C/Al composites [16]. Therefore, the severe interface reaction at high temperature was unfavorable to the comprehensive properties of the composites [17,18].

According to the reports of Pyzik [11], the combination mode between Al and B₄C depended mainly on the reactive synthesis. However, the fabrication temperature of B₄C/Al composites was very crucial to their mechanical property because of the B₄C content and the effect of reaction product [19–22]. Therefore, selecting the appropriate preparation temperature and making clear the reaction products of B₄C/Al was of great significance for the study of their mechanical properties [23–25]. In order to clearly confirm the phase transition during the reaction process, in-situ XRD was used to investigate the phase composition at different reaction temperature stages. In addition, the stratified structure has been designed to depress the sintering temperature and acquired high performance B₄C/Al composites.

### 2. Experimental

The starting material, B₄C and Al with the average grain size of 50 μm and 1–3 μm were both provided from Shanghai ST-Nano Science and Technology, China. There were three components prepared and listed in Table 2. B₄C and Al powders were weighted as these three components and then mixed in absolute ethyl alcohol and grounded by Al₂O₃ balls with various multiple sizes. To obtain the preferable dispersion effect, the mass ratio of Al₂O₃ balls and mixed powders was adopted beyond 5:1. These materials were placed in a planetary ball mill to mix and grind for 8 h with a rotational speed of 180 r/min until the slurry phase was acquired. Afterwards, the slurry was dried in a vacuum drying oven at 60 °C until the liquid phase exhausted. In order to observe the reaction process of Al and B₄C preferably, the group with the highest B₄C content, as the 25 vol.% B₄C/Al powders were employed to the in-situ XRD test.

These three groups of powders were formed into the circular composites with the shape of φ45 × 5 mm after sintering via the sintering technology sintering temperature 680 °C, sintering pressure 30 MPa, and soaking time 90 min. The sintering technology was picked out based on the results of our previous work, which was verified as the optimal method to acquire the compact microstructure and excellent mechanical properties. We aim to use a larger particle size of Al powder, and control the slower heating and pressurization processes, thus ensuring Al will maintain favorable formability even become liquid at 680 °C under the pressure of 30 MPa. Furthermore, a group of lamellar materials with the outermost shell of 25 vol.% B₄C/Al, innermost layer of 5 vol.% B₄C/Al, and interlayer of 15 vol.% B₄C/Al arranged with symmetrical gradient, was prepared by the same sintering process. Meanwhile, another sample which made up of the B₄C sheet and Al powders showed in Fig. 1, was sintered via the above sintering method to explore the interface reaction between Al and B₄C. In the present study, we aim to use a larger particle size of Al powder, and control the slower heating and pressurization processes, ensuring the formability of B₄C/Al composites at sintering temperature 680 °C.

After sintering, the powders would be formed as a φ45 mm disk. In order to measure the bending strength, the disks were cut into specimens with dimensions of 36 × 4 × 3 mm as the standard of GB/T 23806-2009. The flexural toughness testing specimens were cut into 36 × 4 × 2 mm with groove (0.5 mm deepness and 0.2 mm breadth) in the middle of specimens (GB/T 23806-2009). According to the standard, the computa-
where P was breaking load, L was span of support, b and h were breadth and thickness of sample, Y was shape factor, a was depth of notch.

An electronic universal testing machine was used to measure the flexural strength via sample crushing, the span and chamfer were 30mm and 0.2°, respectively. Moreover, the slippery surface of the samples was used to characterize the hardness with the Vickers test. The transformation of the phases and the microstructure of the composites were investigated by X-ray diffraction (XRD) and scanning electron microscopy (SEM), respectively. Electron microprobe analysis (EMPA) was used to observe the element diffusion distance. The relative density was measured using the Archimedes method. In addition, transmission electron microscopy (TEM) was used to observe the interior structure of the composites to help us understand the distinct microscopic compositions. Moreover, selected area electron diffraction (SAED) was taken to affirm the reaction products in this system.

