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AUTHOR(S):

Suh, Min-Soo; Hinoki, Tatsuya; Kohyama, Akira

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EROSIVE WEAR MECHANISM OF NEW SiC/SiC COMPOSITES BY SOLID PARTICLES

Min-Soo Suh

Graduate School of Energy Science, Kyoto University

Gokasho, Uji, Kyoto 611-0011, Japan

Tatsuya Hinoki

Institute of Advanced Energy, Kyoto University

Gokasho, Uji, Kyoto 611-0011, Japan

Akira Kohyama

Institute of Advanced Energy, Kyoto University

Gokasho, Uji, Kyoto 611-0011, Japan

ABSTRACT

Solid-particle erosive wear test by impinging SiC powders was carried out at room temperature over a range of median particle sizes of 425–600 μm , speed of 100 m/s and impact angle of 90° by wear measurements and scanning electron microscopy. Erosive wear behaviour was examined on newly fabricated NITE SiC/SiC composites and two commercial composites by CVI and NITE fabrication route. Microstructural observation was performed to examine the correlation between erosive wear behaviours and fabrication impurities. Conspicuous defects were observed in the prototype materials as the forms of porosity, fibre deformation, residual oxide, PyC deformation, PyC cleavage, and, etc. Erosive wear behaviour was rather serious in prototype of fabricated composites, which employ Pre SiC-fibre and phenolic resin. Two dominant erosive wear mechanisms were observed, one is delamination of constituents mainly caused by erosive crack propagation. Another is

fragmentation and detachment of constituents, which usually resulted from erosive impact. A unit size of delamination was the most decisive factor on wear volume. Bonding strength of each constituent was mostly affected by various forms of porosities. Therefore, fundamental cause and consequent results will be carefully elucidated. In addition, to reduce the dominant wear by improving the fabrication conditions, the correlation of microstructural defect and wear behaviour was investigated. The final product of cost effective composite shows over 2.5times wear resistance in comparison to commercial CVI composite. Consequently, by controlling the fabrication impurities, the improvements have been successfully made for a new fabrication technique, as a result, the known defects are rarely observed in final product. Schematic wear model of erosive wear mechanisms are proposed for the newly fabricated SiC/SiC composites under particle erosion.

1. INTRODUCTION

Considerable efforts have been given in the evaluation of a SiC or erosion related ceramic and ceramic composite materials [1-42] under engineering components in such applications as gas turbine parts, sealing bearings, and burner parts [43-63] where all these applications may involve with solid-particle impact and erosive wear due to the necessity of a knowledge regarding behaviours and mechanisms before it can be used with confidence. However, most are focused on particulate composites and only a few works can be found for advanced fibre-reinforced SiC/SiC composites [41-42, 61-63], and particularly some in impact and erosive wear [59-63]. Continuous SiC fibre-reinforced SiC matrix (SiC_f/SiC) composites are a promising candidate for a structural application, particularly in severe conditions such as high temperature and wear resistant environments [59-73]. It is well known that SiC has one of the highest hardness of all single-phase ceramics, moreover, possesses fascinating performance in various conditions [61-73]. Brittle behaviour is the dominant failure factor for most ceramics, but SiC_f/SiC composites have solved most of the inherent brittle issue. It is also known as one of the most advanced composite material systems due to the commercial availability as well as

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3 promising mechanical properties in elevated temperature. The use of SiC_f/SiC composites such as
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5 combustor liners and turbine vanes provides the potential of improving next-generation turbine engine
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7 performance, through lower emissions and higher cycle efficiency, relative to today's use of super
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9 alloy in high temperature components. The demand of the new advanced materials is increasing,
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11 especially in the recent high-efficiency advanced energy system and/or severe environments, at the
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13 same time the understanding of wear mechanisms can lead to improve material performance and also
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15 essential to design advanced tribosystems.
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20 SiC_f/SiC composite is composed mainly by matrix, fibre, and matrix-fibre interface as a
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22 constituent part, which follows the definition of composite. A significant progress has been described
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24 in our previous works [65-72]. In case of the highly qualified grade SiC_f/SiC composite developed in
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26 Kyoto University, the Tyranno SATM grade fibre and the pyrolytic carbon (PyC) interface by CVD
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28 route are employed as fibre-reinforcement and fibre-interface, respectively. The mechanical properties
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30 are promising due to fascinating microstructures e.g. near-full dense, on-demanded distinct thickness
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32 of the interface, high crystallized grains, stoichiometric compositions, and no residual carbon or
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34 silicon area (see figure 1). State of the art in SiC/SiC composites has solved most of the potential
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36 issues of near-net shaping and machining, joining technology, and evaluation technology [73-90].
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38 There are no doubts that SiC/SiC composites are at the forefront of advanced materials technology and
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40 prime candidates for structural material in severe environments. However, it still has issues of brittle
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42 reliability and extremely high cost due to the complication of many complex processes for production.
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Figure 1. High densification and crystallization of high-qualified grade SiC_f/SiC composite.

