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COMPOSITE MATERIALS FOR TOKAMAK WALL ARMOR, LIMITERS,
AND BEAM DUMP APPLICATIONS

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Studies of wall armor, limiters, and beam dump materials for Tokamaks have demonstrated the necessity of using low Z materials to prevent plasma poisoning. Additionally, these materials must have high thermal stress resistance, high mechanical fatigue resistance, and low erosion rates to survive under the very high heat and radiation loads they will encounter. Graphite meets the first three criteria very well, but is unsatisfactory from the erosion standpoint. It has been suggested that the application of refractory low Z materials as surface coatings on these graphite shapes would lessen the erosion problem.

It has been our experience that such coatings on flat graphite surfaces have a tendency to spall when subjected to thermal stress, and hence the coatings would only be effective for a short time. However, if the refractory low Z material and graphite are fabricated as a composite material, the spalling problem can be minimized leading to new materials which have a potential for Tokamak first wall applications.

This paper describes materials which are composites of carbon fibers and low Z number carbides. The composite materials are fabricated by applying chemical vapor deposition (CVD) coats of either low Z number elements (i.e., boron, titanium, silicon, or nickel) or carbides (B_4C , TiC , or SiC) onto graphite fibers, in the form of yarn, cloth, or three-dimensional structures, and then hot pressing the coated material to full density. The benefits of this approach are: (1) Each graphite filament ($\sim 9 \mu m$ diameter) is surrounded by a refractory carbide which offers better resistance to erosion loss than graphite. If some material is spalled from the surface, the underlying graphite fibers are still coated, and thus still protected from hydrogen bombardment; (2) The composites should have longer thermal fatigue lives than carbides because of the graphite fiber reinforcement running through the composite; (3) Enhanced mechanical properties are obtained because of completely interconnected networks of carbide and graphite.

Preliminary metallographic evaluation of nickel and boron coated graphite yarn and cloth, as well as metallographic and thermomechanical evaluation of hot pressed $Ni-C$ and B_4C-C composite material will also be presented.

This new generation of composite materials will aid in understanding and offers a potential solution to very serious first wall problems of the Tokamak.

This work performed under the auspices of the USDOE.

COMPOSITE MATERIALS FOR TOKAMAK WALL ARMOR, LIMITERS, AND BEAM DUMP APPLICATIONS

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A new generation of composite materials, graphite fiber reinforced metal carbides and borides, is being developed. These materials have high strengths and excellent chemical and mechanical stability. Their properties can be tailored over wide ranges to meet service requirements. By using metal components such as boron, silicon or titanium, these composites offer outstanding promise as low Z number materials for limiters, wall armor, beam stops, etc., in Tokamaks.

1. INTRODUCTION

A major materials problem being encountered on the road to power producing Tokamak fusion reactors is the lack of satisfactory heat sink material for use in limiters, wall armor, beam stops, diverter targets, etc. Most existing machines have used the refractory metals molybdenum and tungsten for these components; however, severe surface melting and thermal fatigue cracking have resulted. In addition to these problems, severe plasma poisoning occurs from the presence of the high Z materials in the Tokamak atmosphere. It is obvious that future machines cannot use these high Z materials in the first wall region.

The only low Z material examined seriously to date, carbon, has its own set of problems. Although graphite has good thermal fatigue resistance, and plasma poisoning by graphite heat sink components can be reduced to acceptable limits, the reactivity of carbon with hydrogen and the high sputtering rate cause an unacceptably high erosion of uncoated graphite.

Coating graphite with a low Z material to protect it from the Tokamak atmosphere has been proposed to lessen these problems; however, because of the differences in thermal expansion and conductivity between graphite and the low Z coatings being considered, poor adherence and spalling are seen as very serious problems. Further, if a break occurs in the coating, the graphite plate is exposed to the hydrogen atmosphere and the damage accelerates.

