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Effect of fiber type on mechanical properties of short carbon fiber reinforced B_4C composites

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Abstract

In order to enhance the mechanical properties of B_4C without density increase, the short carbon fibers M40, M55J and T700 reinforced B_4C ceramic composites were fabricated by hot-pressing process. The addition of the carbon fibers accelerates the densification of the B_4C, decreases their densities, and improves their strength and toughness. The enhancement effects of the three kinds of carbon fibers were studied by investigating the density, Vickers hardness and the mechanical properties such as flexural strength, flexural modulus and fracture toughness of the composites. The fiber type has a great influence on the mechanical properties and enhancement of the short carbon fiber reinforced B_4C composites. The flexible carbon fiber with high strength and low modulus such as T700 is appropriate to reinforce the B_4C matrix ceramic composites.

Keywords: C. Mechanical property; B_4C; Carbon fiber; Ceramic composites

1. Introduction

Boron carbon (B_4C) possesses excellent physical and mechanical properties such as low density, high melting point, high elastic modulus, high hardness and good wear resistance. In addition, B_4C ceramics exhibit unique properties such as good chemical stability and high neutron absorption cross-section. They are currently used in lightweight armor, wear proof apparatus, nuclear energy and thermo-electric conversion [1]. However, their widespread applications have been restricted due to the low strength and fracture toughness. Many previous studies have been developed to enhance the densification and the mechanical properties by introducing various additives. The addition of TiB_2 [1–3], SiC [3–5], TiC [6], WC [7], Si_3N_4 [8], and metals [9,10] can improve the strength and the toughness in different degrees. However, all of these additives will increase the density of B_4C ceramics. The density increase of B_4C ceramics is unacceptable in some weight-first applications such as bulletproof ceramic.

Carbon fibers have been used as reinforcement successfully in polymer matrix composites for their excellent properties. Since carbon fibers possess high strength, high modulus and low density, the addition of carbon fibers to B_4C ceramics is one possible way to enhance the mechanical properties and decrease the density at the same time.

In the present work, the B_4C reinforced by different carbon fibers were fabricated and studied. The mechanical properties of the composites such as flexural strength, flexural modulus, and fracture toughness of the ceramic composites were investigated. In order to understand the effect of fiber type on the mechanical property of the composites, the reinforcing mechanism caused by the fiber type was analyzed.

2. Experimental

2.1. Materials

The B_4C powder with the average particle size of 3.5 μm was purchased from Mudanjiang Jingangzuan Boron carbide Co., Ltd.

Three types of carbon fiber T700, M40 and M55J were used in the present work. They represent high-strength, high-modulus and high-strength-high-modulus carbon fibers, respectively. The basic properties of the three types of carbon fiber are listed in Table 1, which are provided by the fiber manufacturer Toray Co., Ltd.

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Table 1
The basic properties of carbon fibers

Fiber	Strength (MPa)	Modulus (GPa)	Elongation (%)	Density (g cm^{-3})
T700	4900	230	2.1	1.80
M40	2740	392	0.7	1.81
M55J	4020	540	0.8	1.91

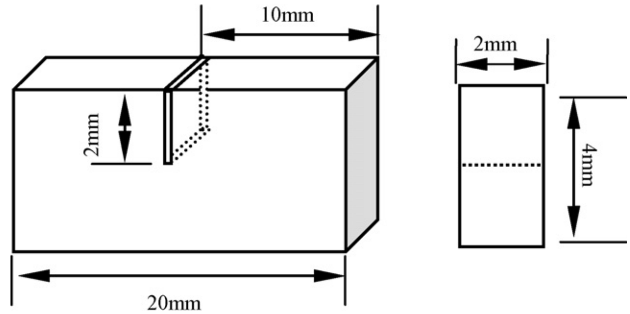

Fig. 1. The SENB sample for fracture toughness test.