A novel cost effective fabrication on SiC/SiC composites (the rest is omitted as a new SiC/SiC composite) has been developed for high erosion resistance. To accomplish both cost issues and foreign object damage (FOD) resistance, Pre-SiC fibre was employed as fibre-reinforcement with adopting a new phenolic resin as fibre-interface, in particular to substitute CVD coated PyC interface. In order to investigate the dominant wear mechanism correlated to crucial parameters of material fabrication to answer the purpose, a number of new SiC/SiC composites were fabricated. Wear control by improvement of materials and design of operating conditions has become a strong need for the advanced and reliable technology in order to ensure the consequence of durability and reliability issues caused by wear. This study intended to improve not only erosion performance but material properties by following methods. Optimization of the fabrication conditions of prototype SiC/SiC composites through controlling the microstructural defects was accomplished by analysing the wear behaviours of all constituents of composites (matrix, fibre and interface).

2. EXPERIMENTAL PROCEDURES

2.1. Material preparation

Nano-powder Infiltration and Transient Eutectoid (NITE) process has been selected to fabricate SiC/SiC composites for superior characteristics [67-91]. It is a highly optimized liquid phase sintering

(LPS) process, available in commercial. Figure 2 shows the brief concept and procedures regarding manufacture of NITE process. Fabrics are prepared as a form of prepreg sheet after interface pre-coating by the methods explained in figure 3 for employing the PyC interface around the fibre tows. The prepreg is impregnated with the matrix precursor by passing through the slurry. A powder mixture of over 90wt% SiC and below 10wt% of sintering additives was prepared by milling process for raw material of slurry. To make a green body, the prepreg sheet is cut into a demanded size, stacked up in desired orientation, and warm pressed in a certain temperature. A burnout process was carried out to eliminate the organic impurities out of the sample specimen resulting in almost near-full dense composite. Finally, hot-pressed into a dimension of on-demanded size, in this study 40 mm x 20 mm sized plate was fabricated, under Ar atmosphere at 1850 °C, applying 20 MPa of load by a graphite mould. Figure 3 illustrates major differences of fibre coating process in comparison of pre-existing method. Generally, the CVD coating produces on-demanded distinct and homogeneous thickness of coating layer, in opposite a large amount of time and processing complication is inevitable. According to the previous studies the porosity is one of a dominant factor on material performance against erosive wear [65-71]. The focus of fabrication was applying the easiest and cheapest coating method as the substitution of the CVD coating, nonetheless to fabricate distinct interface between the matrix and fibre. This new coating method using a phenolic resin needs the following procedures, infiltration of phenolic resin into the fibre tows, thickness control, and pyrolysis of phenolic resin. These processes anticipate giving a certain thickness of PyC around the fibre tows. Pre-SiC fibre is a state of polymer driven SiC fibre as a precursor of SiC fibre, that the mechanical strength is not decided yet, nevertheless it has a strong merit of commercial price competitiveness.

New SiC/SiC composites were fabricated in different conditions by modifying both the amounts of employed PyC and fibre heat treatment for interface-control and bonding-control among the fibre tows, respectively. Sintering conditions (e.g. temperature, applied pressure, and holding time) and fabrication compositions (e.g. amount of SiC powder and sintering additives) are remained as

constant. Fabrication characteristics of the various composite materials used in this test are listed in table 1.

Figure 2. Schematic concept and process of NITE fabrication route.

Figure 3. Schematic comparison of fabric preparation.

Table I. Fabrication characteristics of various SiC/SiC composites

SiC _f /SiC composites	Fabrication route	Employed coating	Fibre coating method	Fibre type	Thickness of employed PyC	Fibre heat treatment
Commercial product #1	NITE	PyC	CVD	Cef-NITE™	500 nm	N/A
Commercial product #2	CVI	PyC	CVD	Tyranno SA™	80 nm	N/A
Prototype(LOT#11)	NITE	PyC	Pre-pyrolysis	Pre-SiC fibre	Very thick	500 °C
Prototype(LOT#12)	NITE	PyC	Pre-pyrolysis	Pre-SiC fibre	Thin	500 °C
Final product(LOT#17)	NITE	PyC	Pre-pyrolysis	Pre-SiC fibre	Very thin	Delicately Controlled

2.2. Erosion wear test

Erosive wear test was carried out by impinging SiC powder (green carborundum #36) on the surface of a test specimen. Using jets to utilize repeated impact erosion with a small nozzle delivering a compressed gas containing those abrasive particles which coincident with ASTM G76, as depicted in figure 4. Figure 5 illustrates a close-up view of impact on the test specimen focused on surface wear, each of a broken line and solid line indicates the example of real surface before and after the test, respectively. When impinging the erodent on the composite materials, considering the difference of crack propagation rate on PyC interface and SiC matrix/fibre, the direction of reinforced fibres will play an important role for wear performance. The composite material shown in figure 5 is highly over exaggerated to emphasize the direction of reinforced fibretows; the erodent used in this study is over 42 times bigger than the fibre, for reference, average diameter of commercial SiC fibre is 7.5 – 14 μm . Table 2 shows the experimental conditions for the test. It is well known that the effect of impingement angle on wear rates is the greatest close to perpendicular for brittle materials.

Figure 4. Schematic illustration of particle erosion environment.

Figure 5 Schematic of the solid particle impingement using gas jet on the surface of a test specimen.

