Tribological Behavior of Silicon Carbide Ceramics - A Review

Sandan Kumar Sharma, B. Venkata Manoj Kumar†, and Young-Wook Kim*

Department of Metallurgical and Materials Engineering, Indian Institute of Technology (IIT) Roorkee, Roorkee 247667, India
*Functional Ceramics Laboratory, Department of Materials Science and Engineering, the University of Seoul, Seoul 02504, Korea

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ABSTRACT

A comprehensive review on sliding and solid particle erosion wear characteristics of silicon carbide (SiC) ceramics and SiC composites is provided. Sliding or erosion wear behavior of ceramics is dependent on various material characteristics such as mechanical properties, and microstructural and mechanical properties of SiC ceramics are particularly focused to understand tribological performance of SiC ceramics. Results obtained between varieties of pairs of SiC ceramics indicate complexity in understanding dominant mechanisms of material removal. Wear mechanisms during sliding are mainly divided in two groups as mechanical and tribochemical. In solid particle erosion conditions, wear mechanisms of SiC ceramics are explained by elastic-plastic deformation controlled micro-fracture on the surface followed by radial-lateral crack propagation beneath the plastic zone.

Key words : Silicon carbide, Sliding wear, Erosion wear, Microstructure, Wear mechanisms

1. Introduction

Silicon carbide, a well-recognized structural ceramic material has been used in industries for a long period owing to its unique combination of properties such as high hardness, high modulus, high temperature strength, good oxidation resistance, excellent wear resistance, good thermal shock resistance, and high thermal conductivity. The fundamental structure of covalently bonded silicon carbide is a coordinated tetrahedron, either SiC or CSi. Although a great variety of SiC polytypes is known, important are cubic polytype referred as β-SiC, and non-cubic structures (hexagonal or rombohedral) as α-SiC. The strong covalent bond and extremely low self-diffusion coefficient (10^{-13} – 10^{-15} cm^2/sec) pose difficulties in densification of SiC powders at lower temperatures. The densification is possible only at extremely high pressure (30-100 MPa) and temperatures exceeding 2100°C. In order to achieve high density at lower temperatures and pressures, use of sintering aids is necessary.

Metal oxides, Al-B-C, AlN–metal oxides as sintering additives during liquid-phase sintering tailor the microstructure and improve fracture toughness of SiC ceramics. The platelet-reinforced microstructures exhibit enhanced toughness due to the combination of intergranular crack mode, introduced by the glassy grain boundary phase, and energy dissipating processes in the crack wake. Sintering additive composition also affect the crystallinity of grain boundary phase of SiC ceramics. Further details on sintering and microstructure can be found elsewhere.

Owing to attractive properties, liquid phase sintered silicon carbide (LPS-SiC) ceramics are preferred for several tribological and structural applications such as turbine parts, heat exchanger tubes, mechanical seals, bearings, cylinder liners, burner parts in fluidized bed combustion system, bullet proof vests, cutting tools etc. A thorough understanding on tribological behavior of SiC ceramics is required for their successful application as triboelements. Accordingly, extensive research has been carried out towards estimating tribological potential of Si and SiC-based composites. Available literature on tribology of SiC ceramics can be broadly divided into two categories: sliding and erosion.

Based on the conditions of sliding and characteristics of SiC and SiC composites, the coefficient of friction (COF) in unlubricated sliding studies reported to be varied in the wide range of 0.2 - 0.8, which decreased up to 0.02 in lubricating media like water, paraffin oil etc. Wear rates in sliding conditions varied in the order of 10^{-1} - 10^{-4} mm^3/N.m. Erosion of SiC ceramics is mainly studied in solid particle erosion conditions, while that in cavitation conditions is limited. Solid particle erosion of SiC and SiC-based composites is reported to occur generally by brittle fracture as a result of lateral and radial cracking. Erosion rate ranges from 10^{-1} to 10^{-3} mm^3/kg based on erosion parameters, and microstructural and mechanical characteristics of SiC ceramics. The complex tribological behavior of SiC ceramics and their composites in sliding and solid particle erosion conditions was mostly explained by several material removal mechanisms such as mechanical fracture, chipping, plastic deformation, ploughing, and/or formation and removal of triboxide layer.

Considering the importance of the influence of microstruc-
structure and mechanical properties of SiC ceramics in different wear conditions, a comprehensive understanding on sliding and solid particle erosion wear behavior of SiC ceramics and composites is provided in the present review. Effects of material parameters on wear behavior are extensively reviewed. The other important part of the review is focused on understanding dominant mechanisms of material removal as function of microstructure and mechanical characteristics of SiC ceramics in the sliding and erosion conditions.

2. Sliding Wear of SiC Ceramics

Sliding wear of SiC ceramics are reported mainly using ball-on-disk or pin-on-disk tribometer. SiC ceramics showed complex behavior of wear influenced by sliding test, material or environmental parameters in lubricated/unlubricated sliding conditions. In this section effect of microstructure and mechanical characteristics on sliding wear of SiC ceramics are separately discussed. This is followed by detailed understanding on dominant wear mechanism of SiC ceramics in sliding conditions.

2.1. Effect of microstructure

Lopez et al. studied the sliding wear behavior of LPS-SiC ceramics with different microstructures like elongated SiC grains (in situ toughened LPS SiC), coarse equiaxed SiC grains, and fine equiaxed SiC grains. Sliding wear resistance of elongated grain SiC ceramics was better than that of equiaxed SiC ceramics owing to a hard interlocking network of in situ toughened LPS α-SiC. This was in contrast to the equiaxed SiC ceramics, where the grains were embedded within a continuous YAG phase matrix.