3. Results

3.1. In-situ X-ray diffraction of B$_4$C/Al powders

Considering the efficiency of experiment, the highest B$_4$C content, namely 25 vol.% B$_4$C/Al hybrid powders were used to analyze the course of reaction via in-situ X-ray diffraction characterization. Through comprehensive analysis of sintering conditions in this experiment, the maximum temperature of in-situ XRD was set as 700 °C. Additionally, several temperature points exhibited in Table 3 were selected to probe the phase composition at the corresponding stages.

The selection basis of temperature points could be summarized as following. Referring to the Al-B binary phase diagram in Fig. 2, it was seen obviously that the transformation temperature of Al-B was about 450-500 °C. Based on the

![Fig. 1 – Design of interface reaction under limit conditions of B$_4$C/Al composites.](image1)

![Fig. 2 – Al-B binary phase diagram.](image2)
literature of Yuvaraj [10], a mass of AlB₂ started to generate when the heat treatment temperature exceed 600 °C. Meanwhile, the differential thermal analysis (DTA) curve was listed in Fig. 3. We could get the message that there was a distinct endothermic peak at 650–700 °C, demonstrating the reaction between Al and B₄C happened. Thus, we chose per 200 °C as a temperature point below 600 °C and 20 °C as a temperature point upon 600 °C.

Fig. 4 showed the image of in-situ XRD from room temperature to 700 °C of 25 vol.% B₄C/Al powders. The results illustrated that the new phases have generated but displayed unconspicuously in Fig. 4. There was another phenomenon, the peaks of Al offset to the small angle, appeared in the high temperature reaction process between Al and B₄C. In order to observe the change of diffraction peak of Al more obviously, the diffraction angle from 75–80° has been extracted in Fig. 5.

Compared the diffraction of Al at different temperature, the excursion of peaks was distinct. The variation trend of the diffraction angle became lager in accord with that of the test temperature. According to the Bragg equation: 2d (hkl) sinθ = nλ, where h, k, and l were the reciprocals of the crystal plane intercept in the three - dimensional coordinate the, (hkl) was the indices of crystal face, diffraction constant n and wavelength λ were known, diffraction angle θ became lager, therefore the interplanar distance d would become smaller. Furthermore, to the cubic system, the relationship between lattice constant a and interplanar distance d could be expressed as \( \frac{1}{d^2} = \frac{h^2 + k^2 + l^2}{a^2} \), so \( a = d \sqrt{h^2 + k^2 + l^2} \). According to the Bragg equation, the interplanar distance d at each temperature segment was calculated and showed in Table 4. The results showed that the d value increased in keeping with the temperature raised.

Due to the relationship of d and a : \( a = d \sqrt{h^2 + k^2 + l^2} \), the lattice constant a could be figured out in Table 5. Similarly, the variation tendency of a value was corresponding with that of d value, achieving the maximum at 700 °C. Lattice distortion would lead to strain inside of the grain. The strain in the heating process could be formulated as \( \epsilon \).
Table 6 – Strain ε of each crystal face at different temperature.

<table>
<thead>
<tr>
<th>T°/C crystal plane ε/°</th>
<th>25</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>(111)</td>
<td>0</td>
<td>0.399303</td>
<td>0.383264</td>
<td>1.334402</td>
<td>1.672671</td>
</tr>
<tr>
<td>(200)</td>
<td>0</td>
<td>0.362062</td>
<td>0.867454</td>
<td>1.328137</td>
<td>1.67005</td>
</tr>
<tr>
<td>(220)</td>
<td>0</td>
<td>0.379378</td>
<td>0.870921</td>
<td>1.349906</td>
<td>1.686028</td>
</tr>
<tr>
<td>(311)</td>
<td>0</td>
<td>0.391733</td>
<td>0.877882</td>
<td>1.345414</td>
<td>1.696332</td>
</tr>
<tr>
<td>(222)</td>
<td>0</td>
<td>0.380071</td>
<td>0.871903</td>
<td>1.370404</td>
<td>1.720424</td>
</tr>
</tbody>
</table>

$\frac{\Delta T}{\Delta t} \times 100\%$. According to the further extrapolation, we could get the information of the strain ε at different temperature showed in Table 6. It was assumed that the elastic modulus E of aluminum did not change during heating, the relationship between stress σ and strain ε was $\sigma = E\varepsilon$. The elastic modulus E of Al was about 70 GPa. Therefore, the stress σ could be figured out, and the results have been listed in Table 7.