Table II Experimental conditions of particle erosion wear test

Test parameters	Erosion method	Erodent	Step of erosion	Impingement conditions		
				Angle	Distance	Jet pressure
Value	Solid particle compressed air	SiC powder ^a GC #36	3 steps	90 °	40 mm	5 atm

^aGreen carborundum (GC) is a bulk grinding compound generally for polishing purpose

Distribution of particle size is #36 is 600 ~ 425 μm

Average particle size is around 510 μm

A total of 100 g of particles are impinged on composites surface in 33 g increments were impacted at room temperature on the surfaces of the composite. Protection seal was adopted to protect the partial surface of a test specimen from severe particle impingement while the erosion tests. Detachment of the protection seal and removal of debris by air-gun precedes the measuring of surface topography by a surface profilometer after each increment of erosion. The average worn depth was calculated by the difference in topography between the baseline of uneroded surface and eroded surface. Erosive wear rate was calculated by the average volume of worn surface divided by the total area of eroded surface.

Figure 6.Procedure of wear amount measurement after each erosion step

3. RESULTS AND DISCUSSION

3.1. Erosion performance and material analysis

Erosive worn surface of various SiC/SiC composite specimens are observed by direct-eye as illustrated in figure 7. The pores in CVI material, and traces of reinforced-fibre in newly fabricated composites are conspicuously stand out compared to commercial NITE composite. Erosion wear result shows that newly fabricated SiC/SiC composite has reasonable wear resistance compared to the two commercial composites (see figure 8). Erosion performance of newly fabricated composites, especially for the final product (LOT#17) was superior almost twice more resistance against commercial product by CVI (chemical vapour infiltration) route. Cef-NITETM fibre-reinforced NITE composite shows the best erosion resistance while the final product (LOT#17) shows only 20 % inferior to Cera-NITETM performance.

Figure 7. Bare eye observation on the worn surfaces of composites before and after the erosion test.

Figure 8. Wear rate under solid particle erosion test for various SiC/SiC composites.

Prototype material LOT#11 has a highervolume fraction about treble thePyC compared to the final product LOT#17,figure 9shows the amount of PyC presence between the fibre tows. SE micrograph in back scattered electron imaging (BEI) mode indicates fibres and PyC in a colour of grey and black, respectively. Severe fibre deformation and micro-pore formationare observed in prototype LOT#11.Increase of PyC amount results in severe fibre deformation and/or pore generation, which plays an important role for the erosive wear performance. Despite the PyC amount, LOT#12 shows the worst erosion performance. It is because of the fabrication methods and material properties, the related

parts are described in the author's other papers [67-71]. In short, it results from the porosity as shown in figure 10.

Figure 9. Employed amount of PyC, in (a) Final product, and in prototype materials (b), and (c).

Figure 10 Wear rate as a function of open porosity.

Figure 11 shows conspicuous defects in prototype material; a) irregular fibre deformations, b) insufficient densification of the matrix, c) distribution of residual oxide, d) micro-pores, e) deformation and crack formation on PyC, f) weak bonding strength between fibre and interface, and g) melted-flowed oxide phase around the fibre.

Figure 11. Conspicuous defects observed in typical region of prototype specimen LOT#11.

3.2. Wear behaviours and wear mechanisms

Two dominant erosive wear mechanisms were observed in this study, one is delamination of constituents. Another is fragmentation and detachment of constituents, the former usually caused by erosive crack propagation and later caused by an erosive impact.

A unit size of delamination is determined by the crack propagation length, mostly along the interface of constituents. It is the most decisive factor on the amount of wear. When a crack reaches to the interface, two kinds of crack branching mechanism will simultaneously occur. In case of the strong bonded interface, the crack neither propagates to the next crack nor results in any delamination. However, in the opposite case, the crack easily propagates to the next crack and

consequently, causing huge delamination. It is observed that most of the erosive crack propagates through the weakest points. Evidential proof was confirmed in two prototype materials that the fragmentation of matrix and detachment of fibre were conspicuously observed in plenty of areas, which results from weak bonding strength. The final product was relatively strong in bonding strength, so that the fragmentation and detachment of those matrix and fibre were hardly observed. Comparatively, fragmentation of matrix and fibre was rarely occurred by an erosive impact. In case of strong bonding between the fibre and interface the material can absorb the impact energy below critical and the critical energy depends on the bonding without crack propagation along the interface or delamination of the fibre. This leads to gradual wear of the constituents, as shown in figure 14b. In the final product LOT#17 the fragmentation of constituents is the dominant factor, due to the strong bonding among all constituents.

3.2.1. Wear on matrix

Different erosive wear behaviour was observed on new composites, as depicted in figure 12. Eroded surface of new composites by SEM observation shows the great difference between the coarse matrix and dense matrix. Due to inadequately applied pressure, phenomena of insufficient densification of matrix and scarce grain growth were observed in prototype LOT#11. Dense matrix also can be found in prototype materials; however the size of grain shows that their growth was relatively premature. Grain size of final product was relatively larger according to sufficient grain growth. Both grain pull-out and intergranular fractures by erosive impact were observed in eroded surface of final product (see figure 12d).

Figure 12. SE micrographs of eroded surface on (a) coarse matrix of prototype LOT#11, and a typical eroded region of (b) prototype LOT#11, (c) LOT#12, and (d) final product LOT#17.

