Low Pressure Joining of SiC_f/SiC Composites Using Ti₃AlC₂ or Ti₃SiC₂ MAX Phase Tape

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ABSTRACT

SiC_f/SiC composites were joined using a 60 μm-thick Ti₃AlC₂ or Ti₃SiC₂ MAX phase tape. The filler tape was inserted between the SiC_f/SiC composites containing a 12 wt.% Al₂O₃-Y₂O₃ sintering additive. The joining was performed to a butt-joint configuration at 1600°C or 1750°C in an Ar atmosphere by applying 3.5 MPa using a hot press. Microstructural and phase analyses at the joining interface confirmed the decomposition of Ti₃AlC₂ and Ti₃SiC₂, indicating the joining by solid-state diffusion. The results showed sound joining interface without the presence of cracks. Joining strengths higher than 150 MPa could be obtained for the joints using Ti₃AlC₂ or Ti₃SiC₂ at 1750°C, while those for joined at 1600°C decreased to 100 MPa approximately without the deformation of the joining bodies. The thickness of initial filler tape was reduced significantly after joining because of the decomposition and migration of MAX phase owing to the plasticity at high temperatures.

Key words : SiC_f/SiC composites, Joining, Ti₃AlC₂, Ti₃SiC₂, Tape

1. Introduction

Silicon carbide (SiC) is an attractive high temperature structural material owing to its excellent mechanical, thermal, and chemical properties.¹⁻⁴⁾ In addition, the high resistance under neutron irradiation makes SiC as a best candidate for the structural component of nuclear reactors.⁵⁾ Because a monolithic SiC shows an inherent brittleness, however, SiC fiber-reinforced SiC composite (SiC_f/SiC) has attracted considerable attention to alleviate the brittleness under a mechanical load.⁶⁻¹¹⁾

For many practical applications, SiC_f/SiC needs to be fabricated to large size with complex shape, which is difficult to prepare using a simple hot press technique. Therefore, the development of an adequate joining technology is essential to broaden its applications. Several methods developed so far include the solid-state diffusion bonding,^{12,13)} glass-ceramic bonding,^{14,15)} transient eutectic phase joining,¹⁴⁾ SiC reaction bonding,^{16,17)} and MAX phase joining.¹⁸⁻²⁰⁾ Most studies used SiC monolith as a joining body, while the joining of SiC_f/SiC is more difficult than the joining of SiC monolith. For example, Singh reported the joining of SiC monolith by infiltrating molten silicon and achieved a flexural strength up to 255 MPa.²¹⁾ However, Lewinsohn *et al.* joined SiC_f/SiC composites using the same method and obtained a moderate flexural strength of 78 MPa.¹⁷⁾ Nevertheless, joining strengths higher than 100 MPa are generally needed for practical applications.²²⁾ Accordingly, further

study to obtain higher SiC_f/SiC joining strengths is needed.

With this background, the joining of SiC_f/SiC was performed using 2 types of MAX phases, such as Ti₃AlC₂ and Ti₃SiC₂, because both phases show good mechanical properties as well as high resistance under neutron irradiation.²³⁻²⁸⁾ Both Ti₃AlC₂ and Ti₃SiC₂ are expected to be good filler materials for the joining of SiC_f/SiC by solid-state diffusion owing to their easy decomposition in the presence of SiC at high temperatures.^{29,30)} To the best of the authors' knowledge, there are no reports on the joining of SiC-based materials using Ti₃AlC₂, although the joining using Ti₃SiC₂ MAX phase only for monolithic SiC has been reported.¹⁸⁻²⁰⁾

2. Experimental Procedure

The SiC_f/SiC joining body was fabricated by the electrophoretic infiltration of a matrix slurry, containing SiC and 12 wt.% Al₂O₃-Y₂O₃ sintering additive, into a 2 dimensionally-woven SiC fabric (TyrannoTM-SA grade-3, Ube Industries Ltd., Japan) preform. The SiC fabrics were coated with a 400 nm-thick PyC layer through the decomposition of CH₄ at 1100°C. Fifteen layers of infiltrated SiC fabrics were stacked after inserting the SiC green tapes alternately, which have the same composition with the matrix slurry. Hot pressing was performed at 1750°C and 20 MPa for 2 h in an Ar atmosphere. The resulting SiC_f/SiC with a dimension of 200 × 200 × 3 mm³ showed 94% density, which was cut to 30 × 15 × 3 mm³ for the further joining test. The experimental setup and detailed procedures for SiC_f/SiC fabrication can be found elsewhere.³¹⁻³³⁾ Ti₃AlC₂ and Ti₃SiC₂ (both purchased from Beijing Jinhezhi Materials Co., Ltd., China) with a purity ≥ 98% and a mean particle size of 32

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Fig. 1. Schematic of the (a) joining configuration and (b) illustration for the joining interfaces: A = SiC_f/SiC body, B = joining interface and C = joining filler.

and 21 μm , respectively, were used as the filler materials by casting into a 60 μm -thick green tape.

