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Tribological behavior of silicon nitride-based ceramics - A review

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ABSTRACT

Silicon nitride ceramic owing to its excellent fracture resistance and high strength behavior, has find its place in industry as well as in biomedical applications. The works related to the tribological behavior of silicon nitride based ceramic materials against different material combinations were reviewed in this study. The experimental studies which include POD pin-on-disc (POD) tribometer (mostly for commercial applications), hip simulator (for orthopedic applications) and computational approaches were mostly used to investigate the wear behavior. The effect of friction, wear rate and hardness of these ceramics based on other influencing parameters were summarized. Overall, the tribological behavior of silicon nitride-based ceramics showed better tribological behavior rather than silicon nitride depending on various applications. The use of different bio-lubricants also showed improved wear behavior because of reduced dissolution rate of silicon nitride for biomedical applications. The parameters like loads, sliding distance, type of lubricant used, material combination influencing tribological behavior were highlighted in this study based on field of applications.

1.0 INTRODUCTION

Silicon nitride (Si_3N_4) being non-oxide ceramic has superior mechanical properties compared to that of alumina (Al_2O_3) and zirconia (ZrO_2)(Bal and Rahaman, 2012). Due to the absence of oxide groups, which is comparatively brittle in nature, silicon nitride has better wear resistance

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and finds its applications in many fields like automotive, industrial and biomedical. Silicon nitride based composites like carbon nano tube (CNT) reinforced silicon nitride showed improved fracture toughness which could be used in biomedical, aerospace and defense applications(Qadir et al., 2020). The first synthesis of Si_3N_4 ceramic was developed by Deville and Wöhler in 1859(Riley, 2000). The excellent biocompatible properties of Si_3N_4 without any cytotoxic effect has found tremendous applications in biomedical field, particularly for joint replacement applications (Bal and Rahaman, 2012).

The diversified applications of Si_3N_4 have made many researchers to study and investigate the tribological behavior of Si_3N_4 against different material combinations to predict friction and wear behavior in service life. Most of the tribological studies in biomedical applications were conducted via in-vitro or experimental way by means of POD or ball-on-disc (BOD) tribometer and hip joint simulator depending on applications. In addition to that, effect of different lubricants on friction and wear were also investigated. Alongside bulk Si_3N_4 , Si_3N_4 coated substrate or bulk Si_3N_4 coated with different materials like N, C, Cr, Nb and diamond like carbon (DLC) film were also investigated for orthopedic applications (Correa et al., 2020; Pettersson et al., 2013; Schmidt et al., 2019; Shi et al., 2012). The detailed wear behavior of Si_3N_4 under different loading and temperatures were mentioned elsewhere(Dong and Jahanmir, 1993). The wear behavior of self-mated Si_3N_4 as well as with different materials were investigated based on humidity and microstructure (Takadoum et al., 1998). The effect of sintering aids like Y_2O_3, Al_2O_3 and Ytterbium oxide (Yb_2O_3) helps in enhancing the mechanical properties of silicon nitride under shear and tensile loading as reported in literature though silicon nitride lacks oxide element (Bocanegra and Matovic, 2010). Generally, there are three methods used for manufacturing of ceramics for joint replacements in particular subtractive manufacturing is widely used. Other two techniques include near-net-shape and additive manufacturing process. However, to make intricate shape of the components, subtractive process could not be used, for that, near net shaping process is adopted, though each technique has own advantages and disadvantages (McEntire et al., 2015).

Most of the articles available in literature on Si_3N_4/ Si_3N_4 based composites focused on industrial and biomedical applications (Bal and Rahaman, 2012; Qadir et al., 2020; Rahaman and Xiao, 2018) and deposition techniques of Si_3N_4 rich thin films(Kaloyeros et al., 2017). In that respect tribological aspect of Si_3N_4/ Si_3N_4 based composites as well as coated Si_3N_4 substrate was somewhat out of the focus, in spite of potential tribological applications of Si_3N_4. Keeping this shortcoming in mind, usage of Si_3N_4 from tribological applications point of view were reviewed for the first time in this study. Different parameters influencing the tribological behavior such as load, sliding distance, type of lubricant was also reviewed in this current study. The detailed flow chart regarding materials and methodology on tribological investigation of Si_3N_4 is shown in Fig.1. In addition to that, computational approach using modeling software like ANSYS/ABAQUS to investigate the contact pressure and its influence on wear were also discussed. Such comprehensive review will help researchers to figure out the current status on tribological aspects of Si_3N_4 related research along with limitations and future prospects.

