

A REVIEW OF JOINING TECHNIQUES FOR SiC_f/SiC COMPOSITES FOR FIRST WALL APPLICATIONS - C.A. Lewinsohn and R.H. Jones (Pacific Northwest National Laboratory)*

OBJECTIVE

The objective of this work is to review the methods currently available for joining silicon carbide composites and to critique their suitability for structural applications in fusion energy systems.

SUMMARY

Many methods for joining monolithic and composite silicon carbide are available. Three techniques are candidates for use in fusion energy systems: in-situ displacement reactions, pre-ceramic polymer adhesives, and reaction bonding. None of the methods are currently developed enough to satisfy all of the criteria required, i.e., low temperature fabrication, high strength, and radiation stability.

PROGRESS AND STATUS

Introduction

The development of fusion energy systems places many demanding criteria on the materials to be used in this application. One criterion, is the need for a hermetic material that can chemically and mechanically withstand high-temperatures and neutron fluxes as the "first-wall" material. In addition, the radioactivation of the material to be used as the first wall should be below the limits for a safe and environmentally benign lifecycle. A candidate material for this application is silicon carbide fiber-reinforced, silicon carbide (SiC/SiC). SiC/SiC composites possess desirable thermal, mechanical, and nuclear stability. A limitation of these materials, however, is that they can only be produced in limited sizes and shapes. Therefore, to fabricate a complete fusion energy system a method of joining SiC/SiC components, without compromising the properties that are needed, is required. This report will review the methods currently available for joining monolithic and composite silicon carbide and critique their suitability for fusion energy system applications.

Since silicon carbide has many desirable properties for use as a "first-wall" in a fusion energy system, it is undesirable to use a joining technique that would expose another material at the inner face of the first wall. In addition, to avoid poisoning the plasma the first wall must be hermetic. Thus, it is highly likely that a means of joining SiC/SiC components to each other is required. In addition, the first wall material will have to be supported by another structure, that may be a metal, which means that joining of SiC/SiC to metals must also be considered.

Joining of ceramics to ceramics or to metals is an area that has been investigated for many years and, because of its complexity, remains an area of extensive research. This review will cover both ceramic to ceramic and ceramic to metal joining, since both situations may be found in fusion energy systems, but it will focus on joining of silicon carbide composites to themselves. From the limited amount of research performed on joining SiC/SiC to itself and other materials there is no reason to believe that it does not behave any differently from

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silicon carbide with respect to joining. Silicon carbide has been successfully joined to itself via direct diffusion bonding, brazing, codensification of green bodies and binders, reactive metal bonding, pressurized combustion reactions, in-situ displacement reactions, preceramic polymer adhesives, glassy interlayers, and reaction bonding. The principles of several joining techniques will be presented, and advantages and disadvantages, relative to other joining techniques, will be addressed. In addition, the suitability of each technique for fusion energy systems, according to current design criteria, will be discussed.

Certain additional issues arise due to the use of composite as opposed to monolithic silicon carbide. The first of these issues concerns the degradation of fibers at an elevated temperature determined by each type of fiber. The second issue concerns oxidation of the fiber to matrix interphase, and the subsequent removal of fiber bridging stresses, above approximately 500°C in the presence of oxygen. Another issue regards the loss in load carrying capacity of fiber-reinforced plies that are machined to obtain the desired component or joint technologies. All of these mechanisms may lead to weak regions in the proximity of the joint. To minimize composite degradation, due to joining, the joining temperature should be as low as possible and post-densification machining of the composite surfaces should be avoided.

Literature Review

A. Methods of Joining Ceramics to Ceramics

1. Mechanical Interlocking

A relatively simple means of joining components is by mechanical means. Due to the difficulty of machining dense ceramics and their brittle fracture properties, conventional fastening techniques that may be used to join metal components, such as nuts and bolts, screws, rivets, etc., are rarely successful when applied to ceramics, especially at high temperatures. Other mechanical fastening techniques, however, are feasible. These techniques include clamping, retaining brackets, and shrink-fit methods. As will be discussed later, the large mismatch in thermal expansion between metals and ceramics inhibits the use of metal fasteners.