After polishing the SiC_f/SiC surface to a 1 μm diamond paste, the filler tape was inserted between two SiC_f/SiC bodies to have a butt-joint configuration.¹⁸⁾ The joining sample was placed in a graphite mold after spraying BN powder for easy sample separation from the mold followed by the binder burn-out at 350°C for 2 h in air at a heating rate of 0.5°C/min. Subsequently, joining was performed at 1600 or 1750°C for 1 h under a pressure of 3.5 MPa in an Ar atmosphere using a hot press. The density after joining was calculated by Archimedes' method and compared to that of the samples before joining.

Joined sample was cut into 4 bars having a dimension of 30 × 4 × 3 mm³ using a diamond saw followed by polishing to a 1 μm diamond paste. For the 4-point bending test, a universal testing machine (UTM AG-50E, Shimadzu, Japan) was used with a load speed of 0.5 mm/min. The following equation was used to calculate the flexural strength:

$$\sigma = \frac{3P(L_2 - L_1)}{4ab^2} \quad (1)$$

where σ is the flexural strength (MPa), P is the applied load (N), a is the width (mm), b is the thickness (mm), L_1 is the inner span (mm), and L_2 is the outer span (mm). Three samples for each condition were tested at room temperature. The fractured surfaces were analyzed by a X-ray diffractometer (XRD, X'Pert-PRO MPD, Pan Analytical with 40 kV and 30 mA) using Cu K α radiation ($\lambda = 0.154$ nm) to check the phase generation and transition upon joining along with the morphological analysis by scanning electron microscopy (SEM, Hitachi S-4800, Japan). One remaining sample was used for microstructural and elemental analyses by SEM equipped with energy dispersive X-ray spectrometry (EDS, Horiba EX-250, Japan). The schematic of joining configuration for the sample is shown in Fig. 1.

3. Results and Discussion

From a practical point of view, joining under low pressure

Fig. 2. Digital images of SiC_f/SiC joined using MAX phase filler tape at 1600 and 1750°C, showing the decrease in length after joining at 1750°C.

or pressureless conditions is desirable as far as sufficient joining strength is ensured. Therefore, a low joining pressure of 3.5 MPa was used because pressureless joining revealed a weak joint based on a preliminary test. No noticeable changes in dimensions were observed after joining at 1600°C, while approximately 10% reduction of the sample to the direction of the applied pressure was observed at 1750°C, as shown in Fig. 2. The shrinkage upon joining at 1750°C resulted from the further densification of SiC_f/SiC; the density of SiC_f/SiC before and after joining at 1600°C was similar to 94% approximately, whereas that after joining at 1750°C increased to 98%.

Table 1 lists the flexural strength of the SiC_f/SiC samples joined in this study using different fillers and joining conditions, while the previously reported values for a SiC monolith joint using Ti₃SiC₂ powder or tape are also shown for comparison.¹⁸⁻²⁰⁾ The joining strength of SiC_f/SiC increased with increasing joining temperature, i.e., 100 to 161 MPa using Ti₃AlC₂ and 92 to 178 MPa using Ti₃SiC₂ after joining at 1600 and 1750°C, respectively. Compared to the values reported for monolithic SiC joints using Ti₃SiC₂ tape or pow-

Table 1. Comparison of the Joining Strength of SiC-based Joints Measured in This Study and Previously Reported Values. A Four-Point Bending Test was Used for the Butt-Joint Samples

No.	Filler material and shape	Joining body	Joining condition	Flexural strength (MPa)	Reference
1	Ti ₃ AlC ₂ tape	SiC _f /SiC	HP: 1600°C, 1 h, 3.5 MPa Tape thickness = 60 μm	100.97 ± 4.79	This study
2			HP: 1750°C, 1 h, 3.5 MPa Tape thickness = 60 μm	161.51 ± 12.41	This study
3	Ti ₃ SiC ₂ tape	SiC _f /SiC	HP: 1600°C, 1 h, 3.5 MPa Tape thickness = 60 μm	92.44 ± 9.55	This study
4			HP: 1750°C, 1 h, 3.5 MPa Tape thickness = 60 μm	170.88 ± 7.52	This study
5	Ti ₃ SiC ₂ powder	SiC monolith	HP: 1600°C, 30 min, 20 - 40 MPa	110.4	Dong <i>et al.</i> ¹⁸⁾
6			SPS**: 1600°C, 5 min, 30 MPa	~ 33	Dong <i>et al.</i> ¹⁹⁾
7	Ti ₃ SiC ₂ tape	SiC monolith	SPS: 1500°C, 5 min, 50 MPa Tape thickness = 60 μm	99.1	Zhou <i>et al.</i> ²⁰⁾
8			SPS: 1600°C, 5 min, 50 MPa Tape thickness = 60 μm	79.3	

*HP: hot press, **SPS: spark plasma sintering

der, this study revealed a comparable or even higher joining strength despite SiC_f/SiC was used as the joining body. Considering the lower pressure of 3.5 MPa in the present study than those of previous studies (20 - 50 MPa), temperature is believed to be a more important factor for the joining strength than the applied pressure.