In sliding of SiC ceramics prepared with YAG (Y2O3:Al2O3 = 3 : 5), Lopez et al. suggested reduced content of the intergranular phase or grain size for improvement in wear resistance of LPS α-SiC ceramics. Reduced content of intergranular phase and the grain refinement resulted in reduction of rate of transition from deformation-controlled wear to fracture-controlled wear and hence in wear loss.

A simple model by Lawn et al. provided a framework for estimating the sliding wear properties in polycrystalline ceramics. The proposed model states that the plastic-deformation damage accumulates within the grains during deformation-controlled wear. This damage is in the form of dislocation pile-ups, confirmed using transmission electron microscopy.

It was earlier concluded that SiC ceramics sintered using 3 wt% AlN–Y2O3 (SCY3) additives revealed mostly large equiaxed grains with amorphous grain boundary phase, while SiC ceramics prepared using 3 wt% AlN–Sc2O3 (SCSc3) additives exhibited duplex microstructure of elongated and fine equiaxed grains with clean grain boundary phase (see Figs. 2(a) and (b)). SiC ceramics prepared using 3 wt% AlN–Sc2O3 additives resulted ~ 18% less wear at 13 N load. Worn surfaces of SCY3 and SCSc3 are shown in Figs. 2(c) and (d), respectively.

Murthy et al. observed that SiC ceramics doped with different p-type (Al, Mg) or n-type (P) doping elements had influence on the wear behavior in two ways: (i) by directly affecting thermodynamics of tribochemical reactions or (ii) by modified frequency of grain boundaries having same orientation angle and change in the kinetics of tribochemical reactions. It was found that doping elements partly made a solid solution with SiC and rest were segregated along grain boundaries. Segregated Al reduced solubility of silica largely in water, whereas P and Mg reduced solubility to a lesser extent. Kinetics of formation of hydrated silica var-

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**Fig. 1.** Typical SEM images of SiC ceramics (a, b) unworn and (c, d) after sliding against Si3N4 ball. Note the presence of elongated grains in (b) and equiaxed grains in (a), and comparatively less wear in (d) than in (c). Other conditions of sintering and sliding wear can be found in.

**Fig. 2.** TEM images of SiC ceramics revealing (a) amorphous grain boundary in SiC ceramics prepared with 3 wt% (AlN-Y2O3) additive (b) clean grain boundary in SiC ceramics prepared with 3 wt% (AlN-Sc2O3). Worn surfaces of (a) and (b) are respectively shown in (c) and (d).
ied with solubility and hence led to change in frictional characteristics of SiC ceramics.

For improvements in the sliding-wear resistance of pressureless LPS-SiC under diesel lubrication, Ciudad et al.\textsuperscript{74} suggested (i) reduction in intergranular phase (second phase) content, and (ii) decrease in grain size or increase in grain aspect ratio. They reported that SiC ceramics with similar grain size (of 1.1 µm) but having large amount of second phase exhibited high wear. Second phase led to decrease in hardness and increase in wear.

Ortiz et al.\textsuperscript{54} proposed a colloidal processing route to produce dense SiC ceramics via pressureless liquid-phase sintering (PLPS). In addition to uniform mixing, the colloidal processing route resulted in a nano film of ~ 5 nm thickness on the surface of SiC particles. Compared to conventional mixing and sintering, complete densification achieved in shorter sintering time and minimum defects found in ceramics sintered using colloidal processed powders. The time required for the transition from mild to severe wear was more than double for SiC ceramics prepared by colloidal processing as compared to that for the SiC ceramics prepared by conventional processing. It was advocated that, though the microstructures were similar in terms of the size and morphology of grains for ceramics prepared through both processing routes, the clear interphase with fully dense structure led to a superior wear resistance.

Zhou et al.\textsuperscript{75} reported that silicon carbide-graphite (SiC-C) composites exhibited lower coefficients of friction during sliding than the monolithic SiC. The flake like graphite particles present in SiC-C composites (see Fig. 3) were expected to provide solid lubrication with easy shear during sliding. However, in the high contact stress condition (pin-on-disk tests), wear rates enhanced sharply from 0.38 to $3.90 \times 10^{-6}$ mm$^3$/N.m for SiC-C composites which was attributed to the fracture of graphite flakes despite lowered coefficients of friction when compared to low contact stress condition (block-on-ring test) (see Table 1).

In other research,\textsuperscript{76} SiC ceramics with 0, 10, 30 or 50 wt% WC were slid against SiC ball. WC reinforcement led to a decrease in size of equiaxed grains from 835 µm to 578 µm of SiC ceramics and resulted improvement in wear resistance from $1.3 \times 10^{-5}$ mm$^3$/N.m to $4 \times 10^{-6}$ mm$^3$/N.m (see Fig. 4).

### 2.2. Effect of mechanical properties

Mechanical properties such as fracture toughness, hardness, and elastic modulus have influence on sliding wear characteristics of SiC ceramics. Hardness and fracture toughness of SiC ceramics are reported to generally range from 16 GPa to 27 GPa, and 2.3 MPa.m$^{1/2}$ to 8.3 MPa.m$^{1/2}$, respectively based on types of sintering/additives, microstructure etc.\textsuperscript{49,51,77-80} Particularly, the influence of hardness and fracture toughness on friction and wear behavior was debated in most of the reports.