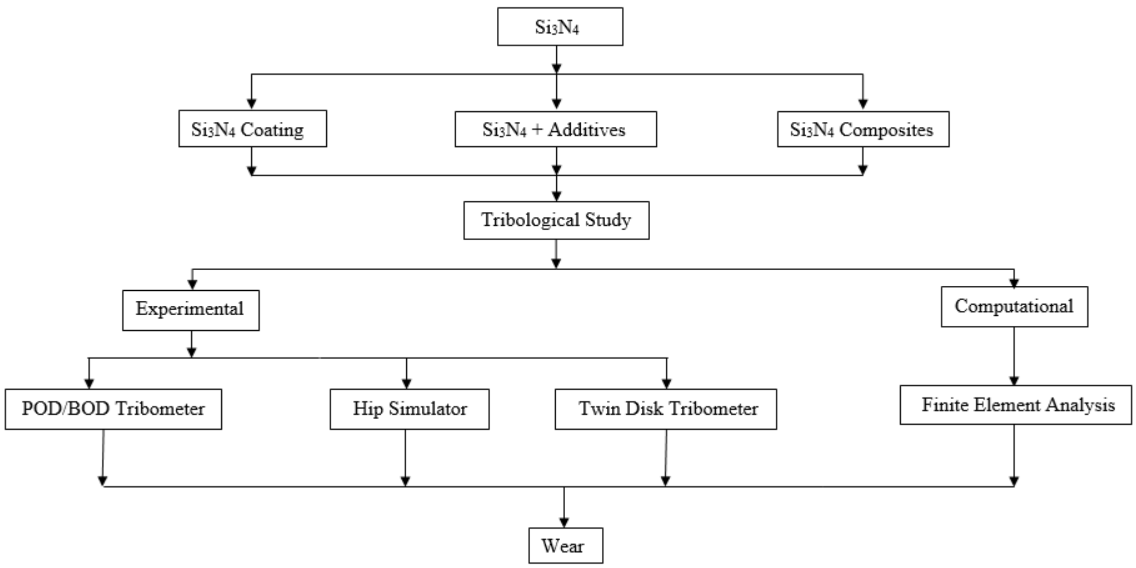

Figure 1: Overview of tribological study of Si_3N_4 and its associated materials.

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2.0 SILICON NITRIDE FOR BIOMEDICAL APPLICATIONS

As mentioned in previous section, due to excellent mechanical properties as well as superior biocompatibility over other ceramics and metallic implants, Si_3N_4 components are widely adopted for biomedical applications (Webster et al., 2012). Most of the time, Si_3N_4 based composites are blended with additives like titania (TiO_2) and calcia (CaO) which results in improved fracture toughness and cell proliferation without any cytotoxicity(Guedes et al., 2020). Alongside additives, surface treatment of Si_3N_4 usually carried out in cryogenic medium which found to be enhance bioactivity of the components (Bock et al., 2015; Hnatko et al., 2020). Similarly surface coating of Si_3N_4 with different substrates were investigated for better tribological properties(McEntire et al., 2015; Pettersson et al., 2013; Schmidt et al., 2019). The Si_3N_4 along with hexagonal boron nitride (hBN) composite was investigated against alumina for improving wear rate using Taguchi method(Ghalme et al., 2016). The metal ion release into blood stream was prevented by surface coating of Si_3N_4 on CoCrMo (Pettersson et al., 2016). In addition, the antibacterial property of Si_3N_4 along with other biomaterials like PEEK and Ti promoted bone growth and osseointegration (Webster et al., 2012; Wu et al., 2020). The combination of SiAlON - Si_3N_4 ceramic composite for artificial implantation was found to be highly biocompatible and could be used as a potential joint replacement material (Zhang et al., 2020). Also another study showed that wear rate was minimum for hip implant made of ceramic composites which include different reinforcements like zirconium oxide, magnesium oxide, chromium oxide and aluminum oxide. The result showed that least wear rate was found for composite containing 2.5 wt.% silicon nitride (Goswami et al., 2019). Recently, robocasting technique together with sintering/ hot isostatic pressing (HIP) was developed to fabricate implants from Si_3N_4 (Zhao et al., 2017). All these recent findings showed that Si_3N_4 could be incorporated with different materials to form Si_3N_4 based composites with improved biocompatibility that favor bone growth without any cytotoxic effect.