Figure 3(a) and (b) present XRD patterns of the fractured surface of SiC_f/SiC joint using a Ti₃AlC₂ or Ti₃SiC₂ filler, respectively, at two different temperatures. TiAl and TiSi₂ intermetallic compounds for the Ti₃AlC₂ and Ti₃SiC₂ fillers, respectively, were detected in the fractured surface, indicating the corresponding phase generation during the joining process. Relative peak height of the intermetallic compounds was increased along with the decrease in MAX phase peak height in Fig. 3, suggesting the intermetallic compounds were formed by the decomposition of MAX phase.

According to previous report on the high temperature stability of Ti₃AlC₂ MAX phase, Ti₃AlC₂ can easily decompose to TiC and Ti₂AlC at 1400°C by the following reaction:³⁴⁾

However, Ti₂AlC was not detected in the fractured surface because Ti₂AlC is not a stable compound above 1400°C,³⁵⁾ thus further decomposition of Ti₂AlC to Ti, Al, and TiC might be occurred by the following reaction:

Because Ti and Al are very reactive elements at high temperatures, they can react each other to form TiAl intermetallic compound, where the Gibbs formation free energy is highly negative, i.e., -46.58 and -42.5 kJ/mol at 1600°C and 1750°C, respectively. This exothermic reaction for the formation of TiAl may enhance the solid-state diffusion for the joining, providing a good bonding.³⁶⁾ The presence of TiB₂ compound in Fig. 3(a) can be explained by the reaction

Fig. 3. XRD patterns of the joining SiC_f/SiC interfaces using (a) Ti₃AlC₂ and (b) Ti₃SiC₂ MAX phases at 1600 and 1750°C.

between Ti from Ti₃AlC₂ and B from BN spray, as shown with the following reaction:³⁷⁾

where TiN can be transformed further to TiB₂ in the presence of BN by the following reaction:³⁸⁾

Because the reaction (4) and (5) are very spontaneous at > 1500°C based on their highly negative Gibbs formation free energy, TiN was not detected in the final product. During the joining at 1600 or 1750°C, however, some metals and intermetallic compounds might be participated as liquid phase for the above reactions because of their relative low melting point (T_m), including, Ti (T_m = 1668°C), Al (T_m = 660°C), TiAl (T_m = 1460°C), and Ti₂AlC (T_m = 1625°C).

Similarly, Ti₃SiC₂ may decompose into TiC_x and Si by the selective outward diffusion of Si at temperature > 1400°C, according to the following reaction:²⁹⁾

Furthermore, the formation of Si (T_m = 1414°C) can enhance the decomposition of Ti₃SiC₂ by forming TiSi₂ (T_m = 1470°C) and SiC, based on the following reaction:³⁹⁾

According to the reaction equations (2), (3) and (6), the decomposition of both Ti₃AlC₂ and Ti₃SiC₂ resulted in the formation of TiC as a final product. Even though the TiC peaks in Fig. 3 are elusive because the TiC peak positions coincide with those for SiC, the presence of TiC was confirmed further by the SEM and EDS results, as shown in Fig. 4 and Table 2, respectively.

Figure 4 presents SEM images of the SiC_f/SiC joining region using a Ti₃AlC₂ or Ti₃SiC₂ MAX phase after joining at 1600 and 1750°C for 1 h, where the joining region could be identified from the SiC_f/SiC body by different contrast. All showed a sound joining morphology without the formation of cracks at the interface as well as joining region. However, a few small pores are found after joining using Ti₃SiC₂ at 1750°C, as shown in Fig. 4(d), owing to the decomposition of MAX phase.^{40,41)} On the other hand, the absence of pores in case of using Ti₃AlC₂ filler might be attributed to the forma-