Microscopic observation on the cross section of prototype materials also confirmed the porosities in the matrix. As shown in figure 13, (b) shows pores between remnant agglomerates compared with (a) relative small amount of pores in the dense matrix. These inadequately pressurized areas and insufficient grain growth are one of the reasons of severe matrix fragmentation.

Figure 13. SE micrographs (BEI mode) of typical porosities in prototype LOT#11

(a) pores in dense matrix and (b) coarse matrix.

3.2.2. Wear on fibre and interface

Detachment of fibre was conspicuously observed in prototype materials. As a form of aperture between fibre and PyC which result in fibre separation, porosity caused easy fibre detachment even by a single impact. It was mainly generated by volume contraction around 24% of Pre-SiC fibre itself during the crystallization process. The effect of fibre detachment caused by weak bonding can be seen in figure 14a, where exact shaped and sized traces of fibre detachment can be found as the evidence. PyC cleavage was also observed, which was generated while the hot-pressing process. For final product LOT#17, bonding strength between fibre and interface was relatively strong that most of the wear was result from gradual eroding (see figure 14b). Consequently, behaviours such as sudden detachment of constituents were rarely observed. These porosities influenced on a bonding strength of each constituent, which results in severe detachment of fibre and fragmentation of interface by an erosive impact (also shown in figure 16).

Figure 14. SE micrographs of fibre detachment and deformation observed in
(a) prototype LOT#11, and (b) final product LOT#17

3.3. Erosion wear mechanism models for new SiC/SiC composites

Unit length of erosive crack propagation and confluence of cracks dominate the unit size of constituent delamination. Figure 15 shows the sequence of minor and huge erosion including delamination of each constituent.

Huge erosion occurs when propagation of erosive crack reaches to the interlayer of constituents where the bonding interface is fragile, and after that the crack branches along the matrix-interface. Erosive impact on α site sequentially leads to an erosion of matrix, a propagation of crack, and a huge unit of delamination, illustrated as α_1 , α_2 , and α_3 , respectively.

Minor erosion occurs when the erosive crack propagates and joined to next confluent crack, marked as β and γ . Erosive crack propagate further and jointo other cracks are also often occurred in the coarse matrix, marked as β . Sequential eroding on γ site shows a propagation of crack on the PyC, a crack propagation to aperture or weak bonding between fibre and PyC, and a crack connection to PyC cleavages, illustrated as γ_1 , γ_2 , and γ_3 , respectively.

Figure 15. Cross sectional view of the erosive wear on the prototype of a new SiC/SiC composite.

Sequential wear of each constituent by erosive crack propagation is shown in this model.

Erosion sites α , β , and γ are shown in micrograph figure 16 for the prototype LOT#11. In α site, the huge impact energy already sweeps through, so that only the eroded matrix and some remains of constituent parts of PyC and fibre are shown. Due to the defects in matrix, resultant behaviour are shown in β site as the matrix eroding and fragmentation, which will soon uncover the underneath constituents. In γ site, plenty of fibre detachments were observed with eroding of PyC.

Figure 16. Erosive wear on each constituent observed in prototype LOT#11 a) focused on eroded fibres and PyC, and b) another focus on eroded matrix where huge delamination occurred.

Figure 17 shows the dominant erosive wear mechanisms on various SiC/SiC composites. Each number represents following erosive behaviours: 1. Matrix eroding and crack initiation, 2. Large and small unit of matrix fragmentation, 3. Interface and/or fibre eroding and cracking, 3a. PyC cleavage by eroding,

4. Fibre detachment, 5. Crack propagation along the interface and/or through the matrix, 5a. Through a weak interface between matrix and PyC layer, and 5b. Through a weak coarse matrix.

Figure 17 Cross sectional view of the erosive wear on SiC/SiC composites

4. CONCLUSION

Erosive wear test was carried out on a number of SiC/SiC composites. Schematic wear models are proposed with following details. Two dominant erosive wear mechanisms were observed for newly fabricated SiC/SiC composites, one is delamination of constituents, which mainly occurred by crack propagation through the weakest interlayer. Another is fragmentation and detachment of constituents by an erosive impact. A unit size of delamination dominated by the erosive crack propagation length, which mostly determine the amount of wear volume.

The fabrication improvements have been successfully made for a newly fabricated SiC/SiC composite, as the result, the known defects are rarely observed in final product. Crucial fabrication factors for erosion wear resistance were; 1. Weak bonding strength of constituent parts, 2. Poor densification of matrix and scarce grain growth, 3. Interface cleavage with micro-pores, and 4. Aperture along the fibre-interface