A sharp indenter model and a blunt indenter model were proposed to estimate the sliding wear broadly in the tribocontact of brittle materials in absence of any layer formation. According to Marshall et al.\textsuperscript{81} for the tribocontact of sharp indenters, wear in brittle materials occurs due to the formation and propagation of lateral cracks. For a given applied load ($P$), total sliding distance ($S$), hardness ($H$), fracture toughness ($K_{IC}$) and elastic modulus ($E$), wear vol-

![Fig. 3. Fracture surfaces of (a) SiC and (b) SiC- 20 vol% graphite (SiC-C) composite. The graphite particles in SiC–C composite remain flake like, as indicated by the arrows.\textsuperscript{75}](image1)

![Fig. 4. Etched surfaces of SiC ceramics prepared with (a) 10% WC, and (b) 50% WC.\textsuperscript{61} Sliding wear volume as function of WC content is shown in (c).\textsuperscript{76}](image2)

### Table 1. Friction and Wear Data for SiC-C Ceramics for Different Triboconfigurations\textsuperscript{76}

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Average coefficient of friction</th>
<th>Wear rate (X 10$^{-6}$ mm$^3$/N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Block-on-ring</td>
<td>Pin-on-disk</td>
</tr>
<tr>
<td>SiC</td>
<td>0.64</td>
<td>0.28</td>
</tr>
<tr>
<td>SiC- 10 vol. %C</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>SiC- 20 vol. %C</td>
<td>0.49</td>
<td>0.14</td>
</tr>
</tbody>
</table>
ume of the brittle solid ($V_s$) can be assessed using the following equation:\(^\text{(1)}\)

$$V_s = \frac{\alpha P^{3/8} R^{17/8}}{K_{IC}^{3/4} H^{5/8}} S^{1/4}$$

where $\alpha$ is a material constant. In case of blunt indenter pressed against a brittle solid, surface ring cracks are generated, which propagate towards downwards with repeated sliding contact and develop conical cracks to cause pull-out of material.\(^\text{(2)}\)

Following Hertzian analysis, when there was no tribochemical layer formation, Tewari et al. estimated wear volume ($V_w$) for brittle materials in ball-on-disk fretting wear contacts as per the following relation:\(^\text{(3)}\)

$$V_w = \frac{2\pi\beta\delta}{3} \left( \frac{3PR}{4E} \right)^{2/3} \left( \frac{\sqrt{2\gamma^2 EP}}{3\beta K_{IC}R} - 1 \right)$$

where $R$ is radius of the ball, $\chi$ and $\beta$ are constants, and $s$ is the stroke length in fretting contact.

SiC ceramics sintered with small amount (0.2 wt%) of Y$_2$O$_3$ additives attributed to high strength (561 MPa) and high hardness (27.7 GPa) than the SiC ceramics sintered with large amount (3 wt%) of Y$_2$O$_3$ additives (542 MPa and 26.1 GPa), and exhibited superior wear resistance.\(^\text{(4)}\)

Li et al.\(^\text{(5)}\) found that toughened SiC prepared by hot pressing showed high hardness and fracture toughness compared to the SiC ceramics prepared through pressureless sintering process using pressureless sintering media on the wear track. Alumina particles, generated as debris from alumina counterbody balls acted as third body for harder surfaces. Third body abrasion of the surfaces led to high wear of harder chemical vapor infiltration treated cotton based sample. On the other hand, porous nature of the coarse wood particle and jute fiber based sample surfaces exhibited high wear.

Candelario et al.\(^\text{(6)}\) introduced graphite nanodispersoids into the microstructure of a fine-grained LPS SiC ceramics fabricated by spark plasma sintering and studied the sliding wear characteristics in regular diesel fuel (viscosity of ~ 3.8 cSt) lubricating conditions. Addition of graphite nanodispersoids was detrimental to mild wear and transition from mild to severe wear occurred in shorter time due to softer graphite particles. On other side, the addition of graphite nanodispersoids led to increased fracture toughness and provided external lubrication after grain pull-out. This was resulted in effectively decreasing wear damage for

![Graph](image.png)

**Fig. 5.** The wear rate and fracture toughness of SiC-graphene nanoplatelets composites as function of content of graphene nanoplatelets.\(^\text{(7)}\)
a prolonged sliding. Important findings from sliding wear studies of SiC based ceramics are listed in Table 2.

### 2.3. Mechanisms of material removal in sliding wear

In this section, studies relating to material removal mechanisms during sliding wear are discussed in terms of material characteristics. Different results for frictional behavior between varieties of pairs of SiC ceramics during wear indicate complexity in frictional mechanism. Kato\(^{92}\) divided wear mechanisms of SiC ceramics in sliding wear conditions into two modes: (a) mechanical wear, where various types of cracks like lateral, median and radial cracks are generated by friction around the Hertzian contact zone (see Fig.6), and (b) tribo-chemical wear, where silicon oxide was found on the surface in unlubricated sliding wear.\(^{93,94}\)

Wang \textit{et al}.\(^{43}\) found that tribological contact stresses predominantly affect mechanisms of material removal. They found that SiC ceramics removed via plastic deformation induced microfracture for less stress on contact surface. As the contact stress increased to a critical level, varieties of cracks like partial cone cracks, lateral/shallow cracks, and radial cracks etc. are generated. Further increase in contact stress propagates cracks to intersect each other and detach...
chunks of material. The detached material crushed into fine particles by further tribological contact and evolved as wear debris. The dominant damage patterns with contact stress severity for indentation, scratch, and wear tests are synchronized in Table 3.