tion of TiAl metallic compound, which could fill the pores due to its inherent ductility. One notable thing in Fig. 4 is the deformation of the initial round-shaped SiC fiber into the polygonal shape upon the joining at 1750°C, while the original round shape was maintained after joining at 1600°C. The deformation of SiC fibers during the initial hot pressing at 1750°C, 20 MPa for 2 h was not significant, while a polygonal-shaped fibers are observed after joining at 1750°C, 3.5 MPa for 1 h, as shown in Fig. 4(b) and (d). This enhanced deformation of SiC fibers at 1750°C during joining might be attributed to the longer exposure at high temperature or concentrated pressure effect, which was applied to the parallel direction to the fiber. On the other hand, the pressure was applied to the perpendicular direction to the woven fabric during initial hot pressing using a large size of 200 × 200 × 3 mm³ SiC_f/SiC, in which the fibers can sustain against the external pressure. The deformation of the microstructure by the combined effects of longer exposure at high temperature and pressure applied to the parallel direction to the fibers can explain the shrinking of the sample and increase in the density after joining at 1750°C, as explained above. The other notable thing in Fig. 4 is the significant decrease in filler thickness from its initial 60 μm-thick tape, which decreases further by increasing the joining temperature from 1600 to 1750°C. The degree of reduction in tape thickness was slightly higher with Ti₃SiC₂ than Ti₃AlC₂, where both tape thickness decreased less than 10 μm after joining at 1750°C from the initial 60 μm, showing a linear shrinkage higher than 80%. Because this shrinkage rate exceeded the typical linear shrinkage of the green tape around 30% after the high temperature treatment, this implies the decomposition of both MAX phases followed by the solid-state diffusion of filler elements into the SiC_f/SiC body.

Table 2 lists the results of EDS elemental analysis for the points marked in Fig. 4. According to the results, the dark phases marked with “A” and “B” in the joining region using Ti₃AlC₂ filler revealed the presence of approximately 27 at.% Si. Because Ti₃AlC₂ does not contain Si, this indicates the inward solid-state diffusion of Si from the SiC_f/SiC bodies into the Ti₃AlC₂ joining region. Moreover, a small needle-shaped phase with different contrast, pointed by the letter “C” in Fig. 4(b), is TiAl intermetallic compound based on its

Table 2. Summary of the EDS Elemental Analysis Results for the Points Marked in Fig. 4. The Values are Shown in Atomic %

Point	Ti	Si	Al	C	Y	O
A	8.34	28.71	0.23	62.71	-	-
B	4.20	26.08	-	69.72	-	-
C	52.89	-	47.11	-	-	-
D	43.72	1.10	-	55.18	-	-
E	4.08	29.41	-	66.50	-	-
F	-	5.90	21.97	-	16.76	55.37
G	35.64	4.90	-	59.46	-	-
H	2.93	20.51	-	76.56	-	-

Fig. 4. SEM images of the joining region for SiC/SiC joints using (a) Ti_3AlC_2 at 1600°C, (b) Ti_3AlC_2 at 1750°C, (c) Ti_3SiC_2 at 1600°C, and (d) Ti_3SiC_2 at 1750°C.

48% Al and 52% Ti composition, which agrees to the XRD results shown in Fig. 3(a).

The migration of bright Ti_3AlC_2 and Ti_3SiC_2 filler phases along the voids in SiC/SiC at the joining interface can be observed in Fig. 4(a) and (c), especially marked with “D” in Fig. 4(c). This is due to the high temperature plasticity of Ti_3AlC_2 and Ti_3SiC_2 MAX phases at above 1200°C under a pressure,^{42,43} which can improve the joining property by eliminating pores and bridging the filler and body. There are many small dark phases in the joining region when the Ti_3SiC_2 tape was used as a filler, as shown in Fig. 4(c). These are estimated as SiC, which was formed by the decomposition of Ti_3SiC_2 , according to the reaction (7). However, the bright phase marked with “F” in the SiC/SiC region is the segregated liquid-phase $\text{Al}_2\text{O}_3\text{-Y}_2\text{O}_3$ sintering additive, based on its compositional analysis shown in Table 2. In addition, the phase marked with “G” in Fig. 4(d) with slightly different contrast is confirmed as TiC phase, based on its atomic composition in Table 2.

The joining mechanism using Ti_3AlC_2 and Ti_3SiC_2 filler is based on the decomposition of MAX phases followed by solid-state diffusion and high temperature plasticity, as explained above. However, the degree of decomposition of MAX phase is reported to be affected by atmosphere, where the presence of SiC seems to be very important for easy decomposition. For example, Bentzel *et al.*²⁹ found more enhanced decomposition of Ti_3AlC_2 , and Dong *et al.*¹⁹ detected faster decomposition of Ti_3SiC_2 in the presence of SiC than the absence of SiC at $\geq 1300^\circ\text{C}$. Therefore, the decomposition of MAX phases seemed to be triggered at the

joining interface,^{19,20} which has a Si-rich environment owing to the contact with SiC/SiC. According to the literatures, Ti_3AlC_2 transforms easily to $\text{Ti}_3\text{Al}(\text{Si})\text{C}_2$ upon the inward diffusion of Si ions because of the smaller Si ionic size than Al along with the low Al vacancy formation energy in Ti_3AlC_2 .⁴⁴⁻⁴⁶ Furthermore, Ti_3SiC_2 and $\text{Ti}_3\text{Al}(\text{Si})\text{C}_2$ can decompose into TiC upon the loss of Al and Si, where the decomposition of Ti_3AlC_2 and Ti_3SiC_2 to TiC is reported to be enhanced in C-rich environment due to its poor carburization resistance.^{29,47}