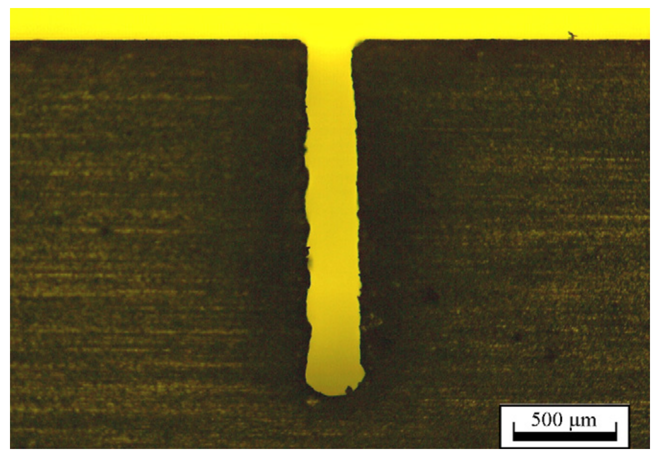

Fig. 2. The notch on SENB sample.

2.2. Sample preparation

The carbon fiber reinforced B_4C matrix ceramic composite were prepared by hot pressing process. After being chopped to a length about 1 mm, the carbon fibers were added into the B_4C powder and blended together in a high-speed mixer. The range of carbon fiber additions to the B_4C was from 0 to 20% by volume. During the blending process, the carbon fibers were dispersed homogeneously throughout the powders and cut short further. The average length of carbon fibers was controlled by the blending time. When the powder achieved a uniform dispersion of carbon fibers and B_4C, the mixture was compressed by cold pressing method in a closed die. The carbon fiber reinforced B_4C ceramic was sintered by hot pressing at 1960 °C for 0.5 h with an applied pressure of 35 MPa in argon atmosphere. For the sake of comparison, monolithic B_4C specimens without carbon fibers were also fabricated by the same procedure.

The samples for flexural strength and modulus measurement were cut from the ceramic tile by electric spark machining and ground with a 600-grit diamond wheel to the dimension of $3 \times 4 \times 40\ mm^3$. The fracture toughness measurement employed the single edge notched beam (SENB) sample with the dimension of 4 mm × 2 mm × 20 mm, shown in Fig. 1. The 2 mm-deep notch in the sample was machined by electric spark machining. A photo of the notch is shown in Fig. 2.

2.3. Testing and characterization

The densities of the specimens were measured by the Archimedes's method. Three-point-bending model was used to measure the flexural strength and modulus over a 30 mm span at a crosshead speed of 0.1 mm/min. The fracture toughness measurement was carried out using three-point-bending method with SENB sample. The span of the supports in fracture toughness test is 16 mm and the crosshead speed is 0.05 mm/min. The Vickers hardness was measured on polished surface with a load of 9.8 N in a hardness tester. Data for hardness, flexural strength, flexural modulus, and fracture toughness were gathered on five specimens.

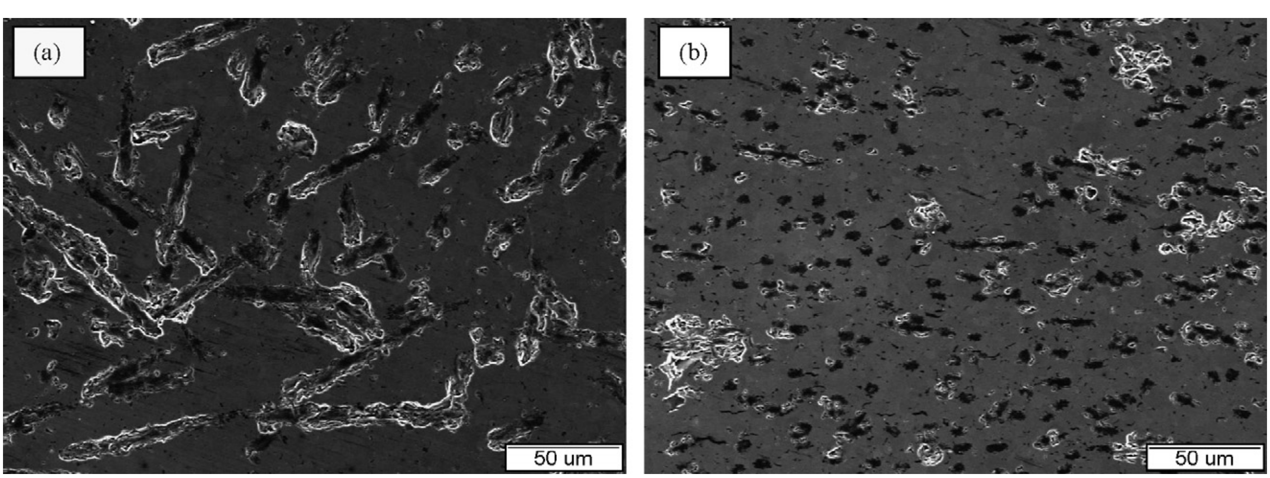

Fig. 3. The anisotropic structure of the carbon fiber reinforced B_4C composites.