Clamping components consists of using an intermediate component to apply pressure to the components to be joined. The current fusion energy systems designs propose toroidal reactors. To obtain a continuous toroidal shape via clamping smaller components would be extremely difficult. The first wall material is designed to be subject to a large thermal gradient, hence large thermal stresses. These stresses are the reason that SiC/SiC, as opposed to monolithic silicon carbide, is considered as a potential candidate material. Any type of clamp that is used would also have to be fabricated from SiC/SiC to retain the desirable thermomechanical and nuclear properties. Clamping, therefore, does not remove the problem of joining SiC/SiC to itself. Clamping may be a suitable mechanical joining technique, but it would have to be complemented with another joining method to obtain a hermetic seal.

In principle, clamping and the use of retaining brackets are similar. These techniques rely on using another component to apply compressive stress on the components to be joined. Retaining fasteners are similar to conventional metal nuts and bolts. The fastener passes through the components to be joined and an attachment is made at each end to hold the

components together. A disadvantage of the use of retaining fasteners is the difficulty in obtaining hermetic seals where the fastener passes through the component. If silicon carbide retainers are used, to avoid introducing another material at the first wall, the problem remains of attaching a piece larger than the hole on each end. Obtaining a strong, hermetic joint in this manner would also be difficult and would rely on some sealant material. Finding a sealant that can withstand the service conditions and can be fabricated easily may be difficult. In addition, the existence of a hole in the SiC/SiC component will likely lead to matrix cracks which could effect the hermetic properties and residual thermomechanical behavior of the component. As with clamping, the use of retaining fasteners does not eliminate the need for joining SiC/SiC to itself since fasteners can only provide mechanical attachment of components without hermetic sealing between the components.

The third method of mechanical interlocking, shrink fitting, may hold some promise for fusion applications. Shrink-fitting is a very well established method that has been used for centuries (notably in gun barrels). The technique relies on thermal expansion to temporarily increase the inner diameter (ID) of an outer component while an inner component is inserted into position. After the outer component cools, the ID is constrained by the outer diameter of the inner component. The difference between the original ID and the constrained ID of the outer piece is called the misfit strain. The misfit strain produces compressive stresses across the interface that holds the components together. Inversely, the inner component could be cooled and the same result would be obtained. Although, shrink fitting is commonly used for cylindrical components, the technique also can be applied to planar geometries.

Although mechanical interlocking methods can be used to achieve strong physical bonding between SiC/SiC components, the additional requirements of hermetic properties and use of radiation tolerant materials (i.e., SiC/SiC or silicon carbide) preclude their use as the sole means to join SiC/SiC components. Clamping or shrink-fitting methods, however, may be considered in combination with other joining techniques.

2. Brazing

Brazing of ceramics involves using a component that forms a liquid phase during joining. The process uses a braze material that is chemically compatible with both components to be joined. The braze material forms strong chemical bonds with surfaces to be joined. Since self diffusion rates in ceramics, especially in non-oxide ceramics, are relatively slow in comparison to most metals, braze materials that form strong chemical bonds with ceramics and have acceptable diffusion rates are used. Two types of brazes are commonly used: noble metal brazes and reactive metal brazes. Noble metal brazes are typically silver or platinum alloys and may include copper or nickel. The use of noble metal brazes usually requires metallization of the ceramic surfaces. Since many metal brazes do not wet ceramic surfaces, metals that are more thermodynamically reactive than the ceramic cationic species are often used. The addition of minor amounts of reactive metals (i.e., Ti, Al, etc.) allows formation of an oxide or carbide layers that are compatible with corresponding ceramic materials.

Brazing with reactive metals requires processing in vacuum or inert environments to prevent a reaction between the braze metal and the environment. If it is not possible to braze under a vacuum or in an inert atmosphere the ceramic material must be pre-metallized to enhance bonding between the braze material and the ceramic. A common metallization technique, useful for oxide ceramics or ceramics with oxide containing grain boundaries, involves

applying a slurry of molybdenum and manganese to the surface of the ceramic and firing under conditions that oxidize the manganese but not the molybdenum (1). Under the right conditions, MnO forms a glassy phase bonds with oxide ceramic phases while the molybdenum forms a porous layer that the MnO glassy phase also infiltrates. Often this layer is then electroplated with nickel to create a good surface for brazing. Another form of metallization involves coating the ceramic surface with titanium hydride. The material is fired under reduced pressure under which the hydride decomposes and titanium undergoes a redox reaction with the ceramic surface to form a strong chemical bond (2). Other metallization techniques include sputter deposition and physical vapor deposition, however metallization of SiC has had limited results (3).