To verify the elemental diffusion upon the joining of SiC/SiC using Ti_3AlC_2 and Ti_3SiC_2 filler, Fig. 5 presents the EDS elemental mapping results at the joining region for the area shown with rectangle in Fig. 4(b) and (d), respectively, revealing the distribution of Ti, Al, Si and C element. It shows that Al has the highest degree of diffusion due to its high vapor pressure and low bonding strength, while Ti reveals the lowest degree of diffusion due to the strong covalent bonding with C in Ti_3AlC_2 along with larger ionic size, as shown in Fig. 5(a) - (d). Moreover, Fig. 5(c) shows the presence of Si in the Ti_3AlC_2 filler region, indicating the solid-state diffusion of Si from the SiC/SiC bodies. Because the MAX phase has a layered structure of two adjacent Ti-C-Ti-C-Ti ($\text{TiC}_{0.67}$) covalent bonding chain, where Al or Si ions intercalated in between the layers, the Al or Si can diffuse easily into the MAX phases.^{48,49} The distribution of Ti, Si and C elements in the Ti_3SiC_2 joining region shown in Fig. 5(e) - (g) is similar to that of Ti_3AlC_2 . This temperature-dependent ionic diffusion confers the high joining strength to the SiC/SiC joining, which increases with the increase in

Fig. 5. Results of the EDS elemental mapping for the SiC_f/SiC joint using (a) - (d) Ti₃AlC₂ and (e) - (g) Ti₃SiC₂ for the area shown in Fig. 4(b) and (d), respectively.

temperature owing to the enhanced solid-state diffusion. However, the significant increase in the joining strength by increasing the temperature from 1600°C to 1750°C, as

shown in Table 1, may not only be attributed to the solid-state diffusion but also be affected by the liquid-phase Al₂O₃-Y₂O₃ sintering additive in the SiC_f/SiC bodies. It is

Fig. 6. Typical fractured surface of the SiC_f/SiC samples joined using Ti₃AlC₂; top-view joined at (a) 1600°C and (b) 1750°C, and side-view joined at (c) 1600°C and (d) 1750°C.

believed that the liquid phase at the joining interface plays a crucial role in promoting the bonding by offering a rapid diffusion path for atomic migration.⁵⁰⁾

Figure 6 shows the typical fractured surface of the SiC_f/SiC samples joined using Ti₃AlC₂ at 1600 and 1750°C. The top-view image for the fractured surface joined at 1600°C in Fig. 6(a) reveals a relatively smooth surface, showing the bare SiC_f/SiC body owing to the fracturing along the joining interface. On the other hand, the fractured surface joined at 1750°C in Fig. 6(b) shows rough surface because of the strong attachment of Ti₃AlC₂ filler onto the SiC_f/SiC body. The side-view image for the sample joined at 1600°C in Fig. 6(c) shows a flat surface, while that joined at 1750°C shows rough surface along with the presence of adjoined SiC fibers. Therefore, the joining of SiC_f/SiC using Ti₃AlC₂ filler at 1600°C is desirable to minimize the damage on the SiC fibers, while the joining should be performed at 1750°C to obtain higher joining strength although the deformation of the SiC_f/SiC body needs to be minimized by increasing the density before joining in this case. However, further experiments are needed to find an optimal condition which ensures the requirements for practical applications.

4. Conclusions

The joining of SiC_f/SiC composites was performed using a Ti₃AlC₂ or Ti₃SiC₂ MAX phase tape at 1600 or 1750°C under 3.5 MPa pressure using a hot press. The joining flexural strength for a butt-joint SiC_f/SiC increased with increasing the joining temperature, i.e., 100 to 161 MPa for Ti₃AlC₂ and 92 to 178 MPa for Ti₃SiC₂ filler after joining at 1600 and 1750°C, respectively. This high joining strength was explained by the elemental diffusion upon the decomposition and high temperature plasticity of the MAX phases along with the effects of Al₂O₃-Y₂O₃ liquid phase sintering additive added to the SiC_f/SiC joining body. To explain the decomposition mechanism of Ti₃AlC₂ and Ti₃SiC₂ MAX phases, the phases generated during the high temperature treatment were confirmed using XRD and EDS mapping results along with the possible reaction equations. The significant decrease in the filler tape thickness upon joining supported the decomposition of the MAX phases, which was enhanced by the presence of SiC. Even though the deformation of SiC_f/SiC was observed for the joining at 1750°C, the joining at this temperature was suggested owing to the significant improvement in joining strength up to 178 MPa and strong interfacial bonding showing a fracturing through the SiC_f/SiC joining bodies rather than the interface.