The microstructure of sintered materials were studied on fracture surfaces and polished sections by scanning electron microscopy (Hitachi S-5800).

3. Results and discussion

3.1. The microstructure of the composites

The SEM micrograph of the ceramic composites is displayed in Fig. 3. Fig. 3(a) shows a vertical section to pressure direction and Fig. 3(b) shows a section parallel to the pressure direction. The composites exhibit anisotropy in the microstructure. The most carbon fibers are in-plane orientation and vertical to the pressure direction. The fiber orientation occurs under the pressure during the green cake compacting and hot pressing process. So the carbon fiber arrangement in the ceramic can be regarded as the 2D random distribution approximately. The structure of the ceramic composites can be illustrated by the schematic diagram in Fig. 4.

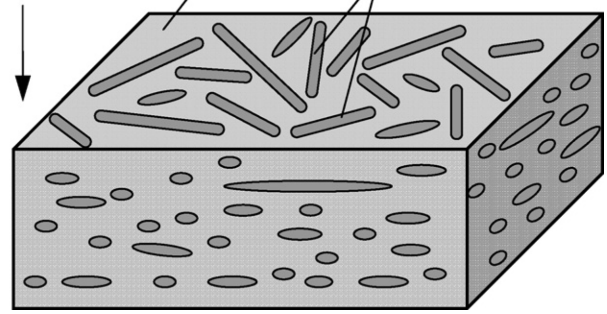

Fig. 4. A schematic diagram of the carbon fiber reinforced B_4C ceramic.

3.2. The densification of the composites

The density, hardness and the mechanical properties including flexural strength, flexural modulus and fracture toughness of the monolithic B_4C ceramic and the carbon fiber reinforced B_4C are listed in Table 2. All the ceramic samples in Table 2 are produced by the same sintering process, so the property variation comes only from the addition of the carbon fibers. In the case of the monolithic B_4C, the relative density is only 97.1%, which is much lower than that of the other samples. It seems that the addition of the carbon fiber can improve the densification of B_4C ceramic. The full densification was achieved in the M40 and T700 carbon fiber reinforced ceramic composites. The relative densities of the M55J carbon fiber reinforced B_4C composites are between 99 and 99.5%, which are slightly lower than the density of the other two types of composites. Furthermore, the more M55J carbon fibers were added, the lower the relative density became.

The densification enhancement in carbon fiber reinforced composites is due to the carbon particulate in the powder mixture. Carbon is the best-known additives for B_4C sintering. The mechanism of the carbon as sintering aid has been illustrated in detail in the literatures [3,11–13]. When the powders were blended in the high-speed mixer, the carbon fibers were crushed by the high-speed B_4C particles and lots of carbon particulates flaked off from the carbon fibers. Fig. 5 shows the spalled carbon particles in the composites.

The lower densification of the composites reinforced by M55J carbon fiber resulted from the high modulus of the reinforcement. As shown in Table 1, the modulus of the M55J is about 235 and 138% of that of T700 and M40. The high modulus makes M55J fibers difficult to transform, and then the fibers counteract the densification behavior of the ceramic composite. With an increase in the content of the M55J, the counteraction increases.

For the hardness of the ceramic composites, the Vickers hardness decreases with the increase of the carbon fiber content. When the fiber content increased from 5 to 10%, the hardness decreased slightly about 1–3 GPa. However, the hardness decreased sharply to 21–27 GPa as the fiber content increased to 20%. The result shows too much carbon fiber addition will enhance the local distortion ability of the ceramic and reduces the hardness. The hardness is a key property and usually should be higher than 30 GPa when B_4C ceramic is used as armor and wear-proof parts, so the fiber content should not be higher than 20% in practice whatever kind of carbon fiber is used.