Lopez et al.\(^{41}\) reported that for equiaxed-grained SiC ceramics, sliding wear initiated with plastic dislocation as mild wear and led to sever wear, with fracture and pull-out of material.\(^{37,69,85,95-96}\) For coarser microstructures, transition in wear mechanism occurred sooner and exhibited poor wear resistance.\(^{43,47,50,69-70,96-99}\) However, these mechanisms were not observed for highly heterogeneous ceramics such as elongated-grain LPS-SiC.\(^{51}\) For elongated grain LPS SiC ceramics, despite the grain-boundary fracture, interlocking network was responsible for the surface integrity of worn surface which delayed transition in wear mechanism.

Kovalcikova et al.\(^{86}\) studied wear mechanisms for SiC ceramics slid against different counterparts Si-N, Al₂O₃, WC-Co and ZrO₂ materials. They found microfracture and removal of oxides against any counterpart. But the extent of material removal was different. The steady state coefficient of friction and specific wear rate were affected with different tribological partners. The SiC/Si₃N₄ couple exhibited the highest friction probably due to chemical similarity of counterparts.

Andersson et al.\(^{45}\) reported two types of oxidation in sliding at elevated contact temperatures: passive oxidation and active oxidation. At elevated temperature (usually above 575°C), SiC oxidizes to SiO₂ according to the following reactions:\(^{100,101}\)

\[
\begin{align*}
2\text{SiC} + 3\text{O}_2 & \rightarrow 2\text{SiO}_2 + 2\text{CO} \quad \text{(passive oxidation)} \\
\text{SiC} + 2\text{O}_2 & \rightarrow \text{SiO}_2 + \text{CO}_2 \quad \text{(passive oxidation)}
\end{align*}
\]

Above reactions occur at an appropriate pressure in oxygen environment. If temperature is above 1000 °C, with low partial pressures of oxygen, the following reactions might occur on SiC ceramic surface.\(^{101}\)

\[
\begin{align*}
\text{SiC} + 2\text{SiO}_2 & \rightarrow 3\text{SiO} + \text{CO} \quad \text{(active oxidation)} \\
\text{SiC} + \text{O}_2 & \rightarrow \text{SiO} + \text{CO} \quad \text{(active oxidation)}
\end{align*}
\]

The SiO powder formed was brownish to yellowish in color and often formed with β-SiC powders in an argon thermal plasma jet.\(^{102}\)

Under passive oxidation layer, loose wear debris consisting of SiO₂ formed a protective and less shear strength tribofilms which further favored to reduced wear rates. Against passive oxidation layer, wear rates varied from 10⁻⁴ to 10⁻⁵ mm/N*m and the coefficients of friction was approximately 0.5. As SiO did not form tribofilms and favored to active oxidation to some extent, wear rates increased to 10⁻⁴ -10⁻³ mm/N*m and the coefficients of friction to 0.8. It was found that the additive composition had minimal effect on frictional behavior of SiC ceramics under dry sliding conditions when compared to sliding load.\(^{2}\) Wear mechanisms changed from surface grooving and micro-cracking at lower load (1 N) to dominant tribochemical wear at higher (6 or 13 N) load for all the ceramics. In other study,\(^{103}\) sliding wear behavior of SiC ceramics sintered with (0.2 wt.% or 3 wt.%) Y₂O₃ additive, microcracks induced fracture and pull-out were found responsible for the material removal.

In self-mated sliding of SiC ceramics, Gahr et al.\(^{41}\) reported that running-in period was much longer in vacuum than in humid air and would favor tribochemical smoothening of surface roughness. At a tribocontact of relatively

<table>
<thead>
<tr>
<th>Contact Stress</th>
<th>Dominant damage patterns in sliding of SiC ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indentation</td>
</tr>
<tr>
<td>Small (below the elasticity limit)</td>
<td>No damage (Elastic Deformation)</td>
</tr>
<tr>
<td>Moderate (below the plastic limit)</td>
<td>Plastic deformation</td>
</tr>
<tr>
<td>Large (near the critical failure stress)</td>
<td>Cone/Ring cracks</td>
</tr>
<tr>
<td>Very large (exceeds the critical stress)</td>
<td>Radial crack</td>
</tr>
</tbody>
</table>

Fig. 6. Various types of cracks induced by friction in un lubricated sliding wear conditions.\(^{50}\) (where W is load and F is frictional force).
smooth surface, formation of thin water film led to increased friction owing to menisci formed at asperities. On the other hand, thick water films separated the mated bodies and resulted for reduced friction due to low viscosity of H₂O and assumed a proper wettability of tribosurfaces with water film, i.e. hydrophilic surfaces.

Available data on the effect of humidity on coefficient of friction and wear rate of self-mated SiC ceramics is compiled and presented as Fig. 7. Murthy et al. found that at lower humidity, major wear mechanism was fracture of tribosurface followed by attrition, while tribochemical reaction (oxidation or hydrolysis) was a leading wear mechanism at higher humidity. Owing to the availability of more water molecules, oxidation (SiC + 2H₂O → SiO₂ + CH₄) and hydrolysis (SiO₂ + H₂O → Si(OH)₄) reactions were accelerated at higher humidity. The faster kinetics of tribochemical reactions resulted in decreased wear with a narrow difference in friction.