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REFERENCES

1. Y. K. Seo, Y. W. Kim, T. Nishimura, and W. S. Seo, "High-Temperature Strength of a Thermally Conductive Silicon Carbide Ceramic Sintered with Yttria and Scandia," *J. Eur. Ceram. Soc.*, **36** [15] 3755-60 (2016).
2. F. Rodríguez-Rojas, A. L. Ortiz, F. Guiberteau, and M. Nygren, "Anomalous Oxidation Behaviour of Pressureless Liquid-Phase-Sintered SiC," *J. Eur. Ceram. Soc.*, **31** [13] 2393-400 (2011).
3. V. M. Candelario, O. Borrero-López, F. Guiberteau, R. Moreno, and A. L. Ortiz, "Sliding-Wear Resistance of Liquid-Phase-Sintered SiC Containing Graphite Nanodispersoids," *J. Eur. Ceram. Soc.*, **34** [10] 2597-602 (2014).
4. E. Ciudad, E. Sánchez-González, O. Borrero-López, F. Guiberteau, M. Nygren, and A. L. Ortiz, "Sliding-Wear Resistance of Ultrafine-Grained SiC Densified by Spark Plasma Sintering with 3Y₂O₃ + 5Al₂O₃ or Y₃Al₅O₁₂ Additives," *Scr. Mater.*, **69** [8] 598-601 (2013).
5. L. L. Snead, T. Nozawa, Y. Katoh, T. S. Byun, S. Kondo, and D. A. Petti, "Handbook of SiC Properties for Fuel Performance Modeling," *J. Nucl. Mater.*, **371** [1] 329-77 (2007).
6. Y. Zhou, W. C. Zhou, F. Luo, and D. M. Zhu, "Effects of Dip-Coated BN Interphase on Mechanical Properties of SiC_f/SiC Composites Prepared by CVI Process," *Trans. Nonferrous Met. Soc. China*, **24** 1400-6 (2014).
7. K. Yoshida, H. Akimoto, T. Yano, M. Kotani, and T. Ogasawara, "Mechanical Properties of Unidirectional and Crossply SiC_f/SiC Composites Using SiC Fibers with Carbon Interphase Formed by Electrophoretic Deposition Process," *Prog. Nucl. Energy*, **82** 148-52 (2015).
8. J. Yin, S. H. Lee, L. Feng, Y. Zhu, X. Liu, and Z. Huang, "Fabrication of SiC_f/SiC Composites by Hybrid Techniques of Electrophoretic Deposition and Polymer Impregnation and Pyrolysis," *Ceram. Int.*, **42** [14] 16431-35 (2016).
9. Y. Mu, W. Zhou, Y. Hu, D. Ding, F. Luo, and Y. Qing, "Enhanced Microwave Absorbing Properties of 2.5D SiC_f/SiC Composites Fabricated by a Modified Precursor Infiltration and Pyrolysis Process," *J. Alloys Compd.*, **637** 261-66 (2015).
10. R. Usukawa, H. Oda, and T. Ishikawa, "Conversion Process of Amorphous Si-Al-C-O Fiber into Nearly Stoichiometric SiC Polycrystalline Fiber," *J. Korean Ceram. Soc.*, **53** [6] 610-14 (2016).
11. T. Ishikawa and H. Oda, "Structural Control Aiming for High-performance SiC Polycrystalline Fiber," *J. Korean Ceram. Soc.*, **53** [6] 615-21 (2016).
12. S. Grasso, P. Tatarko, S. Rizzo, H. Porwal, C. Hu, Y. Katoh, M. Salvo, M. J. Reece, and M. Ferraris, "Joining of β -SiC by Spark Plasma Sintering," *J. Eur. Ceram. Soc.*, **34** [7] 1681-86 (2014).
13. Y. I. Jung, J. H. Park, H. G. Kim, D. J. Park, J. Y. Park, and W. J. Kim, "Effect of Ti and Si Interlayer Materials on the Joining of SiC Ceramics," *Nucl. Eng. Technol.*, **48** [4] 1009-14 (2016).
14. M. Ferraris, M. Salvo, V. Casalegno, A. Ciampichetti, F.