3.2. **SEM and EDS of B₄C/Al composites**

The fracture surface of homogeneous B₄C/Al (namely 5, 15, 25 vol.% B₄C/Al) and lamellar B₄C/Al composites were signed and showed in Fig. 6. It could be seen that the dimples in 5 vol.% B₄C/Al composites were most obvious and deepest because of the effect of maximum Al content among these composites in Fig. 6(a). The dimples in 25 vol.% B₄C/Al composites was shallowest, and 15 vol.% B₄C/Al composites was somewhere in between, which could be found in Fig. 6(b and c). In other words, the higher the content of aluminum, the fracture form of composites tends to be that of metals. Fig. 6(d and e) has showed the fracture surface of lamellar B₄C/Al composites who included the fracture characteristics of these three homogeneous materials. Therefore, the special structure endowed the lamellar B₄C/Al composites with good deformation coordination to better resist the damage of external load.

The interface of Al and B₄C, which was designed under the limited condition in Fig. 1, has been listed in Fig. 7. The SEM image showed that Al was formed while B₄C was not completely sintered. The EDS image revealed the distinct hierarchy between Al and B₄C, additionally, some of Al has been diffused into the side of B₄C.

The sample was further analyzed by line scanning in Fig. 8, because of B and C elements were very light and hard to detect, thus Al element was applied to contrast the diffusion of elements in the interface. Apparently, Al had entered into B₄C by observing the energy spectrum, which was corresponding with the result of map scanning.

3.3. **EPMA of interface of Al and B₄C**

The interface of Al and B₄C was used to reveal the element diffusion via surface scanning analysis of EPMA. Backscattered electron diffraction pattern of the juncture of Al and B₄C has been exhibited in Fig. 9(a). Al and B₄C could be seen obviously in the image. It was clear that the distribution of Al has a distinct gradient, becoming less from right to left showed in Fig. 9(b). Similarly, less C and B were found in the side of Al in Fig. 9(c and d), which reflected that the element diffusion happened in the interface of Al and B₄C.

3.4. **TEM of B₄C/Al composites**

Field emission transmission electron microscopy (FETEM) was adopted to investigate the phase transformation during the sintering process. Fig. 10 showed the high-resolution image and electron diffraction pattern of the composites. Selected area electron diffraction (SAED) displayed in Fig. 10(b) illustrated that the diffraction spots R1, R2, R3 respectively correspond with the crystal faces (111), (11-1), and (220) of matrix Al.

Fig. 11 exhibited another region of the composites. It was easy to distinguish that the gray area with a black particle inseted was matrix Al in Fig. 11(a). SAED of the particle showed the bright spots respectively correspond with the lattice plane (101), (110), (211), which belong to [1–1–1] crystal system of B₄C. It was proved that there was a reaction between Al and B₄C in the previous study. It can be seen distinctly that there were some particles with the size of 200–500 nm distributing in the interface of Al–B₄C and interior of Al. The result of SAED of the black particles showed that the reaction products were AlB₁₂ and Al₃BC in Figs. 12 and 13, which was corresponding with the foregone spots. Similarly, the results of TEM analysis were also consistent to that of in-situ XRD.

3.5. **Mechanical properties of B₄C/Al composites**

Due to their unique structural characteristics and good deformation coordination, lamellar materials generally behaved better in the aspect of mechanical properties than that of common materials. To compare the properties of layered and homogeneous materials, the three components composites (5, 15, 25 vol.% B₄C/Al) have been fabricated by the same sintering process as the lamellar B₄C/Al composites. The mechanical properties of lamellar and homogeneous B₄C/Al composites were listed in Table 8.