Li et al. observed difference in wear mechanism during sliding in water lubrication conditions for SiC ceramics prepared through different processing routes. The wear occurred by pull-out of grains, which was mainly controlled by free Si along grain boundary for the reaction sintered SiC. Tribochemical oxidation in water and local grain fracture occurred due to its low toughness for the pressureless sintered SiC. Excellent tribological properties and low friction were attributed for the hydrodynamic lubrication for the toughened SiC. It was believed that tribochemical oxidation took place and an ultraflat surface consisting of SiO₂ and (SiO₂·nH₂O) formed on the worn track.

Candelaria et al. found less wear of SiC with graphite nanodispersoids compared to SiC ceramics, due to the combination of (i) higher toughness, which hinders the crack propagation and coalescence responsible for the grain pull-out, (ii) lower hardness of the wear debris due to its lower SiC concentration, and (iii) external lubrication imposed by pull-out of graphite nanoparticles, which reduced abrasion by third bodies. Zhu et al. studied polishing of SiC ceramics in oxidant solution of 3 wt% CrO₃. The removal of material by a chemical dissolution, stimulated by friction was referred to as tribochemical.

Ciudad et al. studied wear mechanisms in diesel for pressureless LPS-SiC. They found a two-step wear process, initially controlled by plastic deformation (corresponding to mild wear regime) followed by fracture of materials (corresponding to severe wear regime). Major characteristics of surfaces in mild wear and severe wear regimes are schematically illustrated in Fig. 8. Erickson et al. observed chemical wear on mated surface as major deterioration mechanism in oil/water lubricated sliding conditions along with several mechanisms like plastic deformation, subsurface microcrack formation, microfracture and microabrasion of the surface of worn SiC. The absence of tribofilm on the contact surface indicates that wear debris transported out of the system or directly dissolved by the oil/water lubricant as water is able to dissolve SiO₂ easily.

Zhou et al. reported that the tribochemical reaction led to material removal for monolithic SiC and SiC-C (graphite) composite. For SiC, they found rough worn surfaces resulted in fracture and three body abrasion, whereas graphite particles exerted a lubricating effect and resulted in lower coefficients of friction for the SiC–C composites. Miclee et al. studied the tribological characteristics of SiC–MoSi₂ composites against alumina in dry sliding. The material loss was caused by ploughing effects, while no significant effect of brittle fracture observed on the worn surface of the ceramic composite.

Recently, sliding wear mechanisms were studied for monolithic SiC and SiC-WC composites against SiC counterbody. For monolithic SiC ceramics, blunt indenter-induced mechanical fracture with micro-cracking was found as dominant material removal mechanism, while WC addition reduced grain pull-out for SiC-WC composites leading to reduced wear rates. Analysis of debris collected from worn surfaces indicated increase in compaction or oxidation with WC addition. Wasche and Klaffke studied the wear mechanism for SiC–TiC–TiB₂ in water when slid against SiC or Al₂O₃. In case of SiC/SiC and Al₂O₃/SiC, no films were formed. An oxide film was formed during wear of SiC–TiC and SiC–TiC–TiB₂ materials. Reduction in wear of materials was affected by formation of titanium oxide at the tribo-contact. In case of Al₂O₃ ball and composite disk system, the tribooxidatively formed layer was partly adhered on to the ball. The wear of SiC–TiC or SiC–TiC–TiB₂ disk against

![Fig. 7. Average steady state coefficient of friction and wear rate of SiC ceramic with respect to humidity against SiC counterbody.](image)

![Fig. 8. Schematic illustrations of worn surface characteristics of SiC ceramics after sliding in diesel in (a) mild wear and (b) severe wear regimes.](image)
SiC or Al₂O₃ ball was reduced by a factor of 10 compared to monolithic SiC disk system.

3. Erosion Wear of SiC Ceramics

Erosion can be defined as removal of material from a surface due to interaction between the surface and a fluid, or impinging liquid or solid particles. Considerable research has been carried out in understanding solid particle erosion wear behavior of SiC ceramics and their composites.

3.1. Effect of microstructure and mechanical properties

Solid particle erosion of SiC ceramics and their composites is reported to occur generally by brittle fracture as a result of lateral and radial cracking. Bell and Rogers noted fracture toughness as predominant factor in estimating erosion wear characteristics of brittle materials at normal impact of erodent, whereas hardness was found important at low impingement angles. Shetty et al. also reported hardness as predominant property of reaction-bonded SiC ceramics to estimate erosion behavior of ceramics. Routbort and Matzke studied the erosion for SiC ceramics prepared through hot-pressing and reaction-bonded sintering techniques. The Vickers hardness (H) and fracture toughness (Kᵥc) of these ceramics were used to estimate the erosion rate (∆W) of ceramics using following equation:

\[ \Delta W = C H^a K_{vc}^b \]  

where, C is proportionality constant and the exponents a and b valued according to details of the used erosion model (see Table 4). However, the wear rates estimated using existing wear models were not in agreement with the experimentally measured wear rates. This can be primarily attributed to the fact that these models neglected important contributions from microstructure of the target material in estimating erosion loss.

Wang et al. studied the effect of microstructure on erosive wear of SiC ceramics, prepared by pressureless sintering, hot pressing and hot isostatic pressing techniques. Microcracking with some extent of plastic deformation was observed as main material removal mechanism at higher impact angles. Grain refinement and reduction in the amount and size of pores of hot isostatically pressed SiC resulted in superior wear resistance.