- Smeacetto, and M. Zucchetti, "Joining of Machined SiC/SiC Composites for Thermonuclear Fusion Reactors," *J. Nucl. Mater.*, **375** [3] 410-15 (2008).
15. M. Ferraris, M. Salvo, V. Casalegno, S. Han, Y. Katoh, H. C. Jung, T. Hinoki, and A. Kohyama, "Joining of SiC-Based Materials for Nuclear Energy Applications," *J. Nucl. Mater.*, **417** [1] 379-82 (2011).
 16. H. C. Jung, Y. H. Park, J. S. Park, T. Hinoki, and A. Kohyama, "R&D of Joining Technology for SiC Components with Channel," *J. Nucl. Mater.*, **386-388** 847-51 (2009).
 17. C. A. Lewinsohn, M. Singh, T. Shibayama, T. Hinoki, M. Ando, Y. Katoh, and A. Kohyama, "Joining of Silicon Carbide Composites for Fusion Energy Applications," *J. Nucl. Mater.*, **283-287** 1258-61 (2000).
 18. H. Dong, S. Li, Y. Teng, and W. Ma, "Joining of SiC Ceramic-Based Materials with Ternary Carbide Ti₃SiC₂," *Mater. Sci. Eng. B*, **176** [1] 60-4 (2011).
 19. H. Dong, Y. Yu, X. Jin, X. Tian, W. He, and W. Ma, "Microstructure and Mechanical Properties of SiC-SiC Joints Joined by Spark Plasma Sintering," *Ceram. Int.*, **42** [13] 14463-68 (2016).
 20. X. Zhou, Y. H. Han, X. Shen, S. Du, J. Lee, and Q. Huang, "Fast Joining SiC Ceramics with Ti₃SiC₂ Tape Film by Electric Field-Assisted Sintering Technology," *J. Nucl. Mater.*, **466** 322-27 (2015).
 21. M. Singh, "A Reaction Forming Method for Joining of Silicon Carbide-Based Ceramics," *Scr. Mater.*, **37** [8] 1151-54 (1997).
 22. G. Aiello, L. Giancarli, H. Golfier, and J. F. Maire, "Modeling of Mechanical Behavior and Design Criteria for SiC_f/SiC Composite Structures in Fusion Reactors," *Fusion Eng. Des.*, **65** [1] 77-88 (2003).
 23. A. Zhou, C. Wang, and Y. Hunag, "Synthesis and Mechanical Properties of Ti₃AlC₂ by Spark Plasma Sintering," *Synthesis (Stuttg.)*, **8** 3111-15 (2003).
 24. Y. Zhou and Z. Sun, "Temperature Fluctuation/Hot Pressing Synthesis of Ti₃SiC₂," *Simulation*, **35** [17] 4343-46 (2000).
 25. X. Xu, Y. Li, B. Mei, J. Zhu, H. Liu, and J. Qu, "Study on the Isothermal Oxidation Behavior in Air of Ti₃AlC₂ Sintered by Hot Pressing," *Sci. China, Ser. E Technol. Sci.*, **49** [5] 513-20 (2006).
 26. J. Xie, X. Wang, A. Li, F. Li, and Y. Zhou, "Corrosion Behavior of Selected M_{n+1}AX_n Phases in Hot Concentrated HCl Solution: Effect of A Element and MX Layer," *Corros. Sci.*, **60** 129-35 (2012).
 27. E. N. Hoffman, D. W. Vinson, R. L. Sindelar, D. J. Tallman, G. Kohse, and M. W. Barsoum, "MAX Phase Carbides and Nitrides: Properties for Future Nuclear Power Plant In-Core Applications and Neutron Transmutation Analysis," *Nucl. Eng. Des.*, **244** 17-24 (2012).
 28. H. Lee, D. Kim, Y. S. Jeong, J. Y. Park, and W. Kim, "Formation of Ti₃SiC₂ Interphase of SiC Fiber by Electrophoretic Deposition Method," *J. Korean Ceram. Soc.*, **53** [1] 87-92 (2016).
 29. G. W. Bentzel, M. Ghidui, B. Anasori, and M. W. Barsoum, "On the Interactions of Ti₂AlC, Ti₃AlC₂, Ti₃SiC₂ and Cr₂AlC with Silicon Carbide and Pyrolytic Carbon at 1300°C," *J. Eur. Ceram. Soc.*, **35** [15] 4107-14 (2015).
 30. C. S. Park, F. Zheng, S. Salamone, and R. K. Bordia, "Processing of Composites in the Ti-Si-C System," *J. Mater. Sci.*, **36** [13] 3313-22 (2001).
 31. H. W. Yu, P. Fitriani, S. Lee, J. Y. Park, and D. H. Yoon, "Fabrication of the Tube-Shaped SiC_f/SiC by Hot Pressing," *Ceram. Int.*, **41** [6] 7890-96 (2015).