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REFERENCE

1. Brennan, J.J., Prewo, K.M.: Silicon carbide fibre reinforced glass-ceramic matrix composites exhibiting high strength and toughness. *Journal of Materials Science* 17 (8), pp. 2371-2383 (1982)
2. Sternitzke, M., Dupas, E., Twigg, P., Derby, B.: Surface mechanical properties of alumina matrix nanocomposites, *Acta Materialia* 45 (10), pp. 3963-3973 (1997)
3. Prouhet, Stephane, Camus, Gerald, Labrugere, Christine, Guette, Alain, Martin, Eric: Mechanical characterization of Si-C(O) fiber/SiC (CVI) matrix composites with a BN-interphase. *Journal of the American Ceramic Society* 77 (3), pp. 649-656 (1994)
4. Xu, Y., Cheng, L., Zhang, L., Yin, H., Yin, X.: Mechanical properties of 3D fiber reinforced C/SiC composites. *Materials Science and Engineering A* 300 (1-2), pp. 196-202 (2001)
5. Mogilevsky, P., Werner, A., Dudek, H.J.: Application of diffusion barriers in composite materials. *Materials Science and Engineering A* 242 (1-2), pp. 235-247 (1998)
6. Anya, C.C.: Wet Erosive Wear of Alumina and its Composites with SiC Nano-particles. *Ceramics International* 24 (7), pp. 533-542 (1998)
7. Marschall, J., Erlich, D.C., Manning, H., Duppler, W., Ellerby, D., Gasch, M.: Microhardness and high-velocity impact resistance of HfB₂/SiC and ZrB₂/SiC composites. *Journal of Materials Science* 39 (19), pp. 5959-5968 (2004)
8. Bajwa, S., Rainforth, W.M., Lee, W.E.: Sliding wear behaviour of SiC-Al₂O₃ nanocomposites. *Wear* 259 (1-6), pp. 553-561 (2005)
9. Xu, Y., Cheng, L., Zhang, L., Yin, X., Yin, H.: High performance 3D textile Hi-Nicalon SiC/SiC composites by chemical vapor infiltration. *Ceramics International* 27 (5), pp. 565-570 (2001)
10. Jones, R.H., Henager Jr., C.H.: Subcritical crack growth processes in SiC/SiC ceramic matrix composites. *Journal of the European Ceramic Society* 25 (10 SPEC. ISS.), pp. 1717-1722 (2005)

11. Zhan, Y., Zhang, G., Zhuang, Y.: Wear transitions in particulate reinforced copper matrix composites. *Materials Transactions* 45 (7), pp. 2332-2338 (2004)
12. Tuersley, I.P., Hoult, T.P., Pashby, I.R.: The processing of SiC-SiC ceramic matrix composites using a pulsed Nd-YAG laser: Part II. The effect of process variables. *Journal of Materials Science* 33 (4), pp. 963-967 (1998)
13. Liu, Y.M., Mitchell, T.E., Wadley, H.N.G.: Anisotropic damage evolution in unidirectional fiber reinforced ceramics. *Acta Materialia* 45 (10), pp. 3981-3992 (1997)
14. E Routbort, J.L.: Degradation of structural ceramics by erosion. *Journal of Nondestructive Evaluation* 15 (3-4), pp. 107-112 (1996)
15. Aigbodion, V.S., Hassan, S.B.: Effects of silicon carbide reinforcement on microstructure and properties of cast Al-Si-Fe/SiC particulate composites. *Materials Science and Engineering A* 447 (1-2), pp. 355-360 (2007)
16. Hohler, V., Weber, K., Tham, R., James, B., Barker, A., Pickup, I.: Comparative analysis of oblique impact on ceramic composite systems. *International Journal of Impact Engineering* 26 (1-10), pp. 333-344 (2001)
17. E Kobayashi, A.S.: Dynamic fracture of ceramics and ceramic composites. *Materials Science and Engineering A* 143 (1-2), pp. 111-117 (1991)
18. El-Hija, H.A., Krenkel, W., Hugel, S.: Development of C/C-SiC brake pads for high-performance elevators. *International Journal of Applied Ceramic Technology* 2 (2), pp. 105-113 (2005)
19. Ham, A.L., Yeomans, J.A., Watts, J.F.: Elevated temperature solid particle erosion of silicon carbide continuous fibre reinforced calcium aluminosilicate glass-ceramic matrix composite. *Wear* 203-204, pp. 387-392 (1997)
20. E Sarva, S., Nemat-Nasser, S., McGee, J., Isaacs, J.: The effect of thin membrane restraint on the ballistic performance of armor grade ceramic tiles. *International Journal of Impact Engineering* 34 (2), pp. 277-302 (2007)
21. Raghuraman, S., Stubbins, J.F., Ferber, M.K., Wereszczak, A.A.: Crack propagation in SiCf/SiC ceramic matrix composite under static and cyclic loading conditions. *Journal of Nuclear Materials* 212-215 (PART 1), pp. 840-844 (1994)
22. Ramulu, M., See, H.-W., Wang, D.H.: Machining of ceramic composite TiB₂/SiC by spark erosion. *Manufacturing Review* 3 (2), pp. 123-129 (1990)
23. Kim, J.J., Park, S.K.: Solid particle erosion of SiC and SiC-TiB₂ composite hot-pressed with Y₂O₃. *Wear* 222 (2), pp. 114-119 (1998)