SiC ceramics sintered with 10, 30 or 50 wt% WC particles via hot press technique were subjected to erosion against SiC and alumina erodent. Compared to erosion rates against alumina erodent, erosion rates against SiC erodent increased by two orders (from 10 to 10⁻³ mm³/kg) for normal impingement (see Table 5). SiC ceramics achieved steady state erosion after 5 min of erosion against SiC erodent which delayed to 20 min against alumina. Maximum erosion resistance was obtained for SiC ceramics sintered with 30 wt% WC which possessed maximum hardness. SiC ceramics sintered with 50 wt% WC ceramics having highest fracture toughness showed lower wear resistance than SiC ceramics sintered with 30 wt% WC (see Fig. 9). This implies that hardness played important role in erosion of SiC-WC composites.

<table>
<thead>
<tr>
<th>Materials</th>
<th>HP-SiC</th>
<th>RB-SiC+0.2 vol% Si</th>
<th>RB-SiC+0.13 vol% Si</th>
<th>Measured Erosion Rate (× 10⁻³ g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.54</td>
<td>0.73</td>
<td>0.80</td>
<td>2.00</td>
</tr>
<tr>
<td>Kᵥc</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>12.00</td>
</tr>
<tr>
<td>H</td>
<td>1.34</td>
<td>16.20</td>
<td>18.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Kᵥc</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Table 4. Values of (H, Kᵥc) Calculated for the Various Steady-state Erosion Models and Experimentally Measured Erosion Rates for SiC Ceramics. HP-SiC and RB-SiC respectively Indicate Hot Pressed SiC and Reaction bonded SiC, while H and Kᵥc Indicate Hardness and Fracture Toughness, Respectively

<table>
<thead>
<tr>
<th>Material</th>
<th>Average erosion rate (mm³/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina erodent</td>
<td>1044.63</td>
</tr>
<tr>
<td>SiC- 30 wt% WC</td>
<td>850.73</td>
</tr>
<tr>
<td>SiC- 50 wt% WC</td>
<td>1223.24</td>
</tr>
</tbody>
</table>

Table 5. Average Erosion Rates of SiC–WC Composites at Normal Impact of Alumina and Silicon Carbide Erodents

![Fig. 9. Eroded surfaces of (a) SiC (b) SiC-30 wt % WC and (c) SiC-50 wt % WC composites at normal impact of SiC erodent.](image) Hardness data for the respective ceramics is also shown.
Wang and Levy\textsuperscript{(123)} studied the erosion behavior of SiC fiber reinforced SiC composite at 25°C and 850°C and found an inverse relation of density and hardness to the erosion rate of the composite. The erosion rate reduced by one order of magnitude at 850°C (0.10 mg/g) compared to that at 25°C (2.20 mg/g). At 850°C, the difference between erosion rates at 90° and 30° (0.02 mg/g) was much less than that found at 25°C (1 mg/g), which attributed to increased ductility of composite at 850°C. Similarly in a recent study,\textsuperscript{(66)} solid particle erosion rate of SiC-Si$_3$N$_4$ composite at elevated temperature increased firstly up to 800°C, and then decreased with increase in temperature to 1400°C. At lower temperature (up to 800°C), wear occurred by brittle fracture where stripping of aggregates of composite resulted in loss of protection from the matrix. On the other hand, plastic deformation and oxidation protection dominated at higher temperature (beyond 800°C). The highest erosion rate at 800°C for SiC-Si$_3$N$_4$ is contradictory to the lowest erosion at 850°C for SiC ceramics.\textsuperscript{(66)}

Amirthan et al.\textsuperscript{(124)} found cleavage like brittle fracture on biomorphic Si/SiC composite surface exposed to erosion. Fine teak wood particle based Si/SiC composite showed least erosion compared to other Si/SiC composite. Further, coarse teak wood particle based Si/SiC composite with large pores caused the highest erosion rate. Lopez et al.\textsuperscript{(125)} studied the erosion behavior of biomorphic (eucalyptus and pine reinforced) SiC, reaction-bonded SiC, and hot-pressed SiC and found that erosion resistance was highest for biomorphic based SiC ceramics. Owing to the highest hardness, hot-pressed SiC exhibited least erosion rate.

### 3.2. Mechanisms of material removal in erosion wear

The dominant mechanisms of material removal in solid particle erosion wear conditions of brittle ceramics are elastic-plastic deformation based micro-fracture, and crack formation below the plastic zone of subsurface.\textsuperscript{(62,67,110-112)} Major findings from studies on erosion wear mechanisms for SiC ceramics are listed in Table 6.

A detailed investigation of impact sites of worn surface in brittle materials exhibits an intense plastic deformation beneath the immediate area of the contact.\textsuperscript{(116-119)} The elastic-plastic zone at the impact site is the major driving force for the surface fracture that led to material loss on erosion.\textsuperscript{(116-119)} The residual stresses generated under plastic zone on impact of erodent to the brittle materials originate small lateral cracks to grow beneath the impact sites. Initially