Brazing has been used to join silicon nitride (Si_3N_4) and SiC to themselves using copper-titanium and nickel-titanium (4-7). A number of braze compositions based on silver-copper alloys have been found to be successful in joining ceramics to metals and ceramics to themselves (3,4). Other metals include aluminum (8), silicon (9), and tin (10,11). Since even those metals developed for brazing do not wet most ceramic surfaces completely, active metal fillers are often used to promote wetting and to improve the properties of the brazed joints. Alloys of silver, copper, and more than 10 atomic % titanium have produced extremely good joints between silicon carbide materials (4, 12-15). A variety of other metals, such as zirconia, hafnia, nickel, beryllium, chromium, vanadium, indium, and cobalt have also been used as active metal fillers in brazes for ceramics (16-21).

The low temperature strength of brazed joints between silicon carbide and itself are relatively high. Naka et al. used an alloy of copper and titanium and were able to obtain maximum values of the shear strength of 80 MPa (22). Lemoine et al. obtained values of the shear strength of single and double lap joints between SiC/SiC and itself, brazed with silicon, of about 20 MPa, tested in flexure (9). Ferro and Derby obtained typical values of 200-250 MPa for the tensile strength of aluminum metal brazed joints between reaction-bonded silicon carbide (8). Iseki reported tensile strengths of as high as 490 MPa for silicon carbide joined to itself with a complex joint of metal interlayers (23). Nakamura and Shigematsu obtained a mean strength of 96 MPa, with a Weibull modulus of 3.2, for joints formed by an alloy of silver, copper, and titanium between silicon carbide composites consisting of hot pressed fibers (24). Since joints will generally fail under shear stresses (if the structure is designed correctly), the relevance of a tensile strength for a joint is questionable. Furthermore, it is difficult to compare strength values from one study to another due to the different test methodologies used. Nevertheless, it is apparent that a variety of brazing techniques can be used to obtain reasonably strong joints between monolithic or composite silicon carbide at room temperature.

Unfortunately, all of the brazing techniques presented so far suffer from one of two problems at elevated temperatures: the formation of brittle reaction products, or stresses due to thermal expansion mismatches. Although attempts have been made to insert diffusion barrier or compliant interlayers between the braze material and the ceramic to be joined, these approaches have met with limited success. Thus, it is doubtful that a brazing technique can be developed to satisfy the requirements of fusion energy systems.

3. Diffusion Bonding

Since there are limited metal systems that wet ceramics and due to the thermal expansion mismatch stresses present in many brazed joints, solid state diffusion is also used to join

ceramic materials to each other, or metals, when it is important to preserve the high temperature properties of the ceramics. Generally a metal that reacts forms thermodynamically stable chemical bonds with the ceramic materials to be joined is sandwiched between the surfaces to be joined. The joint forms by diffusion. Variables that effect the quality of diffusion bonded joints are temperature, metal melting temperature, applied pressure (25,26). Generally, the temperature used to form the joint affects the kinetics of the joining reaction. Since diffusion bonding is controlled by diffusion rates it can be time consuming, hence temperature becomes an important variable. Interdiffusion of the metal and ceramic will most likely occur by diffusion the metal into the ceramic. In some cases, however, the phases formed during joining will also vary with the temperature used to form the joint. It has been found, empirically, that the strength of ceramic to metal joints increases with increasing melting point of the metal (27).