24. Fang, Q., Sidky, P., Hocking, M.G.: Erosive wear behaviour of aluminium based composites. *Materials and Design* 18 (4-6), pp. 389-393 (1997)
25. Akimune, Yoshio, Katano, Yasushi, Matoba, Kazuo: Spherical-impact damage and strength degradation in silicon carbide whisker/silicon nitride composites. *Journal of the American Ceramic Society* 72 (5), pp. 791-798 (1989)
26. Sykes, M.T., Scattergood, R.O., Routbort, J.L.: Erosion of SiC-reinforced alumina ceramic composites. *Composites* 18 (2), pp. 153-163 (1987)
27. Subhash, G., Maiti, S., Geubelle, P.H., Ghosh, D.: Recent advances in dynamic indentation fracture, impact damage and fragmentation of ceramics. *Journal of the American Ceramic Society* 91 (9), pp. 2777-2791 (2008)
28. Jianxin, D., Lili, L., Jinlong, Z., Junlong, S.: Erosion wear of laminated ceramic nozzles. *International Journal of Refractory Metals and Hard Materials* 25 (3), pp. 263-270 (2007)
29. Jianxin, D., Lili, L., Mingwei, D.: Erosion wear behaviours of SiC/(W,Ti)C laminated ceramic nozzles in dry sand blasting processes. *Materials Science and Engineering A* 444 (1-2), pp. 120-129 (2007)
30. Tamura, H., Mutou, Y.: Quantitative analysis of debris clouds from SiC-fiber-reinforced silicon nitride bumpers. *International Journal of Impact Engineering* 31 (9), pp. 1192-1207 (2005)
31. Al-Dheyylan, K.A.: The low velocity impact loading of Al₂O₃/SiC whisker reinforced ceramic composite. *Journal of Materials Processing Technology* 155-156 (1-3), pp. 1986-1994 (2004)
32. Medvedovski, E.: Silicon carbide-based ceramics for ballistic protection. *Ceramic Transactions* 151, pp. 19-35 (2003)
33. Badini, C., Fino, P., Ubertalli, G., Taricco, F.: Degradation at 1200°C of a SiC coated 2D-Nicalon/C/SiC composite processed by SICFILL® method. *Journal of the European Ceramic Society* 20 (10), pp. 1505-1514 (2000)
34. Ham, A.L., Yeomans, J.A., Watts, J.F.: Effect of temperature and particle velocity on the erosion of a silicon carbide continuous fibre reinforced calcium aluminosilicate glass-ceramic matrix composite. *Wear* 233-235, pp. 237-245 (1999)
35. Hayun, S., Frage, N., Dariel, M.P., Zaretsky, E., Ashuah, Y.: Dynamic response of B₄C-SiC ceramic composites. *Ceramic Transactions* 178, pp. 147-156 (2006)
36. Vanswijgenhoven, E., Wevers, M., Van Der Biest, O.: The transverse strain response of cross-ply fibre-reinforced ceramic-matrix composites. *Composites Science and Technology* 59 (10), pp. 1469-1481 (1999)

37. Unal, O., Eckel, A.J., Laabs, F.C.: Mechanical properties and microstructure of oxidized SiC/SiC composites. *Ceramic Engineering and Science Proceedings* 17 (4), pp. 333-341 (1996)
38. E Akimune, Yoshio: Impact damage and strength degradation in a silicon carbide reinforced silicon nitride composite. *Journal of the American Ceramic Society* 73 (10), pp. 3019-3025 (1990)
39. Van Roode, M., Ferber, M.K.: Long-term degradation of ceramics for gas turbine applications. *Proceedings of the ASME Turbo Expo* 1, pp. 305-321 (2007)
40. Srivastava, V.K.: Damage morphology of C/C-SiC composites under impact tests. *Ceramic Transactions* 175, pp. 181-187 (2006)
41. Xu, Y., Cheng, L., Zhang, L., Yin, H., Yin, X.: Microstructure and mechanical properties of three-dimensional textile Hi-Nicalon SiC/SiC composites by chemical vapor infiltration. *Journal of the American Ceramic Society* 85 (5), pp. 1217-1221 (2002)
42. Cosgriff, L.M., Bhatt, R., Choi, S.R., Fox, D.S.: Thermographic characterization of impact damage in SiC/SiC composite materials. *Proceedings of SPIE - The International Society for Optical Engineering* 5767, art. no. 47, pp. 363-372 (2005)
43. Wiederhorn, S.M. and Lawn, B.R.: Strength Degradation of Glass Resulting from Impact with Spheres. *J. Am. Ceram. Soc.*, 60 [9-10] 451-8 (1977)
44. Wiederhorn, S.M. and Lawn, B.R.: Strength Degradation of Glass Impact with Sharp Particles: I, Annealed Surfaces. *J. Am. Ceram. Soc.*, 62 [1-2] 66-70 (1979)
45. Breder, K., de Portu, G., Ritter, J. E. and Fabbri, D.D.: Erosion Damage and Strength Degradation of Zirconia-Toughened Alumina. *J. Am. Ceram. Soc.*, 71 [9] 770-5 (1988)
46. Ritter, J.E., Choi, S.R., Jakus, K., Whalen, P.J., and Rateick, R. G.; Effect of Microstructure on the Erosion and Impact Damage of Sintered Silicon Nitride, *J. Mater. Sci.*, 26, 5543-6 (1991)
47. Akimune, Y., Katano, Y., and Matoba, K.: Spherical-Impact Damage and Strength Degradation in Silicon Nitrides for Automobile Turbocharger Rotors. *J. Am. Ceram. Soc.*, 72 [8] 1422-8 (1989)
48. Shockey, D.A., Rowcliff, D.J., Dao, K.C., and Seaman, L.: Particle Impact Damage in Silicon Nitride. *J. Am. Ceram. Soc.*, 73 [6] 1613-9 (1990)
49. Knight, C.G., Swain, M.V., and Chaudhri, M.M.: Impact of Small Steel Spheres on Glass Surfaces. *J. Mater. Sci.*, 12, 1573-86 (1977)
50. Taylor, L.N., Chen, E.P., and Kuszmaul, J.S.: Microcrack-Induced Damage Accumulation in Brittle Rock under Dynamic Loading. *Comp. Meth. Appl. Mech. Eng.*, 55, 301-20 (1986)