| Table 6. Summary of Major Findings from Studies on Erosion Wear Mechanism for SiC Based Ceramics |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Materials (SiC based ceramics/ erodent) | Erosion test parameters | Major findings References |
| Reaction Bonded SiC/ Angular Al$_2$O$_3$ | Particle velocity & feed rate: 53.8 m/s to 150.7 m/s, feed rate of 8 gm/min | The steady state erosion rate was lower for smallest erodent particle. With leading brittle fracture, some plasticity also observed in the SEM micrographs. |
| Biomorphic SiC, Reaction-bonded SiC, and hot-pressed SiC/ Angular SiC | Particle velocity 100 m/s, feed rate of 8 gm/min | Both lateral and radial cracks formed for biomorphic SiC ceramics, whereas reaction-bonded SiC eroded by formation and propagation of only lateral cracks. Hardest hot-pressed SiC ceramic found as the most erosion resistant. |
| $\alpha$-SiC target specimens/SiC | Velocity 35, 65 and 90 m/s, feed rate of 10 g/min, | Reduced amount and size of pores, and reduced grain size led to improved wear resistance. Microcracking and some extent of plastic deformation was found as dominant material removal mechanism is mainly with some extent of plastic behaviour of materials. |
| Hot-pressed monolithic SiC and SiC-TiB$_2$/ Angular SiC | Particle velocity 40–100 m/s, feed rate: 0±0.5 gm/min, | The erosion rate was lower for monolithic SiC with higher hardness value than SiC-TiB$_2$ composite of higher fracture toughness. Erosion of these materials was controlled significantly by the plastic deformation. |
| SiC$_p$-SiC / Silica sand | Particle velocity 32 m/s and 44 m/s, feed rate: 1 kg/min, | Higher hardness of SiC$_p$-SiC composite with carbon interface led to least erosion. Composite with boron nitride interface showed lower hardness and higher erosion loss. |
these cracks propagate parallel to the impacted zone of target surface and further interact to the surface resulting in material loss. Wang and Mao\textsuperscript{113} observed that size and type of cracks generated on the eroded surface are dependent on several factors like erodent shape and size, mass flow rate, velocity and angle of impingement of erodent, temperature and hardness, toughness and microstructure of target material.\textsuperscript{61, 63, 113-114}

Two types of crack systems are generally found in erosion at low velocities; (a) cone cracks generated due to impact of blunt (rounded) erodents\textsuperscript{113,134-135} and (b) lateral and median cracks generated due to impact of sharp (angular) erodent angular.\textsuperscript{113,126,136-137} In case of high velocities of erodent, material is removed by plowing, severe cracking and chipping.\textsuperscript{110,113,130,132,134} In other study,\textsuperscript{69} precise mechanisms for the erosion of reaction bonded-SiC were not clear, but reduced erosion wear rate of mixed phase SiC-Si region was related to either by arresting of cracks around the small SiC grains or by increased apparent volume fraction of uncov ered erosion resistant fine SiC grains of the two-phase region, generated beneath the impacted sites.

Suh \textit{et al.}\textsuperscript{137} studied the effect of SiC fiber reinforcement on erosion wear of SiC ceramics. During erosion of the composite, initially SiC fibers were detached from the interface and matrix of SiC subsequently eroded out. Pores presented in matrix with aperture around the fibers led to easy removal of material from the impact sites. The erosion wear was also attributed to issues regarding durability and reliability that depend on geometric discordance, irregular performance, and related energy dissipation.

Gochnour \textit{et al.}\textsuperscript{138} studied erosion behavior of SiC-Al\textsubscript{1}OC composites against alumina erodent. They found surface appeared smooth and polished, with grain pull-out regions in erosion of SiC-5wt % Al\textsubscript{1}OC composites. Softer Al\textsubscript{1}OC phases resulted in grain pull-out regions and smooth zones were corresponded to wear of harder SiC phase. However, severe grain pull-out occurred in erosion of SiC-50 wt % Al\textsubscript{1}OC composite and resulted in isolated smooth regions only. The steady-state erosion rate (\(\Delta E\)) for brittle materials was proportional to erodent size and found to be related as

\[
\Delta E \propto R^{2/3}
\]

where R is the erodent radius.\textsuperscript{113,139} This was predicted by both the dynamic\textsuperscript{118} and the quasi-static\textsuperscript{136} theories of erosion for brittle materials. However, Kim and Park\textsuperscript{140} found that erosion rates of SiC and SiC-TiB\textsubscript{2} were not increased monotonically with the increased erodent size, in contrast to the prediction by theories. The eroded surface of SiC exhibited deformed lips and cracks, whereas intergranular fracture observed together with deformed lips for SiC-TiB\textsubscript{2} composite.

Limited reports are available on erosion behavior of SiC ceramics and composites as function of temperature. Wang and Levy\textsuperscript{49} reported that erosion for SiC fiber reinforced SiC composite at 25°C occurred by cracking and chipping of the matrix as well as the fibers, while erosion rates considerably decreased at 850°C owing to the increased ductility. Li \textit{et al.}\textsuperscript{113} studied the erosion mechanism for SiC-Si\textsubscript{N}\textsubscript{3} composites at different temperatures (25°C-1400°C). At low temperature, material removal occurred mainly by brittle fracture and stripping of aggregates as the protection from the matrix was lost. At higher temperature, erosion mechanisms were primarily ascribed to plastic deformation as well as oxidation protection. Oxidation of Si\textsubscript{N} and SiC on the material surface at 1400°C generated a thin dense layer of SiO\textsubscript{2} glassy film, which further reduced direct contact of erodent with the material surface at a certain extent and resulted in less loss of the material (illustrated schematically as Fig. 10).\textsuperscript{141}

4. Summary and Future Scope

Considering the wide range of tribological applications, wear behavior of SiC and its composites is extensively studied. In the present review, tribological characteristics of SiC ceramics and composites in sliding and solid particle erosion conditions are comprehensively discussed.