Bates et al. (28) bonded silicon carbide to itself by placing a slip of SiC powder on the faying surfaces, cold isostatic pressing (CIP) the pieces together, and sintering the components (temperature, time, and environment not specified). When tested in flexure, these joints exhibited strengths of 140 MPa with a Weibull modulus of 17.0 for one composition of sintered silicon carbide; 351 MPa with a Weibull modulus of 45, for another. The strength of these joints decreased less than 10% when tested at 1530°C. An approach of this type has not been attempted for SiC/SiC composites, however the temperatures that would be required to sinter the silicon carbide slip would be excessively high for SiC/SiC materials. Silicon carbide is typically sintered at above 1500°C, depending on the amount and type of sintering aids used, which would be an unfeasible approach for assembling large scale structures in fusion energy systems. Furthermore, diffusion bonding often requires the application of external pressure during joining which would also be unfeasible for fusion energy system construction.

4. Glassy interlayers

An alternate method to join ceramics without requiring excessively high-temperatures is to use a glassy interlayer between the components to be joined. This method is used commercially to join gas-tight Al_2O_3 envelopes to niobium for sodium vapor lamps (29). Powdered glass or mixtures of glass forming powders can be applied to the surfaces to be joined and heated to obtain mechanical and chemical bonding. Glasses can be made of similar compositions to the base ceramic materials. For example, silicon-oxycarbide and silicon oxy-nitride glasses can be used to bond with silicon carbide and silicon nitride, respectively (3). The composition of glasses can be tailored, or graded near interfaces, to minimize thermal expansion mismatches. In addition, glassy materials typically have low elastic moduli that also reduce residual stresses due to thermal expansion mismatches. A major drawback of glassy materials is that they soften with increasing temperature. Certain compositions of glasses, however, can be devitrified to form crystalline materials known as glass-ceramics. Glass-ceramic materials are typically stronger and tougher, and more heat resistant, than glasses of similar compositions, but their elastic moduli are concomitantly higher.

Ferraris et al. fabricated joints between SiC/SiC composites using borosilicate, boro-aluminosilicate, and barium containing boro-aluminosilicate glasses (30-32). All of the glasses wet the composites and formed joints with minimal porosity. The borosilicate joint was very weak, but the other two glass compositions were reported to be stronger. Ferraris et al. did not report a value of the strength of the joints. Lemoine, Salvo, Ferraris, et al.

investigated other glass compositions and discovered that a zinc-borate glass, also containing MgO , SiO_2 , Al_2O_3 , and Na_2O , wet the surfaces of SiC/SiC readily and penetrated the intrinsic porosity of the composites (33). Unfortunately, the shear strengths of these joints, measured by flexural testing of single and double lap joints was extremely low, approximately 2 MPa. In addition to having poor mechanical properties, boron is not an attractive element in first wall components from a radiological perspective.

5. Cements

Adhesive ceramic joints are usually formed by cement-mortar materials. These materials are a mixture of materials that undergo a variety of low temperature reactions (i.e., hydration, amalgamation, etc.) to form a strongly bonded phase. The suitability of cement type jointing materials for high temperature applications is limited. Certain air-setting materials, usually composed of mixtures of magnesium-alumino-silicates, retain their useful properties up to about $1100^\circ C$. These materials are usually supplied in a solvent and cure by evaporation.

Other cement materials are cured by chemical reactions catalyzed by acids or bases. Phosphate, chloride, and sulfate cement precursors usually cure exothermically, whereas sodium and potassium silicates are non-exothermic. Cements cured by chemical reaction usually offer superior properties relative to those that set due to hydration or evaporation. Cements have been used to join non-oxide ceramics prior to nitride bonding or sinter-HIPping (3, 34).

Recently, amalgams of copper and gallium have been used to join silicon carbide ceramics (35). The base material consists of a mixture of copper and gallium powders that spontaneously alloy when mixed. During amalgamation of copper and gallium there is an increase in volume. To obtain a strong joint with these amalgams it is necessary to utilize joint geometries that have a constrained gap between the parts to be joined. If the gap is filled by the volume increase occurring during amalgamation then the joint will be under residual compression, similar to a joint made by shrink-fitting. The yield strength of the amalgam was approximately 150 MPa at $900^\circ C$. The ability to apply this joining technique without applied temperature and pressure warrants further investigation for fusion energy system applications.