We have developed a new class of composites that have the potential of solving these problems by incorporating the coating materials into the structure of the composites. The composites are fabricated by chemical vapor deposition (CVD) coating carbon or graphite cloth with low Z carbides or borides in such a way as to encase each individual fiber with the coating material. Stacks of these cloths can then be hot

pressed to form a composite structure consisting of a continuous network of carbide or boride reinforced with carbon fiber. Adherence and spalling problems are essentially eliminated and if the coating is ruptured, the damage is restricted to the individual fibers involved. Consequently, attack of the graphite by hydrogen or by sputtering is minimized since little or no graphite would be exposed to the plasma. Further, the fiber reinforced carbides or borides have superior strength properties and should exhibit excellent thermal shock and thermal fatigue properties [1,2].

2. FABRICATION PROCEDURE

Low Z refractory compounds (i.e., B₄C, SiC, TiB₂, TiC, etc.) can be deposited on the surfaces of carbon or graphite fibers assembled as yarn, cloth, or woven three dimensional structures by hydrogen reduction of the chlorides. For example:

To achieve uniform micro structural control in the finished hot pressed composite, it is essential that the ceramic material be deposited to a uniform thickness on the surface of the fibers contained in the carbon or graphite structure. This is achieved by coating at reduced pressure, controlled temperatures and coating gas compositions. Figure 1 illustrates the uniform highly adherent deposition of TiB₂ obtained on Union Carbide WCA cloth at 975 K with a pressure of 4 kPa.

The choice of the carbon or graphite fiber assemblage is dependent on the directional properties which one wishes to achieve in the final hot pressed composite. For example, unidirectional composites can be fabricated by coating

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Fig. 1 Photomicrograph of Union Carbide WCA cloth coated with TiB_2 at a pressure of 4 kPa and a temperature of 975 K.

yarn, cutting to equal lengths, making a uni-directional layup in a graphite die, and hot pressing to full density; laminate composites by coating cloth, cutting square or circular shapes, stacking in a graphite die, and hot pressing; and three dimensional composites by coating woven structures and then isostatically hot pressing.

The hot pressing step is particularly critical if the optimum properties of both the ceramic and graphite fibers are to be maintained in the finished composite. As a general rule, the hot pressing temperature must be above the ceramic brittle-to-ductile transition temperature to assure that a nearly theoretically dense composite is obtained with minimum damage to the fibers. However, if the temperature is too far above the transition temperature, it appears that the ceramic phase dissolves and re-precipitates in the core of the graphite fibers with corresponding reorganization. The resultant material then has mechanical properties similar to those found in hot pressed particulate composites.

As an illustration of the deterioration of the graphite fiber due to hot pressing at too high a temperature, flexure strengths of two uni-directional billets (17 vol.%-TaC/90 vol.%-HM 3000 and 35 vol.%-TaC/65 vol.%-HM 3000 graphite fiber) are compared with other TaC/C composites in Fig. 2. In this instance tantalum was deposited as the metal, and its carbide was formed by reaction with carbon fibers during the hot pressing(3).

The 17 vol.%-TaC billet was hot pressed at 2930 K and 41 MPa and the 35 vol.%-TaC composite at 3130 K and 41 MPa. The flexure strength of 17 vol.%-TaC composite was 155 MPa which is five times greater than that for an equivalent particulate composite, whereas the 35 vol.%-TaC

Fig. 2 Flexure strength as a function of volume percent TaC for various TaC/C composites.

composite was 106 MPa, which is lower than that expected for a composite containing strong undamaged graphite fibers. Figures 3 and 4 show

Fig. 3 Scanning electron micrograph of fracture surface of unidirectional 17 vol.%-TaC/83 vol.%-HM 3000 graphite fiber composite.

SEM's of the fracture surfaces of the 17 vol.% and 35 vol.% composites, respectively. It is apparent that considerably less reprecipitation and reorganization occurred in the 17 vol.% composite which was hot pressed at the lower temperature. We feel this demonstrates the necessity to carefully control the hot pressing temperature and are currently investigating this area.