3.0 IN-VITRO TRIBOLOGICAL BEHAVIOR of Si_3N_4/ Si_3N_4 COMPOSITES

In-vitro experiments are conducted in mimic biological environment outside the real biological medium to identify the behavior of material under simulated conditions. This approach is widely used to evaluate the behavior of materials intended for biomedical applications. The parameters considered in tribological study of Si_3N_4/ Si_3N_4 composites for hip joint replacement include gait load, duration of test being carried out, type of bio-lubricant used, cup inclination angle, head diameter and microseparation. Mechanical properties of some common materials for biological applications, together with Si_3N_4 are shown in Table.1. Some of the mechanical properties of $Si_3N_4$and Si_3N_4 based materials like SiAlON were found to be far superior than widely used Al_2O_3 ceramics. This once again proves that Si_3N_4 based materials could improve the tribological behavior and gives insights to further improvements and developments in near future.

3.1 Tribological Study Using Hip Simulator

For joint replacements, friction and wear rate were investigated for material combinations for acetabulum cup and femur head used in hip prosthesis. Wear behavior of Si_3N_4-CoCr and Si_3N_4-Si_3N_4 pair was investigated for 1.2 million cycles and result showed that Si_3N_4- Si_3N_4 exhibited coefficient of friction (CoF) of 0.001 compared to 0.08 with Al_2O_3- Al_2O_3. Si_3N_4-CoCr combination showed lesser wear than Al_2O_3- Al_2O_3 (Bal et al., 2008). Similar kind of studies like Si_3N_4-CoCr and Si_3N_4- Si_3N_4 pair for 10 million cycles also showed lower wear rate than Al_2O_3- Al_2O_3 pair (Bal et al., 2009). The hip simulator wear study of Si_3N_4 for different head diameters and radial clearances were investigated and volumetric wear rate was low for 36 mm diameter even for larger radial clearance(Häußler et al., 2014). The wear of Si_3N_4 against CoCr and PE were investigated for 5 million cycles and result revealed that Si_3N_4 - PE combination showed excessive wear than that of Si_3N_4- CoCr (B. J. McEntire et al., 2016). The different parameters adopted using hip simulator to study the wear rate of biomaterials is shown in table.2. Overall, Si_3N_4 with metallic combination showed improved tribological behavior and also exploring the possibilities of using ceramic-on-metal (C-o-M) combination in hip joints or coatings of Si_3N_4 on metallic substrate for joint replacements (Schmidt et al., 2019).

Table 1: Mechanical properties of some common materials for tribological applications.

Sl. No.	Material	Density (g/cm^3)	Grain Size (μm)	Poisson Ratio	Thermal Conductivity (W/m.K)	Thermal Expansion Coefficient ($10^{-6}K^{-1}$)	Tensile Strength (Mpa)	Comp. Strength (Mpa)	Elastic Modulus (Gpa)	Hardness (Gpa)	Fracture Toughness ($Mpa.m^{1/2}$)	Flexural Strength (MPa)	Surface Composition
1.	Si_3N_4	3.15-3.26	0.4	0.25-0.27	30 - 40	3.0 - 3.5	350-400	2500-3000	300-320	13 - 16	8-11	800-1100	$SiNH_2$ & SiOH Groups
2.	Al_2O_3	3.97	2.6	0.27	30	8.0 - 8.5	250-300	2000-3000	400-450	14 - 16	3.7	300-500	Al_2O_3
3.	ZTA	4.15	2.4	0.24	23	8.5	360	4300	350	14.71	4.8	1000	Al_2O_3/ 20% ZrO_2
4.	PSZ	5.75	40	0.23	3	10	500	2000	250	10.3	11.3	1050	MgO-ZrO_2
5.	SiC	3.14	2.3	0.35	110	7.9 - 11	240	130 - 1395	90 - 137	26.38	3.7	550	Si-0.5% free C
6.	SiAlON	3.25	5.6	0.24	21	3.3 - 3.7	400-700	1500 - 4500	275 -300	14.12	6.1	760	$Si_3Al_3O_3N_5$
7.	AISI 52100 Steel	7.8	0.33 ± 0.08	0.27-0.30	46.6	11.9	968 ± 30		325	18.1±0.5	5.5 ± 0.1		
8.	CoCr	8.5		0.27-0.32	100	14		600 - 1800	210-250	3-4	50 - 100	800-1000	CoO/Cr_2O_3
9.	UHMWPE	0.93-0.94		0.4	0.42 - 0.51	130 - 200	386-483		0.894-0.963	6.28 - 8.14	1.72 - 5.6	214-276	UHMWPE
10.	GCr15 Steel	7.81		0.27-0.30	46.6		1902		190-210	63		1617	
11.	Titanium Alloy	4.43	1 - 24	0.3	6.7	8.6 - 9.6	920-980	950 - 990	110	3.4	75	48 - 320	Ti6Al4V
12.	GH2132 (Stainless Steel)	818			14.2		1050		0.414	29			
13.	Inconel 718	8.192		0.291	6.5		965		204.905	32 - 40		550	Nickel Alloy