6. In-situ Displacement Reactions

A displacement reaction, between a metal and a ceramic material, involves the exchange of the cation of the ceramic with the metal yielding a new ceramic compound and a metal phase of the original cation. These reactions occur when the new ceramic phase is thermodynamically more stable than the original one, although sometimes heat or energy must be supplied for the reaction to proceed. Not only can novel materials be produced via displacement reactions, but self-reinforced microstructures may also result (36). When the displacement reaction is performed in the region to be joined it is referred to as in situ. In situ displacement reactions have been used to join monolithic silicon carbide components with very good high temperature mechanical properties (37,38).

Rabin joined SiC/SiC to itself using titanium, carbon, and nickel powders applied to the faying surfaces and subsequently hot-pressing, at $1400^\circ C$ under 20 to 50 MPa (37). During hot-pressing, the powders react to form TiC in a Ni matrix. There was evidence of some reaction between the phases in the joint material and the silicon carbide. Due to the large mismatch

in thermal expansion coefficient of the TiC/Ni layer and the SiC/SiC material cracks formed upon cooling. Rabin also joined sintered silicon carbide to itself using an in situ reaction method that formed SiC and MoSi₂ (37). This method required the formation of a porous carbon framework that obtained by pyrolysis of a furfural alcohol resin. Silicon and silicon containing 3% molybdenum were used to infiltrate the porous carbon layer created between the pieces to be joined. Infiltration was conducted at 1400-1460°C. Extremely dense joints, with little free silicon, were obtained. The strength of the joints was 251 ± 61 MPa, when tested in flexure at room temperature.

Henager and Jones have also used in situ displacement reactions to fabricate joints between silicon carbide and itself (38). Powder mixtures of TiC and Si were made into thin tapes, approximately 100 μm thick, by tape casting. The tape cast layers were placed between pieces of silicon carbide and heated to either 1200°C or 1400°C under 20 MPa of compressive stress. The resulting joints consisted of a continuous Ti₃SiC₂ phase containing high aspect ratio and equiaxed SiC particles. The interlaminar shear strength was measured using a modified double edge notched sample in compression. Interlaminar shear stress values of about 35 MPa, at room temperature, were obtained.

A disadvantage of the in-situ displacement reaction technique is that the current methods require application of external heat and pressure during joining that would be unfeasible for large structures. Nevertheless, joints made from in-situ displacement reactions have exhibited equal to or higher strengths than the monolithic ceramics that they have been used to join. The possibility of obtaining tough, self-reinforced joints with similar thermomechanical properties as the materials to be joined warrants further investigation of this approach for components used in fusion energy systems.

7. Preceramic Polymers

A relatively new technique for joining ceramic material has been the use of preceramic polymers (39-47). This approach has been applied mainly to joining of non-oxide ceramics, since many of the traditional methods of ceramic-to-ceramic joining were developed for oxide ceramics. Preceramic polymers are organometallic materials consisting of polymerized hydrocarbon compounds containing various metallic elements. These materials can be readily pyrolyzed to form ceramic materials when heated to temperatures between 800-1400°C. Two commonly used polymers are siloxanes and carboranes. Both polymers convert to silicon oxycarbide materials after pyrolysis. The main advantage of using preceramic polymers is that they can be applied as liquids, slurries, and pastes, and converted to ceramic materials with similar thermomechanical properties as the materials to be joined. Furthermore, conversion of preceramic polymers to silicon carbide joints creates a joint material with the required radiation stability desired in fusion energy system applications.

Colombo obtained joints between pieces of reaction bonded silicon carbide with tensile strengths, measured in flexure at room temperature, of almost 220 MPa and interlaminar shear strengths, also measured at room temperature, of 26.6 MPa (46). These joints were obtained by pyrolysis of a silicone resin at 1200°C without applied pressure. Pyrolysis of a polycarbosilane preceramic precursor failed to create satisfactory joints. The joint formed by pyrolysis of the silicon resin did not react with the reaction bonded silicon carbide and, therefore, acted as an adhesive layer. Yajima also obtained unsatisfactory joints with polycarbosilane materials (39). An understanding of the physical mechanisms that occur

during joining with preceramic precursors may provide an explanation for these observations and lead to improvements in this method of joining.