51. Mouginot R., and Maugis, D.: Fracture Indentation beneath Flat and Spherical Punches. J. Mater. Sci., 20, 4354–76 (1985)
52. Evans G., and Wilshaw, T.R.: Dynamic Solid Particle Damage in Brittle Materials: An Appraisal. J. Mater. Sci., 12, 97–116 (1977)
53. Liaw, M., Kobayashi, A.S., and Emery, A.G.: Theoretical Model of Impact Damage in Structural Ceramics. J. Am. Ceram. Soc., 67, 544–8 (1984)
54. Richerson D.W., and Johansen, K.M.: Ceramic Gas Turbine Engine Demonstration Program. Final Report, DARPA/Navy Contract N00024-76-C-5352, Garrett Report 21-4410 (1982)
55. Boyd, G.L. and Kreiner, D.M.: AGT101/ATTAP Ceramic Technology Development. Proceeding of the Twenty-Fifth Automotive Technology Development Contractors' Coordination Meeting, p.101 (1987)
56. M. van Roode, et al., Ceramic Stationary Gas Turbine Development—Fourth Annual Summary, ASME Paper No. 97-GT-317 (1997)
57. Hara, Y., Matsubara, K., Mizuno, K., Shimamori, T., and Yoshida H.: Development and Evaluation of Silicon Nitride Components for Ceramic Gas Turbine. ASME Paper No. 98-GT-498 (1998)
58. Yoshida, H., Chaudhri, M.M., and Hoshi, Y.: Quasistatic Indentation and Spherical Particle Impact Studies of Turbine-Grade Silicon Nitrides. Philos. Mag. A., 82 [10] 2031–40 (2002)
59. E Bu-Qian Wang, Levy, A.V.: Erosion behavior of SiC fiber-SiC matrix composites. Wear 138 (1-2), pp. 125-136 (1990)
60. Ogi, K., Okabe, T., Takahashi, M., Yashiro, S., Yoshimura, A., Ogasawara, T.: Experimental characterization of high-speed impact damage behavior in a three-dimensionally woven SiC/SiC composite. Composites Part A: Applied Science and Manufacturing 41 (4), pp. 489-498 (2010)
61. Choi, S.R., Pereira, J.M., Janosik, L.A., and Bhatt, R. T.: Foreign Object Damage of Two Gas-Turbine Grade Silicon Nitrides at Ambient Temperature. Ceram. Eng. Sci. Proc., 23 [3] 193–202 (2002)
62. Choi S.R. et al.: Foreign Object Damage in Flexure Bars of Two Gas-Turbine Grade Silicon Nitrides. Mater. Sci. Eng. A 379 411–419 (2004)
63. Choi S.R. et al.: Foreign Object Damage in Disks of Gas-Turbine-Grade Silicon Nitrides by Steel Ball Projectiles at Ambient Temperature, J. Mater. Sci., 39 6173–6182 (2004)
64. K. Komeya, M. Matsui, in Materials Science and Technology Vol. 11, ed. M.V. Swain (VCH, Weinheim. pp. 517–565 (1994)

65. Suh, M.-S. et al.: Friction and Wear Behavior of Structural Ceramics Sliding against Zirconia. Wear 264 (9-10), 800-806 (2008)
66. Suh, M.-S. et al.: Tribological Evaluation of Structural Ceramics under Sliding Friction. Int. J. of Modern Phys B20 (25-27), pp. 4407-4412 (2006)
67. Suh, M.-S., Kohyama, A., Hinoki, T.: Mechanical Properties and Microstructure of SiC/SiC Composites Fabricated for Erosion Component. First Int. Symposium of Global COE Prog. Proc., pp 261-265 (2009)
68. Suh, M.-S. Kohyama, A.: Erosion Wear Mechanism of SiCf/SiC Composites by Solid Particles. World Tribology Congress 2009. Proc., p 909 (2009)
69. Suh, M.-S. Kohyama, A.: Effect of Porosity on Particle Erosion Wear Behavior of Lab. Scale SiCf/SiC Composites. Int. J. of Modern Phys B, under press (2009)
70. Suh, M.-S. Kohyama, A.: Special Issues on “in situ” Crystallized SiC/SiC Composites. Int. Symposium on Advanced Engineering, pp. 439-442 (2009)
71. Suh, M.-S. et al.: Fabrication of SiCf/SiC by means of "In-situ" Crystallization of SiC Fibers. J. of Nucle. Matr., under press (2010)
72. DiCarlo, J.A. et al.: in Handbook of Ceramic Composites, ed. P.B. Narottam P. Bansal (Kluwer Academic Publishers, Boston), p. 33. (2005)
73. Hinoki, T., Zhang, W., Kohyama, A., Sato, S., Noda, T.: Effect of fiber coating on interfacial shear strength of SiC/SiC by nano-indentation technique. Journal of Nuclear Materials 258-263 (PART 2 B), pp. 1567-1571 (1998)
74. Zhang, W., Hinoki, T., Katoh, Y., Kohyama, A., Noda, T., Muroga, T., Yu, J.: Crack initiation and growth characteristics in SiC/SiC under indentation test. Journal of Nuclear Materials 258-263 (PART 2 B), pp. 1577-1581 (1998)
75. Ferraris, M., Salvo, M., Isola, C., Appendino Montorsi, M., Kohyama, A.: Glass-ceramic joining and coating of SiC/SiC for fusion applications. Journal of Nuclear Materials 258-263 (PART 2 B), pp. 1546-1550 (1998)
76. Fenici, P., Frias Rebelo, A.J., Jones, R.H., Kohyama, A., Snead, L.L.: Current status of SiC/SiC composites R&D. Journal of Nuclear Materials 258-263 (PART 1 A), pp. 215-225 (1998)
77. Araki, Hiroshi, Yang, Wen, Shi, Ying, Sato, Shinji, Noda, Tetsuji, Kohyama, Akira: Bending properties of CVI SiCf/SiC composites at elevated temperatures. Ceramic Engineering and Science Proceedings 20 (4), pp. 371-378 (1999)