Table 2
Mechanical properties of the carbon fiber reinforced B_4C

Sample	Additive	Theoretical density (g cm^{-3})	Relative density (%)	Hardness (GPa)	Strength (MPa)	Modulus (GPa)	Fracture toughness (MPa m$^{1/2}$)
0#	–	2.52	97.1	30.19 (6.96)	220.7 (5.23)	397.5 (2.01)	1.70 (8.18)
1#	M40-5%	2.48	~100	36.22 (3.01)	259.4 (3.81)	424.6 (1.73)	2.40 (7.52)
2#	M40-10%	2.45	~100	35.14 (5.87)	294.0 (6.40)	404.0 (3.61)	3.01 (2.84)
3#	M40-20%	2.38	~100	26.94 (2.33)	283.9 (5.24)	301.1 (0.51)	2.13 (9.04)
4#	M55J-5%	2.49	99.5	35.39 (4.01)	343.1 (12.2)	411.9 (0.37)	2.69 (4.48)
5#	M55J-10%	2.46	99.2	32.95 (5.64)	381.5 (8.50)	334.3 (1.68)	2.75 (2.21)
6#	M55J-20%	2.40	99	21.21 (5.37)	347.3 (3.47)	284.2 (1.24)	2.46 (5.54)
7#	T700-5%	2.48	~100	37.57 (4.90)	399.8 (11.6)	402.9 (4.07)	2.52 (7.27)
8#	T700-10%	2.45	~100	36.10 (6.08)	409.9 (4.01)	386.9 (2.56)	2.93 (3.55)
9#	T700-20%	2.38	~100	23.61 (5.71)	319.2 (3.93)	296.8 (1.76)	2.28 (5.02)

Note: Data in brackets are the coefficient of variation, which unit is %.

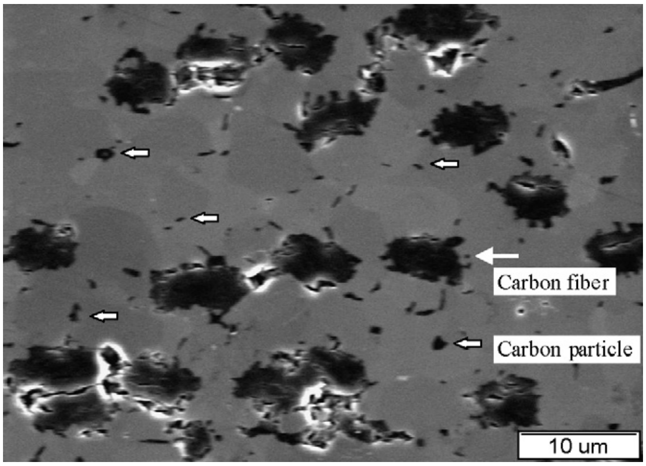

Fig. 5. The spalt carbon particles in the composites, some of them were arrowed.

3.3. Mechanical properties of the composites

3.3.1. The flexural strength

Fig. 6 shows the strengths of the ceramic composites reinforced by different type of carbon fibers. Three distinct characteristics can be concluded from the figure. First, the ceramics with 10% fiber addition have the highest strength for each kind of composites. Secondly, the strength of the composites reinforced with T700 is higher than that of the other two kinds of composites in most case. And thirdly, the strengths of the composites are higher than the strength of the monolithic B_4C.

According to the mixture rule, the strength of the composites will increase as the fiber content is increased. This is true when the fiber content is low. For example, the strength of the composites with 10% carbon fiber added is higher than that of the composites with 5% added. But the case is quite different at high carbon fiber content. When the carbon fiber volume fraction is up to 20%, there are too many fibers contacting one another. The interlacement of the carbon fiber counteracted the densification of the ceramic composite. At the same time, the interlacement of the carbon fiber increased the interface flaw between carbon fiber and the B_4C matrix. The interface flaw will also decrease the strength of the composites.