Sherwood et al. (41) have developed a novel method for joining SiC/SiC using hydro-polycarbosilane resins mixed with chopped fibers and reactive metal filler particles (i.e., silicon). The joints were formed by heating at 1000°C for 1 hour. The method involves cutting the surfaces to be joined so that fibers extend from the surfaces to provide mechanical interlocking with the joining material. Using this technique, butt joints with flexural strengths of between 27 and 55 MPa were obtained. Modification of the joint geometry, by creating an augmented dovetail (with an additional, unimpregnated layer of Nicalon fiber cloth at each surface to be joined), and incorporation of silicon powder led to an increase in the strength value to 103-110 MPa. In addition, Sherwood et al. reported promising preliminary results using a mixture of SiC powders and HPCS to join monolithic silicon carbide (41). The results described above indicate that the use of preceramic polymers to form joints between SiC/SiC and itself is relatively poorly understood, yet exhibits promise for use in fusion energy systems.

8. Reaction Bonding

Another method for obtaining joints consisting of mostly silicon carbide is reaction bonding. Reaction bonding consists of combining silicon, carbon, and sometimes silicon carbide precursors, followed by causing a reaction at elevated temperatures, to form silicon carbide. Since the volume of the products is greater than that of the reactants, the reaction typically can not proceed to completion and residual silicon or porosity remains. Numerous investigators, however, have optimized the composition and microstructure of the reactants to obtain dense silicon carbide products with the least amount of residual silicon (3). In addition, the silicon carbide formed by reaction bonding often interpenetrates with silicon carbide components it is used to join. At elevated temperatures, near the melting point of silicon (1410°C), the silicon can deform plastically. A more severe failure mechanism due to the presence of the residual silicon is also possible. Since the silicon does not wet silicon carbide it will gradually "sweat" out of the structure to the surface and form nodules. These nodules can act as failure origins for brittle fracture. Nevertheless, reaction bonded silicon carbide is an attractive material for joining applications in fusion energy systems.

Rabin developed a technique for joining sintered silicon carbide to itself using layers of SiC and C powders applied to the surfaces to be joined (48). Powders of silicon carbide and carbon were either mixed in a slurry or tape cast. The pieces to be joined were held together and small amounts of silicon metal were placed near the joints. The specimens were heated to either 1400°C and 1460°C and the silicon was drawn into the joint by capillary forces where it reacted to form silicon carbide. The joint material reacted with the silicon carbide specimens to form continuous grains of silicon carbide across the interface. The tape casting technique allowed formation of thin joints, however it was difficult to control the amount of carbon in the tape cast layer. Joints formed from powder slurries had room temperature flexural strengths of 166 ± 30 MPa, whereas joints formed by using tape cast layers had strengths ranging from 222 to 376 MPa, at room temperature. If the tape cast layers were densified, by uniaxial pressing, prior to joining higher strength could be obtained due to the higher initial density of the carbon in the tapes. If the carbon density is too high then the volume increase associated with reaction bonding prohibits transport of silicon and porosity remains. If the carbon density is too low then the reaction will be incomplete and residual silicon will remain.

Anderson et al. modified one of the joining techniques described by Rabin involving pyrolysis of an organic resin to microporous carbon followed by infiltration of aluminum, silicon, and boron powders (42). Although this method does not technically involve preceramic polymers it could be adapted to involve infiltration of a microporous ceramic material formed by pyrolysis of a preceramic polymer. Anderson et al. fabricated joints with room temperature strengths of about 90 MPa, and shear strengths of about 50 MPa (42).

Singh has joined reaction bonded, sintered, and composite silicon carbide using a reaction bonding approach (49-51). Singh's approach consists of making a paste, slurry, or tape of a carbonaceous material and applying this to the surfaces to be joined. The carbonaceous material is cured at 100°C for 15-20 minutes. After curing, the joint is infiltrated with silicon or silicon alloys at 1425°C for 15 minutes. The tensile strength of the joints, measured in flexure, was about 190 MPa and was insensitive to temperature up to 1350°C (50, 51). There was a significant dependency of the joint strength on its thickness. Joints that were approximately 350 μ m thick had strength values of 44 ± 2 MPa. Joints that were 20-55 μ m thick had strength values of about 190 MPa. These results suggest that there are some residual thermal stresses in the thicker joints that are not present in the thinner joint.