Table 2: Hip simulator tribological study of different biomaterial combination with Si_3N_4.

Sl. No.	Material Combination	Simulator Type	Bio-Lubricant	Million Cycles	Volumetric Wear	Reference
1.	Si_3N_4-CoCr /Si_3N_4- Si_3N_4	Bi-Directional rotating Cams - 23° arcs on orthogonal axes hip simulator	90% bovine serum + 10 % standard additives of sodium azide and ethylene-diamine-tetra-acetic acid	1.2	0.2 mm^3 & 0.18 mm^3	(Bal et al., 2008)
2.	Si_3N_4-Si_3N_4/Si_3N_4-CoCr	Unidirectional rotating cams - 23° arcs on orthogonal axes hip simulator	90% bovine serum + 10% standard additives of sodium azide and EDTA)	1	0.2 mm^3 & 0.18 mm^3	(Bal et al., 2009)
3.	Zirconia platelet toughened alumina - silicon Nntride (Al_2O_3-Si_3N_4)	Servo-hydraulic hip simulator	Newborn calf serum supplemented with Ethylene-Diamine - Tetra acetic acid	5	135.72 ± 7.17 mm^3	(Häußler et al., 2014)
4.	Si_3N_4-XLPE/Si_3N_4-Si_3N_4	12-Station SWM hip simulator	Alpha-calf serum	0.5 - 5	53.1 ± 4.8 mm^3 & 66.0 ± 5.8 mm^3	(B. J. McEntire et al., 2016)

3.2 Tribological Study Using POD/BOD Tribometer

3.2.1 Based on Biomedical Applications

The POD tribometer is mainly used to predict the tribological behavior of different material combinations under dry as well as lubrication conditions (Aher et al., 2020; Nuraliza et al., 2016; Sapawe et al., 2014). The coated Si_3N_4 balls of two different diameters against CoCrMo alloy discs was investigated using reciprocating BOD wear test machine for 10000 cycles using two different loads. The wear coefficient was found to be lower for coated Si_3N_4 sample(Schmidt, Leifer, et al., 2019). The wear study of sintered Si_3N_4 balls against Si_3N_4 was investigated using BOD tribometer in simulated body fluid (SBF) environment and found two folds reduction in wear rate(Das et al., 2018). The wear of ultra-high molecular weight polyethylene (UHMWPE) against Si_3N_4 was evaluated using BOD tribometer under four sliding modes and result revealed that lower mass loss was observed for uni-directional reciprocating sliding(Ge et al., 2008). The POD tribometer wear study of Si_3N_4–hBN (hexagonal boron nitride) composites- Al_2O_3 combination was studied and result revealed that 8 % hBN in Si_3N_4 showed minimum mass loss(Ghalme et al., 2016). The wear studies of Si_3N_4- Si_3N_4 using POD was investigated for different bio-lubricants and showed least wear rate for PBS and bovine serum lubricants(Olofsson et al., 2012). The wear of $Si_xC_yN_z$ against Si_xN_y coatings for 1000 and 10000 revolutions was investigated using POD for bio-lubricant and coatings showed lower wear resistance(Pettersson et al., 2013).