With the increase of B₄C content, Vickers hardness of the composites increased obviously from 48.69 ± 5.42 Hv of 5 vol.% B₄C/Al composites to 114.29 ± 4.85 Hv of 25 vol.% B₄C/Al composites. In addition, bending strength reached to 601.47 ± 27.58 MPa of 25 vol.% B₄C/Al composites who was nearly triple than that of 5 vol.% B₄C/Al composites. There was an interesting phenomenon that the fracture toughness also increased keeping in line with the B₄C content. This could be explained as that: Al was the matrix of these composites that cause them favorable plasticity, and then leading to them hard to break, meanwhile with the increase of B₄C, it had to exert greater load to break the composites, therefore the fracture toughness 25 vol.% B₄C/Al composites was larger than that of

Table 7 – Stress σ of each crystal face at different temperature.

<table>
<thead>
<tr>
<th>T°/C crystal plane σ/MPa</th>
<th>25</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>(111)</td>
<td>0</td>
<td>286.3</td>
<td>598.8844</td>
<td>956.7666</td>
<td>1199.305</td>
</tr>
<tr>
<td>(200)</td>
<td>0</td>
<td>259.5982</td>
<td>621.9648</td>
<td>952.2746</td>
<td>1197.426</td>
</tr>
<tr>
<td>(220)</td>
<td>0</td>
<td>272.0142</td>
<td>624.4507</td>
<td>967.8827</td>
<td>1208.882</td>
</tr>
<tr>
<td>(311)</td>
<td>0</td>
<td>280.8729</td>
<td>630.087</td>
<td>964.6617</td>
<td>1216.27</td>
</tr>
<tr>
<td>(222)</td>
<td>0</td>
<td>272.5107</td>
<td>625.1548</td>
<td>982.58</td>
<td>1238.289</td>
</tr>
</tbody>
</table>
Fig. 6 – SEM of fracture surface of homogeneous and lamellar B₄C/Al composites.

Fig. 7 – SEM and map scanning of B₄C/Al interface.

Fig. 8 – SEM and line scanning of B₄C/Al interface.
Table 8 – Mechanical property of B₄C/Al composites.

<table>
<thead>
<tr>
<th></th>
<th>5 vol.% B₄C/Al</th>
<th>15 vol.% B₄C/Al</th>
<th>25 vol.% B₄C/Al</th>
<th>laminar B₄C/Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness/HV</td>
<td>48.69 ± 5.42</td>
<td>96.53 ± 6.24</td>
<td>114.29 ± 4.85</td>
<td>116.23 ± 5.25</td>
</tr>
<tr>
<td>Relative density/%</td>
<td>99.22 ± 0.21</td>
<td>98.94 ± 0.15</td>
<td>98.55 ± 0.22</td>
<td>99.01 ± 0.13</td>
</tr>
<tr>
<td>Bending strength/MPa</td>
<td>202.25 ± 21.89</td>
<td>423.65 ± 25.75</td>
<td>601.47 ± 27.58</td>
<td>780.45 ± 12.35</td>
</tr>
<tr>
<td>Fracture toughness/MPa m¹/²</td>
<td>4.47 ± 0.34</td>
<td>7.56 ± 0.34</td>
<td>9.45 ± 0.32</td>
<td>12.21 ± 0.23</td>
</tr>
</tbody>
</table>

Fig. 9 – EPMA of B₄C/Al interface.

Fig. 10 – High-resolution image and electron diffraction pattern of Al.

Fig. 11 – High-resolution image and electron diffraction pattern of B₄C.
5 vol.% and 15 vol.% B₄C/Al composites based from the computational formula (2). The hardness of lamellar composites was comparable to 25 vol.% B₄C/Al composites because of its outermost layer was 25 vol.% B₄C/Al. Relative density of these composites changed not obviously. It can be found that the laminar composites showed the better bending strength and fracture toughness than these of random B₄C/Al composites material of the single component.