78. Katoh, Y., Kotani, M., Kohyama, A., Montorsi, M., Salvo, M., Ferraris, M.: Microstructure and mechanical properties of low-activation glass-ceramic joining and coating for SiC/SiC composites. *Journal of Nuclear Materials* 283-287 (PART II), pp. 1262-1266 (2000)
79. Kohyama, A., Kotani, M., Katoh, Y., Nakayasu, T., Sato, M., Yamamura, T., Okamura, K.: High-performance SiC/SiC composites by improved PIP processing with new precursor polymers. *Journal of Nuclear Materials* 283-287 (PART I), pp. 565-569 (2000)
80. Lewinsohn, C.A., Singh, M., Shibayama, T., Hinoki, T., Ando, M., Katoh, Y., Kohyama, A.: Joining of silicon carbide composites for fusion energy applications. *Journal of Nuclear Materials* 283-287 (PART II), pp. 1258-1261 (2000)
81. Hinoki, T., Yang, W., Nozawa, T., Shibayama, T., Katoh, Y., Kohyama, A.: Improvement of mechanical properties of SiC/SiC composites by various surface treatments of fibers. *Journal of Nuclear Materials* 289 (1-2), pp. 23-29 (2001)
82. Dong, S.M., Katoh, Y., Kohyama, A., Schwab, S.T., Snead, L.L.: Microstructural evolution and mechanical performances of SiC/SiC composites by polymer impregnation/microwave pyrolysis (PIMP) process. *Ceramics International* 28 (8), pp. 899-905 (2002)
83. Dong, S., Katoh, Y., Kohyama, A.: Preparation of SiC/SiC composites by hot pressing, using tyranno-SA fiber as reinforcement. *Journal of the American Ceramic Society* 86 (1), pp. 26-32 (2003)
84. Hinoki, T., Jinushi, T., Hirohata, Y., Hashiba, M., Yamauchi, Y., Katoh, Y., Kohyama, A.: Helium gas permeability of SiC/SiC composite developed for blanket component. *Fusion Science and Technology* 43 (2), pp. 184-190 (2003)
85. Yang, W., Kohyama, A., Katoh, Y., Araki, H., Yu, J., Noda, T.: Effect of carbon and silicon carbide/carbon interlayers on the mechanical behavior of tyranno-SA-fiber-reinforced silicon carbide-matrix composites. *Journal of the American Ceramic Society* 86 (5), pp. 851-856 (2003)
86. Kotani, M., Inoue, T., Kohyama, A., Katoh, Y., Okamura, K.: Effect of SiC particle dispersion on microstructure and mechanical properties of polymer-derived SiC/SiC composite. *Materials Science and Engineering A* 357 (1-2), pp. 376-385 (2003)
87. Nozawa, T., Ozawa, K., Katoh, Y., Kohyama, A.: Effect of Heat Treatment on Microstructure and Mechanical Properties of Stoichiometric SiC/SiC Composites. *Materials Transactions* 45 (2), pp. 307-310 (2004)

- 1
2
3 88. Katoh, Y., Kohyama, A., Nozawa, T., Sato, M.: SiC/SiC composites through transient eutectic-
4 phase route for fusion applications. Journal of Nuclear Materials 329-333 (1-3 PART A), pp.
5 587-591 (2004)
6
7
8 89. Igawa, N., et al.: Fabrication of SiC fiber reinforced SiC composite by chemical vapor
9 infiltration for excellent mechanical properties. Journal of Physics and Chemistry of Solids 66
10 (2-4), pp. 551-554 (2005)
11
12
13 90. Shimoda, K., Eiza, N., Park, J.-S., Hinoki, T., Kohyama, A., Kondo, S.: High-temperature
14 mechanical property improvements of SiC ceramics by NITE process. Materials Transactions
15 47 (4), pp. 1204-1208 (2006)
16
17
18 91. Shimoda, K., Hinoki, T., Katoh, Y., Kohyama, A.: Development of the tailored SiC/SiC
19 composites by the combined fabrication process of ICVI and NITE methods. Journal of
20 Nuclear Materials 384 (2), pp. 103-108 (2009)
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