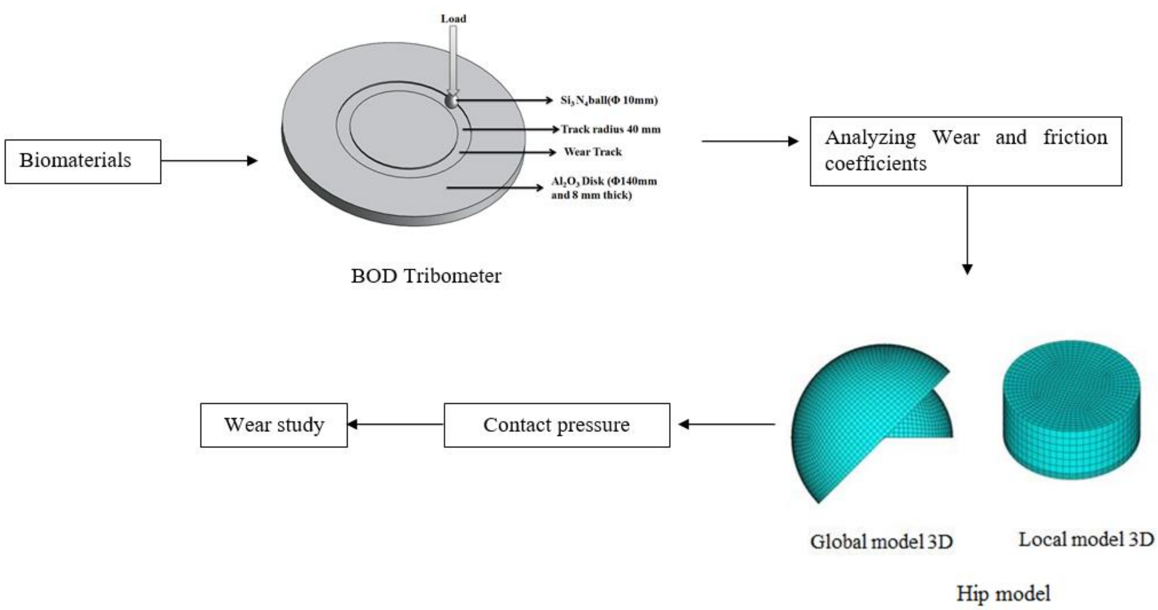
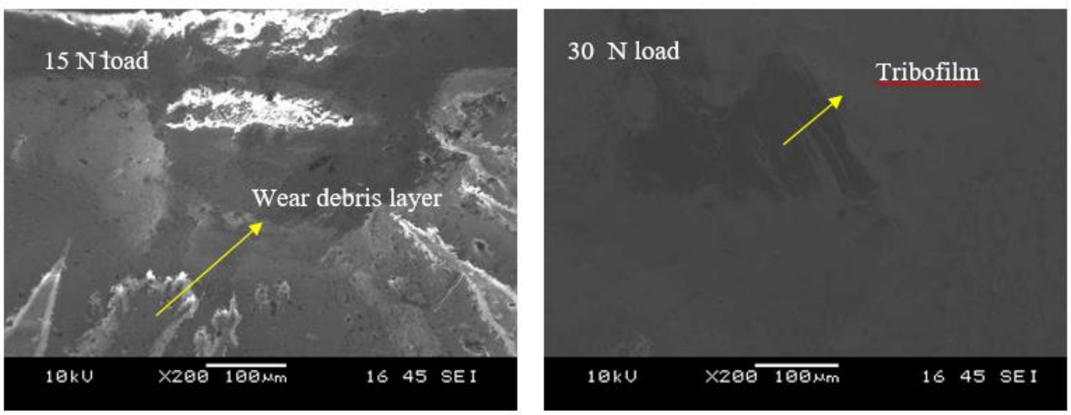
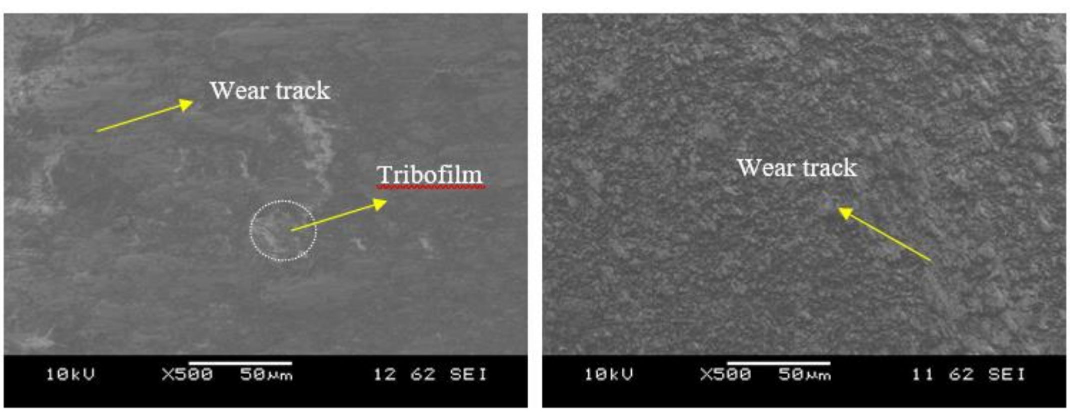


Figure 2: Combined experimental and numerical approach in tribological study of Si_3N_4 as hip-joint implant.