4. Discussion

4.1. Phase transition analysis

It has been proved that there was a chemical reaction between Al and B₄C from the previous literature [26–30]. Similarly, the reaction between these two materials was also verified via XRD and TEM analysis in the present research. The peaks of Al could be found obviously, while the peaks of B₄C and the reaction products were not evident in Fig. 4, that was due to the inferior diffraction capability of B₄C and the fewer phase content of reaction products caused. Nevertheless, according to the transformation of Al peaks from 25 °C to 700 °C, it was easily known that Al has reacted with B₄C because of the diffracted intensity of Al reduced which can reflect the reduction of Al content in the mixed powders. The possible reactions in the system were [11]:

\[ \text{Al} + \text{B}_4\text{C} \rightarrow \text{AlB}_{12} + \text{Al}_3\text{BC} \]  \hspace{1cm} (3)

\[ \text{AlB}_{12} + \text{Al} \rightarrow \text{AlB}_2 \]  \hspace{1cm} (4)

In the initial stage of the reaction, as the heating temperature raised, free Al had good fluidity and B₄C would release a handful of [B] and [C], at this point, they combined to form Al₃BC and AlB₁₂. AlB₁₂ further reacted with Al to form AlB₂ who was essentially stable below 700 °C. There were other parts of AlB₁₂ that did not completely react with Al, therefore, the reaction products contained the new phases Al₃BC, AlB₁₂ and AlB₂. The peaks of Al was migratory which can be observed in Fig. 5, that was because during the heating process, the phase transition between Al and B₄C generated the internal stress, caused the lattice distortion, the spacing between the crystal faces increased, therefore the peaks of Al changed to small angle direction based from Bragg equation. Fig. 14 has exhibited the changing situation between the stress and temperature of different crystal face of Al. In the mass, the stress was increscent linearly with temperature increasing in every crystal face. It could be attributed to that the reaction between Al and B₄C was intensified in the process.
of temperature rise, caused the acceleration of atomic motion, and then lead to the stress increased.

According to the normal relationship between stress and strain, strain will transform with the variation of stress if the elasticity modulus is constant [31,32]. In the present study, the elasticity modulus was considered as stable during heating process. Therefore, the changing relationship between strain and crystal face at different temperature could be expressed in Fig. 15 via calculating. The strain increased keeping in line with the increase of temperature the same as that of stress. Which was due to lattice distortion during heating. In short, it was clear that there was a chemical reaction between the Al and B₄C.

EDS and EPMA tests had proved that there was an element diffusion existing at the interface of Al and B₄C. The diffusion distance of Al at B₄C side was longer than the distance measured from B₄C to Al. That was because of that Al melted at the sintering temperature and permeated into B₄C, on the other hand, B₄C as a kind of ceramics, the dispersal ability and chemical activity were poorer than these of Al. The images of TEM have exhibited the different regions of the B₄C/Al composites. The results of SAED demonstrated that the reaction products of Al and B₄C were Al₃BC, AlB₁₂, which was basically corresponding to the characterization of XRD.

4.2. Mechanical properties analysis

As a structural ceramic material with high strength and hardness, B₄C was often used to strengthen metals. The B₄C particles were evenly dispersed in the matrix by wet ball milling, which played the role of particle enhancement. B₄C ceramic was hard to break than Al, at the same time, it would take effect of nailing to restrict the destruction of Al. During crack propagation, the front end of the crack would bend forward due to the nailing effect of B₄C, thus more fracture energy was needed for material failure. Therefore, moderately compositional B₄C improved the mechanical properties of B₄C/Al composites in the present study.

The mechanical properties of lamellar materials are superior than those of ordinary materials for the following reasons.

Comparing to the ordinary materials, when lamellar materials are damaged, the layers separation will happen in the early stage. Furthermore, during the crack growth period, when the crack extends to the interlaminar junction, interlayer constraints can cause the crack deflects, then the crack propagation path is increased, thereby improving the fracture toughness of lamellar materials [33]. The fracture morphology of the lamellar B₄C/Al composites has been revealed in Fig. 16. Obvious crack deflection can been seen at the junction of 25 and 15 vol.% B₄C/Al composites, the angle of deflection reached to almost 110°. The angle between the deflection of the crack and the radial reached 45°. According to the trigonometric relation, the extended distance of crack increased 41.4% than the normal circumstances. Therefore, lamellar B₄C/Al composites behaved better at the fracture toughness that than of homogeneous B₄C/Al composites. In addition, there was evident plastic zone at the tip of crack. The distance of the plastic zone can be calculated as [34]:

$$r_p = \frac{1}{2} \left( \frac{K_{IC}}{\lambda \sigma_{YS}} \right)^2$$

(5)