It is found during sliding that wear and friction characteristics of SiC ceramics vary with microstructural alteration. Hard interlocking network of elongated grains or high aspect ratio grains led to enhanced wear resistance. Second phases and intergranular phases also play a dominant role on wear and friction behavior. SiC ceramics with reduced weak second phase content and grain refinement exhibited improved wear resistance. Further, SiC ceramics with clear grain boundaries showed improved wear resistance compared to amorphous grain boundaries. The transition from mild to severe wear occurs for SiC ceramics with coarse grain structure than with fine grain structure. Doping elements affect kinetics of tribochemical reaction and lead to different characteristics of friction and wear. In understand-
ing the influence of mechanical properties on wear of SiC ceramics, research is mainly debated on the dominant effect of fracture toughness and hardness. It is widely accepted that crack deflection or crack bridging by reinforced phase led to less extent of material removal during sliding wear of SiC composites. Furthermore, the ratio of hardness and fracture toughness \( (H/K_c) \), known as brittleness index is found to give qualitative estimation of wear for SiC ceramics. Superior resistance to wear was found for ceramics with high brittleness index. Reinforced phases like graphene nanodispersoids led to an increase in fracture toughness and reduced hardness, the combination of which reduced the mild to severe wear transition.

Sliding wear mechanisms of SiC ceramics and composites can be categorized into two groups: mechanical and tribochemical. In mechanical wear, cracks and abrasion dominate the worn surfaces of SiC ceramics, whereas oxides were found on the tribosurface in tribochemical wear. With regards to contact stress conditions, wear occurred through plastic deformation induced microfracture in low contact stress, whereas cracks induced fracture led to material removal in high contact stress. High friction is found against the counterpart having chemical similarity with SiC ceramics, whereas composition of sintering additives had minimal effect on frictional behavior of SiC ceramics. At elevated sliding temperature, two types of oxidation: passive oxidation with reduced wear and active oxidation with increased wear are reported for SiC ceramics. Running-in period is reported to be higher in vacuum than in humid air for SiC ceramics. Tribochemical smooth layer formed in humid air led to less friction. During oil/diesel fuel lubrication, wear occurred in two steps: initially controlled by plastic deformation and then followed by subsurface microcrack formation, microfracture and micro-abrasion.

Solid particle erosion rate is found to be higher whereas steady states attained earlier against harder erodent particles. Erosion resistance is improved for harder SiC ceramics. Grain refinement and reduced amount and size of pores resulted for superior resistance against erosion. Erosion rates of SiC ceramics were estimated by semi-empirical models with mechanical properties like hardness, fracture toughness and elastic modulus. Since none of the proposed models for erosion prediction/estimation was completely satisfactory, it advocated necessary incorporation of microstructural aspects into erosion theories. Incorporation of SiC fibers in SiC matrix resulted in improved erosion resistance at elevated temperature. The difference in erosion rate with change in impingement angle of erodent also found to be less at high temperature. In general, erosion rate of SiC composites increased with increase in temperature up to 800°C and attributed to brittle fracture and stripping of aggregates. Further increase in temperature up to 1400°C resulted in the formation of silica based glassy film and decreased erosion.

Solid particle erosion for SiC ceramics is reported to occur by elastic-plastic deformation based microfracture followed by subsurface crack formation beneath the plastic zone. Size and type of cracks are found to dependent on erodent shape and size, mass flow rate, velocity and angle of impingement of erodent, temperature, hardness toughness and microstructure of target materials. In case of low velocities of erodent, dependent on shape of the erodent, two types of cracks were generally reported. On impact of blunt erodent, generation of cone cracks are observed whereas lateral and/or median cracks are generated beneath the plastically deformed surface against sharp erodent. For high velocities impact of erodent, material removal from target surface is removed by plowing, severe cracking and chipping. Erosion wear of SiC ceramics was dependent on the characteristics of second phase such as geometry, durability, energy dissipation etc. During erosion, SiC fiber reinforced SiC composites initially detached out of matrix which further left pores and then resulted in easy removal of SiC ceramics. Shape, size and size distribution of erodent particles influence erosion of SiC ceramic composites.

The future scope of tribological characteristics of SiC ceramics and composites can be realized. The incorporation of microstructural parameters in contemporary wear model/theories is essential to estimate material removal in sliding or erosion conditions. Most of the studies reported high temperature wear behavior using mechanical and microstructural characteristics of SiC ceramics estimated at ambient temperatures, whereas the effect of mechanical and microstructural features at elected temperatures is to be considered for estimating true potential. Furthermore, SiC ceramics and composites have not been considerably studied for understanding their behavior in low temperature wear applications. A future study on the effect of mechanical or microstructural characteristics at low temperature would explore the potential of SiC ceramics and composites for their use in space or marine applications. Also, the physics of degradation in different wear conditions has to be thoroughly understood. Considering expected improvement of properties in nano composites, the wear behavior of SiC nano ceramics or nano composites is also to be investigated. Studies can also be extended to understand the performance of SiC based cerments for their attractive combination of hardness and fracture toughness. Material removal mechanisms of SiC ceramics in other types of wear like cavitation wear, fretting wear, slurry erosion, corrosion wear etc. are to be thoroughly understood. While most of the reported studies are focused on understanding the behavior in aerospace, automotive, chemical, manufacturing, defense applications, exploring tribological potential of SiC composites for their use in other important fields like nuclear, biomedical, electronics etc. is also a prospective future direction.

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