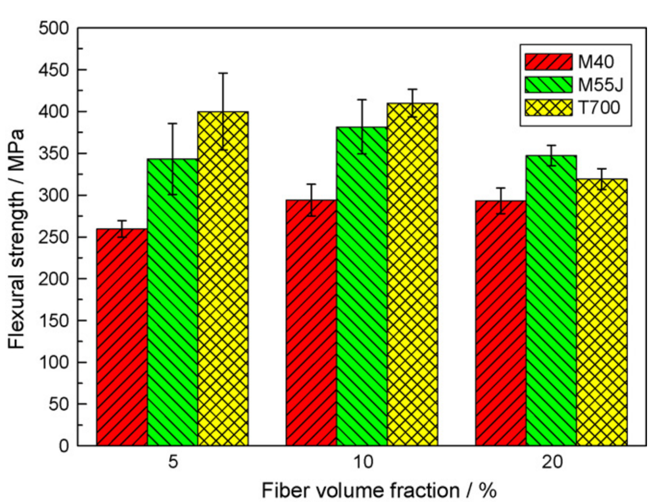

Fig. 6. The strength of the B_4C reinforced by different type of carbon fiber.

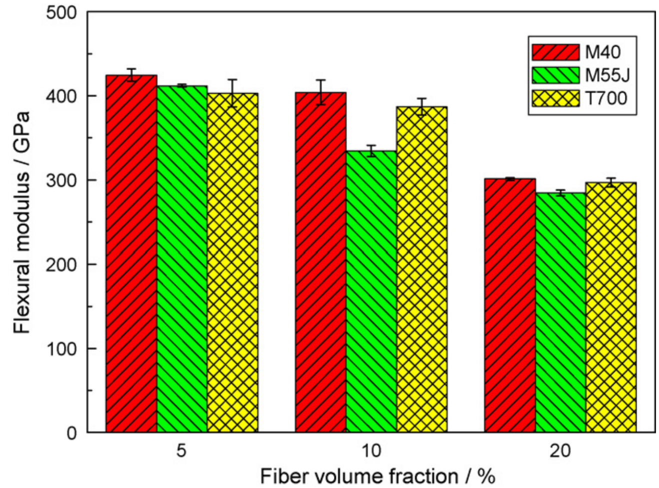

Fig. 7. The modulus of the B_4C reinforced by different type of carbon fiber.

3.3.2. The flexural modulus

The modulus is an important property for bulletproof ceramic. Fig. 7 shows the moduli of the composites. As the fiber content increased, the modulus decreased in all three composites. The modulus of the composites with 20% carbon fibers is approximately 30% lower than the modulus of the composites with 5% carbon fibers. Furthermore, there is no distinct difference among the moduli of the composites reinforced by the three kinds of carbon fibers.

Although the M55J fiber has the highest modulus among the three kinds of carbon fibers, the ceramic reinforced with it has low moduli in most situations. It shows the reinforcement modulus affects the ceramic's modulus only little. On the other hand, the pores in the matrix significantly affect the modulus [14].

3.3.3. The fracture toughness

The fracture toughness is another important property of the ceramic composites. The fracture toughness transformation is shown in Fig. 8, similar to the strength transformation. There is an appropriate fiber volume fraction at which the ceramic composites have the best fracture toughness. The fracture toughness of the ceramic composites can reach about 2.5–3.0 MPa $m^{1/2}$, which is much larger than the 1.7 MPa $m^{1/2}$ of the monolithic B_4C.

3.4. The reinforcing mechanism analysis

The experimental results above show that the mechanical properties of the B_4C reinforced by different types of carbon fibers differ significantly. The B_4C reinforced by the high-strength-low-modulus carbon fibers (T700) have the highest mechanical properties generally. Contrarily, the B_4C reinforced by the high-modulus-low-strength carbon fibers (M40) have low mechanical properties. The contribution of the fiber type to strengthening effect is discussed next.