Where $K_{IC}$ was fracture toughness of materials, $\sigma_{YS}$ was yield strength, $\lambda = 1$ at the state of plane stress. Therefore, Eq. (5) could be expressed as:

$$r_p = \frac{1}{2} \left( \frac{K_{IC}}{\sigma_{YS}} \right)^2$$

(6)

It was significative that the distance of crack plastic zone could be figured out via working out the values of yield strength $\sigma_{YS}$ and fracture toughness $K_{IC}$. At the previous test and calculate, $\sigma_{YS}$ and $K_{IC}$ had been obtained as $\sigma_{YS} = 289.15 \pm 13.12$ Mpa, $K_{IC} = 12.21 \pm 0.23$ M Pa m$^{1/2}$. Plug the values into the formula (6), the distance $r_p$ was getting as about 260μm. This could guide us to reasonably predict the extension distance of the tip of the plastic zone after deformation. The hardness of the lamellar composites at the tip of
crack was measured as nearly 320 Hv, which was triple than that of normal condition. Meanwhile, the lamellar composites behaved better at bending strength than that of homogeneous composites. According to the Taylor model: \( \sigma = \frac{\alpha \cdot M \cdot \mu \cdot b \cdot \sqrt{\rho}}{\rho} \), strength \( \sigma \) was in direct proportion to the dislocation density of the composites [35,36]. Dislocation density could be measured by TEM test. Fig. 17 had exhibited the TEM images of deformed layered \( \text{B}_4\text{C}/\text{Al} \) composites. Take the Fourier and inverse Fourier transform of the deformed region in Fig. 17(a), the lattice fringe in Fig. 17(b) was obtained. There were many dislocations appearing after deformation of the lamellar composites. Crack propagation was a process of dislocation release, as the density of dislocation increased, the strength and hardness of the material would increase, which was the strain reinforcement theory [37–39].

5. Conclusion

The laminar and homogeneous \( \text{B}_4\text{C}/\text{Al} \) composites have been fabricated via the preparation technology of sintering temperature 680 °C, sintering pressure 30 MPa, and soaking time 90 min. In addition, another sample with the separated component of \( \text{Al} \) and \( \text{B}_4\text{C} \) was prepared to investigate the interfacial reaction of these two materials. The conclusions of the present study were listed as follows.

1) In-situ XRD has manifested that there were reactions between \( \text{Al} \) and \( \text{B}_4\text{C} \), thus causing the peaks of \( \text{Al} \) offset and resulting in the residual stress and strain appearing. The stress and strain increased in keeping with the rise of heating temperature. The reaction products were detected as \( \text{AlB}_2, \text{AlB}_12, \text{Al}_3\text{BC} \) via XRD and TEM tests.

2) There was an elemental proliferation at the interface between \( \text{Al} \) and \( \text{B}_4\text{C} \), the distance of \( \text{Al} \) entering into \( \text{B}_4\text{C} \) was deeper than that of \( \text{B}_4\text{C} \) entering into \( \text{Al} \), which was testified via the analysis of EDS and EPMA.

3) Mechanical properties analysis showed that lamellar \( \text{B}_4\text{C}/\text{Al} \) composites presented the optimal Vicker hardness of 116.23 ± 5.25 Hv, bending strength of 780.45 ± 12.35 MPa and fracture toughness of 12.21 ± 0.23 MPa·m\(^{1/2} \), which were better than those of random homogeneous \( \text{B}_4\text{C}/\text{Al} \) composites in the current experiment.

**Conflict of interest**

All authors have reviewed and approved this final version of the article for publication, and due care has been taken to ensure the integrity of the present work. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

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**Appendix A. Supplementary data**

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2019.12.042.

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