 32. G. Y. Gil and D. H. Yoon, "Densification of SiC_f/SiC Composites by Electrophoretic Infiltration Combined with Ultrasonication," *J. Ceram. Process. Res.*, **12** [4] 371-75 (2011).
 33. P. Yonathan, J. H. Lee, D. H. Yoon, W. J. Kim, and J. Y. Park, "Improvement of SiC_f/SiC Density by Slurry Infiltration and Tape Stacking," *Mater. Res. Bull.*, **44** [11] 2116-22 (2009).
 34. W. K. Pang, I. M. Low, B. H. O'Connor, A. J. Studer, V. K. Peterson, Z. M. Sun, and J. P. Palmquist, "Comparison of Thermal Stability in MAX 211 and 312 Phases," *J. Phys. Conf. Ser.*, **251** [1] 12025 (2010).
 35. M. Stumpf, T. Fey, and P. Greil, "Thermochemical Calculations of the Stability of Ti₃AlC in Various Atmospheres," *J. Ceram. Sci. Tech.*, **7** [3] 223-28 (2016).
 36. S. Sen, M. Lake, N. Kroppen, P. Farber, J. Wilden, and P. Schaaf, "Self-Propagating Exothermic Reaction Analysis in Ti/Al Reactive Films Using Experiments and Computational Fluid Dynamics Simulation," *Appl. Surf. Sci.*, **396** 1490-98 (2017).
 37. J. S. Byun, J. H. Shim, and Y. W. Cho, "Influence of Stearic Acid on Mechanochemical Reaction between Ti and BN Powders," *J. Alloys Compd.*, **365** [1] 149-56 (2004).
 38. P. Rogl, "Materials Science of Ternary Metal Boron Nitrides," *Int. J. Inorg. Mater.*, **3** [3] 201-9 (2001).
 39. N. F. Gao, Y. Miyamoto, and D. Zhang, "On Physical and Thermochemical Properties of High-Purity Ti₃SiC₂," *Mater. Lett.*, **55** [1] 61-6 (2002).
 40. M. W. Barsoum, "The Topotactic Transformation of Ti₃SiC₂ into a Partially Ordered Cubic Ti(C_{0.67}Si_{0.06}) Phase by the Diffusion of Si into Molten Cryolite," *J. Electrochem. Soc.*, **146** [10] 3919-23 (1999).
 41. J. Emmerlich, D. Music, P. Eklund, O. Wilhelmsson, U. Jansson, J. M. Schneider, H. Högberg, and L. Hultman, "Thermal Stability of Ti₃SiC₂ Thin Films," *Acta Mater.*, **55** [4] 1479-88 (2007).
 42. H. Zhang, X. H. Wang, P. Wan, X. Zhan, and Y. C. Zhou, "Insights into High-Temperature Uniaxial Compression Deformation Behavior of Ti₃AlC₂," *J. Am. Ceram. Soc.*, **98** [10] 3332-37 (2015).
 43. Z. F. Zhang, Z. M. Sun, and H. Hashimoto, "Deformation and Fracture Behavior of Ternary Compound Ti₃SiC₂ at 25 - 1300°C," *Mater. Lett.*, **57** [7] 1295-99 (2003).
 44. X. Yin, M. Li, J. Xu, J. Zhang, and Y. Zhou, "Direct Diffusion Bonding of Ti₃SiC₂ and Ti₃AlC₂," *Mater. Res. Bull.*, **44** [6] 1379-84 (2009).
 45. X. H. Yin, M. S. Li, T. P. Li, and Y. C. Zhou, "Diffusion Bonding of Ti₃AlC₂ Ceramic via a Si Interlayer," *J. Mater. Sci.*, **42** [17] 7081-85 (2007).
 46. H. Wang, H. Han, G. Yin, C. Y. Wang, Y. Y. Hou, J. Tang, J. X. Dai, C. L. Ren, W. Zhang, and P. Huai, "First-Principles Study of Vacancies in Ti₃SiC₂ and Ti₃AlC₂," *Materi-*

- als*, **10** [2] 103 (2017).
47. R. Radhakrishnan, J. J. Williams, and M. Akinc, "Synthesis and High-Temperature Stability of Ti_3SiC_2 ," *J. Alloys Compd.*, **285** [1] 85-8 (1999).
48. Y. Xu, X. Bai, X. Zha, Q. Huang, J. He, K. Luo, Y. Zhou, T. C. Germann, J. S. Francisco, and S. Du, "New Insight into the Helium-Induced Damage in MAX Phase Ti_3AlC_2 by First-Principles Studies," *J. Chem. Phys.*, **143** [11] 114707 (2015).
49. Y. Zhou and Z. Sun, "Crystallographic Relations between Ti_3SiC_2 and TiC ," *Mater. Res. Innovations*, **3** [5] 286-91 (2000).
50. R. M. German, P. Suri, and S. J. Park, "Review: Liquid Phase Sintering," *J. Mater. Sci.*, **44** [1] 1-39 (2009).