The silicon nitride coated CoCrMo disc investigated against UHMWPE under bovine serum lubrication showed least wear rate and best suited for joint replacement (Correa et al., 2020). Another study using similar approach with modified tribometer to hold coated femur head against UHMWPE disc revealed that coating had lesser impact in wear and friction(Schmidt et al., 2019). The coated Si_3N_4 on CoCr against Si_3N_4 ball under bovine serum lubrication showed that coated CoCr showed better reduction in wear rate (Olofsson et al., 2012). The SiN_x coated CoCr alloy against Al_2O_3 was investigated using reciprocating BOD under bovine serum lubrication and result revealed that wear debris generated were in nanometer range and could be used as potential material for joint replacement(Pettersson et al., 2016). The diamond like carbon (DLC) coated on Si_3N_4 substrate against Si_3N_4 showed decrease in friction and wear rate under dry condition (Bhattacharya et al., 1991). The hip joint loads are converted to equivalent BOD load with sliding velocity of 0.7 m/s equivalent to walking cycle of human being exhibited in their day-to-day activities. The wear and friction coefficients obtained from experimental study were given as input to FEA model to obtain the contact pressure for gait activities. Then volumetric wear is computed for million cycles (Shankar et al., 2020; Shankar et al., 2020). The BOD tribometer wear study of Si_3N_4- Ti6Al4V under five different bio-lubricants was investigated for sliding distance of 20km and results showed that phosphate buffer saline (PBS) showed minimum wear (Shankar et al., 2020).



SEM image of Si_3N_4 against $A1_2O_3$ under low and high load for hip joint application.



SEM image of Si3N4 against Ti6Al4V for PBS bio-lubricant

Figure: 3 SEM image showing wear track of Si3N4 (Shankar et al., 2020).

The wear of Si_3N_4- Si_3N_4 under purified water bio-lubricant was investigated for different loads and high friction was observed due to breakdown of lubrication film (Özmen, 2016). The wear of Si_3N_4 against itself and titanium alloy was investigated based on finite element modeling using Archard wear law(Shankar and Nithyaprakash, 2014; Shankar et al., 2020). For physically demanding human gait activities Si_3N_4-Al_2O_3 combination was found to be better as they showed reduced wear (Shankar et al., 2020). The bio-lubricants reduced the wear rate by forming tribofilm due to adhesion of wear particles which leads to smoothening of surface asperities and reduced wear and friction coefficients. The detailed experimental and computational approach to estimate wear of biomaterial in joint replacement was shown in fig.2. The fig.3 shows wear track of Si_3N_4 under different loads and bio-lubricants with different material combinations revealed tribofilm formation helped in reducing wear and friction. The experimental data obtained which include friction and wear coefficient from hip simulator/BOD were used in computational approach to estimate wear. The global and local modeling was used to investigate the contact stress and wear from hip model. All the findings revealed that Si_3N_4 could be a better pair for both ceramic as well as metallic combinations for joint replacements as it showed improved wear resistance than existing ceramic and metallic combinations.