The results described above indicate that reaction bonding is also a promising technique for joining monolithic and composite silicon carbide. The major drawback to using reaction bonding to join composites is that the specimen must be heated above the melting point of silicon (1410°C). Fortunately, other metals can be combined with silicon to form lower melting eutectic compounds. Another drawback of reaction bonding, however, is the potential for forming joints with excess silicon. Silicon may transmute to ^{29}Al that has been predicted to prohibit "hands-on" recycling of SiC/SiC (52). Since, there currently are not any techniques for recycling unirradiated SiC/SiC, nor are any likely to be developed given the nature of ceramic materials, this limitation may not be critical.

B. Special Issues Concerning Joining of Silicon Carbide for Fusion Energy Systems

Aside from producing economically viable power, fusion energy systems will be required to operate in a safe and environmentally benign manner over their lifetimes. Therefore, the materials used in these systems will be required to have a variety of unique properties. Consideration of these properties has shown that SiC/SiC composites are extremely attractive first wall materials (53-56). In addition to radiation resistance, mechanical integrity, and desirable thermal properties, SiC/SiC is the only low-activation material that has satisfied design criteria of safety during operation and maintenance, injury due to accidental release, and waste management. To preserve the suitability of SiC/SiC for use in fusion energy systems, the joining method used must also satisfy the conditions of radiation resistance, mechanical integrity, desirable thermal properties, safety during operation and maintenance, injury due to accidental release, and waste management.

The requirements of safety, injury, and waste management have been considered from the perspective of identifying elements that form transmutation products, after exposure to fusion energy system operating conditions, that exceed the accepted limits (57,58). From this point of view, several elements that may potentially be attractive for use in joining are excluded. Nickel, molybdenum, niobium, and cobalt are unacceptable. Since the SiC/SiC materials that are currently available satisfy the safety, injury, and waste management criteria as well as the structural and radiation stability criteria it is logical to conclude that the most suitable

joining material should have a composition and microstructure as close as possible to SiC/SiC. In addition, thermally-induced and elastically-induced mechanical stresses would be minimized by use of a joining material with properties similar to that of the material to be joined.

Since the current designs for fusion energy systems incorporate large SiC/SiC components the use of externally applied pressure, during joining, is unfeasible. In addition, since joining will occur at the construction site of a fusion energy system it is preferable that the joining technique be performed in the ambient environment. The mechanical properties of the currently available SiC/SiC materials degrade above 1200-1400°C due to microstructural instabilities in the fibers. Therefore, the temperature used for joining must be below that which causes degradation of the fibers. In addition, the joining technique must be compatible with the other materials and processes used during assembly of the fusion energy system.

CONCLUSIONS

Numerous methods exist for joining SiC/SiC materials, but most have drawbacks that render them unsuitable for use in fusion energy systems. Mechanical joining may be acceptable in combination with another technique that provides hermetic properties. Brazing is generally unsuitable for the proposed service temperatures, due to the formation of brittle phases and thermal expansion mismatch stresses. Direct diffusion bonding is also unsuitable since the temperatures required to obtain bonding are in excess of those that cause damage to the fibers in SiC/SiC. Glassy interlayers are in early stages of development, but the preliminary values of the strength of these joints are disconcerting. In addition, many of the components of good glass forming compositions may pose neutron activation problems. In situ displacement reactions show promise for forming mechanically reliable joints, but methods must be developed that do not require applied pressure during joining. Preceramic polymers appear very promising, but very little is known about their behavior during joining. Finally, reaction bonding is also capable of providing strong joints for SiC/SiC but has two drawbacks: the use of excessive temperatures, and the presence of residual silicon.

FUTURE WORK

Both from a mechanical and a radiological perspective it is desirable to fabricate joints of compositions as close to pure silicon carbide as possible. Aside from further investigation of joining techniques, analysis of optimum joint geometries is required. Furthermore, evaluation of valid techniques for measuring irradiated and unirradiated mechanical properties of joints is also required. Considering the detailed review presented above, polymer precursor methods are strong candidates for detailed investigation while efforts can be made to remove the limitations of in situ displacement reaction and reaction bonding joining methods.

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