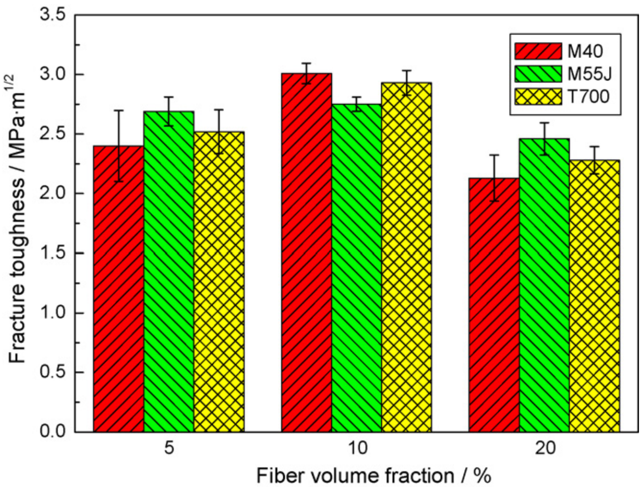

Fig. 8. The fracture toughness of the B_4C reinforced by different type of carbon fiber.

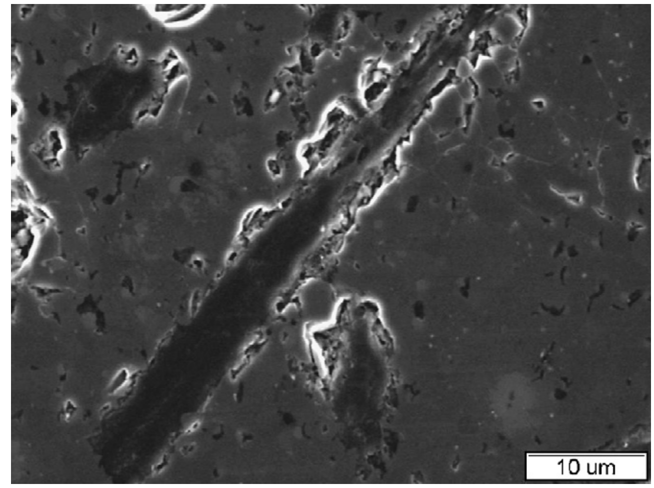

Fig. 9. A typical interface micrograph of carbon fiber and B_4C matrix.

3.4.1. The thermal expansion matching

The carbon fiber reinforced B_4C was sintered near about 2000 °C. The residual stress will develop when the material cools to room temperature due to the difference of the thermal expansion coefficient between carbon fiber and B_4C matrix. The thermal expansion coefficients of B_4C [13] and carbon fibers are listed in Table 3.

The stress that carbon fiber suffered at the interface caused by thermal expansion mismatch can be described as

$$\sigma_{fa} = (\alpha_{fa} - \alpha_m)\Delta T E_f \quad (1)$$

$$\sigma_{fr} = (\alpha_{fr} - \alpha_m)\Delta T E_f \quad (2)$$

The σ_{fa} and σ_{fr} are the stress fiber suffered in axial direction and radial direction. α_m, α_{fa}, α_{fr}, ΔT, and E_f are the thermal expansion coefficient of B_4C, the thermal expansion coefficients of carbon fiber in axial direction and radial direction, the difference of sintering temperature and room temperature, and the modulus of carbon fiber, respectively.

A typical interface micrograph of the carbon fiber/B_4C matrix is shown in Fig. 9. There exist distinct little gap between the fiber and the matrix, so there is no chemical force on the interface. The interface stress state can be analyzed by the thermal expansion property of the fiber and matrix. The stress state of carbon fiber/B_4C interface is illustrated in Fig. 10 according to the formula (1) and (2). Since $\alpha_{fr} > \alpha_m$, the carbon fibers suffer tensile stress at interface in radial direction. The interface tensile stress will decrease the friction between carbon fibers and B_4C matrix and make the fiber easy to pull-out. The increasing of the fiber pull-out will increase the sliding energy and benefit the reinforcing effect.

In axial direction of fiber, $\alpha_{fa} < \alpha_m$, so the fiber is compressed and the matrix is tensed. The tensile stress in the B_4C matrix is disadvantageous to the mechanical property. Among the three kinds of carbon fibers, the T700 has the highest α_{fa}, so it will result in the smallest tensile stress in the matrix [14].

Table 3
The thermal expansion coefficient of the carbon fibers and B_4C

Material	Axial thermal expansion coefficient (°C^{-1})	Radial thermal expansion coefficient (°C^{-1})
T700	-0.38×10^{-6}	
M40	-0.83×10^{-6}	$6–8 \times 10^{-6}$
M55J	-1.1×10^{-6}	
B_4C	4.6×10^{-6}	

Note: The data of thermal expansion coefficients of carbon fibers are provided by the Toray Co., Ltd.