3. TiB_2/C COMPOSITE MATERIAL

Because of the reported low hydrogen ion erosion yields for TiB_2 (4), a limited investigation was undertaken to establish the process conditions for fabricating TiB_2/C composite materials. It was found that TiB_2 could be uniformly deposited on the fiber surfaces of

Fig. 4 Scanning electron micrograph of fracture surface of unidirectional 35 vol.%-TaC/65 vol.%-HE 3000 graphite fiber composite.

Fig. 5 Macrostructure of 35 vol.%-TiB₂/C composite material.

WGA graphite cloth in the temperature range of 473 to 1073 K and a pressure range of 3 to 7 kPa (see Fig. 1). One hot pressing was made (2023 F and 28 MPa) and the results of the property determinations made on this billet are given in Table 1. Figure 5 shows the excellent compaction

Table 1

Properties of TiB₂/C Composite Material

Composition (vol.% TiB ₂)	35
Density (Mg/m ³)	2.83
Flexure strength (GPa) ^a	105 ± 10
X-ray lattice parameters of hexagonal TiB ₂ (nm)	
Before hot pressing	$a_c = 0.3476 \pm 0.0006$ $c_c = 0.3267 \pm 0.0012$
After hot pressing	$a_c = 0.3559 \pm 0.0005$ $c_c = 0.3232 \pm 0.0002$

^aMean value of 4 samples

tion achieved in hot pressing. However, detailed examination of the microstructure at higher magnification and of the fracture surface (Fig. 6) shows that the hot pressing temperature was too high and that the integrity of the graphite fibers were destroyed. Correspondingly, the flexure strength is lower than what can be achieved when the correct hot pressing conditions are established.

4. B₄C/C COMPOSITE MATERIAL

Boron carbide has the lowest electrical conductivity of the low Z carbides and borides considered for protective coatings in the Tokamak (5). Unlike a graphite tile with a protective B₄C coating, a B₄C/C composite tile can be tailored to have a bulk electrical conductivity between the values for graphite (1000 Ω⁻¹cm⁻¹)

Fig. 6 Scanning electron micrograph of fracture surface from 35 vol.%-TiB₂/C composite.

and B₄C (5 Ω⁻¹cm⁻¹) by varying the relative amounts of the components.

We have developed a process using the temperature range 1175 to 1275 K and a pressure range of 3 to 4 kPa to uniformly coat WGA graphite cloth with B₄C (Fig. 7). X-ray diffraction examination of the deposited boron carbide showed that the material was in an amorphous state. Billets of 27 vol.%-B₄C and 43 vol.%-B₄C were hot pressed at 2275 K and 3/ MPa. Figure 8 shows the compaction achieved under these conditions for the 43 vol.%-B₄C composite. X-ray examination of the hot pressed materials showed that hexagonal B₄C ($a_c = 0.5621 \pm 0.0005$ nm, $c_c = 1.2093 \pm 0.0006$ nm) was present after processing. Table 2 summarizes property measurements made on the billets. If an ungraphitized carbon cloth were used, one would expect even lower electrical conductivity values in the full composition range.

Fig. 7 Photomicrograph of Union Carbide WCA cloth coated with B_4C at a pressure of 4 kPa and a temperature of 1275 K.

Fig. 8 Macrostructure 43 vol. % B_4C composite.

Table 2

Electrical Properties of B_4C Composites

Composition (vol. %)	Density (g/cm^3)	Electrical Conductivity ($\Omega^{-1}cm^{-1}$)
27	1.71	440
43	1.97	290
100	2.47	25

^a B_4C powder hot pressed at 2400 °C and 21 MPa

5. CONCLUSIONS

We feel that carbon or graphite fiber reinforced low Z carbides and borides have a potential for solving some of the heat sink material problems being encountered in tokamak fusion reactors. The major strength of composite materi-

als is the ability to tailor material properties to meet engineering needs by selection of carbon or graphite assemblages, ceramic and the relative proportions used; the major weakness is the fact that it is a relatively new material concept and that there is a limited property data base and essentially no testing results in a Tokamak environment.

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