3.4.2. The mechanical property matching

Consider a single carbon fiber inclined from the loading axis by an angle θ as shown in Fig. 11. The stress in the fiber to be pulled-out is assumed to be independent of the surrounding fibers left unbroken or broken. The stresses occurring in the

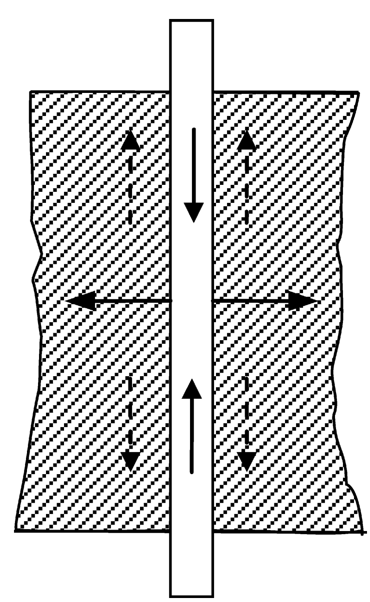

Fig. 10. The stress state of carbon fiber/B_4C.

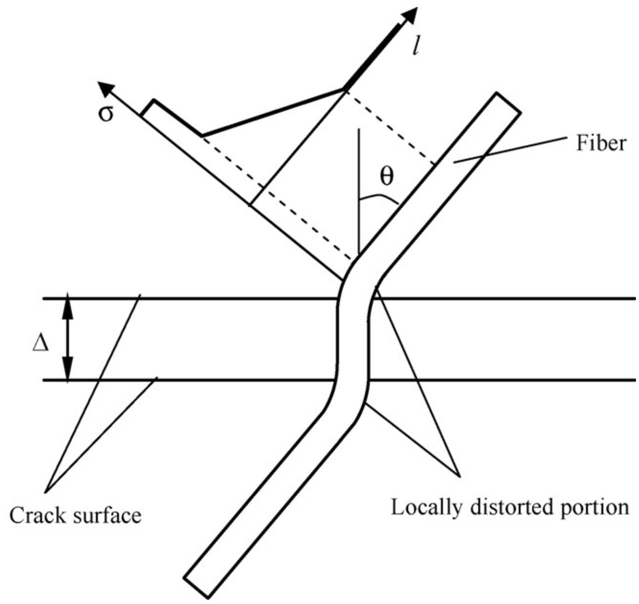

Fig. 11. An analytical model of a bridging fiber to be pulled-out from the matrix.

fiber can be expressed in terms of embedded length l and inclination angle θ [15]. The tensile stress in the fiber embedded in the matrix is a decreasing function of the distance l from the cracked plane. So the breakage of the fiber mostly occurs at the bent portion in the neighborhood of the cracked plane. The fiber with higher tensile strength and bending ability will enhance the mechanical property of the composites effectively. Higher bending ability means lower modulus and larger elongation ratio at fracture.

Among the three kinds of the carbon fibers, the T700 has the highest tensile strength and lowest modulus. Especially, the elongation ratio at fracture of T700 is about three times of that of the M40 and M55J. So the mechanical property of the composites reinforced by T700 is the best.

4. Conclusions

The short carbon fibers reinforced B_4C ceramic composites were obtained, which possess higher strength, higher fracture toughness and lower density compared to monolithic B_4C. Through the mechanical properties investigation and the reinforcing effect analysis, several helpful rules can be concluded.

(1) The addition of carbon fibers to B_4C can accelerate the sintering process.
(2) Tensile stresses develop at the fiber/matrix interface because the radial thermal expansion coefficient of carbon fibers is larger than that of B_4C. The tensile strength at the interface makes the fiber pull-out easy and improves the toughness of the composites.
(3) The fiber type has great influence on the mechanical properties and enhancement of the short carbon fiber reinforced B_4C composites. The flexible carbon fiber with high strength and low modulus such as T700 is appropriate to reinforce the B_4C matrix ceramic composites. On the other side, the brittle carbon fiber with low strength and high modulus such as M40 is not appropriate.

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