3.2.2 Other Commercial Applications

The tribological behavior of Si_3N_4 against titanium alloy in sea water lubrication was investigated for different loads and found elevated wear and friction under high loads (Zhang et al., 2019). The titanium and Si_3N_4 coated stainless steel specimen showed better reduction in wear rate and at elevated temperature coating had negligible influence in reducing wear (Mitchell and Stott, 1992). The tribological behavior of Si_3N_4 and Si_3N_4 based composite containing graphene with SiC and Si_3N_4 investigated using BOD showed that latter had better wear resistance (Maros et al., 2016). The Si_3N_4- Si_3N_4 rolling sliding contact tribological behavior was investigated and showed steady state wear rate due to formation of thin film in contact (Akazawa et al., 1986). Similarly, tribological study of Si_3N_4 for rolling and sliding using twin disk tribometer against hardened steel in sea water lubricant was investigated experimentally and numerically to analyzed to investigate wear propagation (Khader et al., 2012). The modified Si_3N_4 containing 3 wt.% La_2O_3 and 3 wt.% Y_2O_3 investigated by BOD for sliding distance of 1000 m showed difference in wear and friction obtained between two combinations (Carrasquero et al., 2005). The Si_3N_4-hBN composite tested against Ti6Al4V in sea water and salt water condition was evaluated and results showed better tribological behavior under sea water (Chen et al., 2018). Another study used artificial neural network (ANN) to investigate the tribological behavior of Si_3N_4-hBN composite and showed that 8% hBN had better wear resistant property compared to neat Si_3N_4 (Bhalerao, 2016). The wear and friction behavior of Si_3N_4- Si_3N_4 under dry, gas and liquid environment was investigated using pin-on-plate machine and found that rise of CoF was independent of normal load (Fischer and Tomizawa, 1985). The tribological behavior of self-mated Si_3N_4 investigated under water and alcoholic medium showed reduced wear for latter condition(Hibi and Enomoto, 1989). The wear behavior of Si_3N_4 against high temperature alloys such as GH2132, GH4169 and GH605 containing iron, cobalt and nickel using BOD under dry condition revealed that at high temperature, due to formation of oxide layer, friction and wear rate was suppressed (Huang et al., 2016). The tribological study of Si_3N_4 against sintered PCD was investigated at different pH levels and at pH level of 13 for sodium hydroxide solution and found wear and friction rate to be quite minimum. Variation in pH level leads to dissimilar concentration of hydroxyl, which exhibited better tribological behavior due to improved proportion in hydro dynamic lubrication (Sha et al., 2020). The wear of 13 combination of Si_3N_4 material was investigated under dry condition using POD for sliding distance of 1000 m and wear map for these combinations were established(Skopp et al., 1995). The friction behavior of Si_3N_4 and SiC were investigated under low sliding speed with hydrodynamic and mixed lubrication and wear of Si_3N_4 was mainly due to tribochemical dissolution(Tomizawa and Fischer, 1987). The tribological behavior of Si_3N_4 bearing against different steel bearing was investigated and material transfer of steel to Si_3N_4 occurred together with low magnitude of friction(Wang et al., 2003). The wear of Si_3N_4 under water lubrication was investigated and found very low CoF value as well as tribochemical wear occurred(Xu et al., 1997). The wear of Si_3N_4-AISI 321stainless steel was investigated and result revealed that wear of Si_3N_4 increased with increase in normal load(X. Zhao et al., 1997). Another study for using ceramic as cutting tool investigated Si_3N_4 ceramic against Inconel 718 under dry sliding and showed that increase in sliding velocity increase the wear of ceramic(Zhao et al., 2020). The details of different parameters used to study the tribological behavior of Si_3N_4 based material with different material combinations are shown in Table.3. Overall, Si_3N_4/ Si_3N_4 based material showed better tribological behavior in comparison with some of existing well-known materials. The reduced dissolution rate of Si_3N_4 with lubricants was found to be the major reason for showing better tribological behavior when combined with other materials.

Table 3: Various tribological parameters used to investigate tribo application of Si_3N_4.

Sl. No.	Material	Counter Material	Testing Equipment	Load (N)	Sliding Speed (mm/s)	Lubricant	CoF	WearRate (mm^3/N.m)	Ref.
1.	Si_3N_4	Si_3N_4 Ball	CSEM pin-on-disk system	3,5	60,120	Purified water	0.002	6.70E-06	(Özmen, 2016)
2.	Si_3N_4	SiC/Si_3N_4 Ball	UNMT-1tribo-tester (CETR)	40	20,200	Graphene	0.735, 0.803	6.76E-05, 69.9E-05	(Maros et al., 2016)
3.	Alumina, ZTA,PSZ, SiC,Sialon,SS	Alumina,ZTA,PSZ, SiC,Sialon,Stainless Steel	Pin-on-disc tribometer	10	100	Water	0.3-0.7	0.9E-06, 6E-06	(Andersson, 1992)
4.	Si_3N_4	AISI5210Steel Balls/WC Balls	Ball-on-disc tribometer	10	100	Dry sliding	0.62,0.65	7.4E-03, 1.4E-03	(Carrasquero et al., 2005)
5.	Si_3N_4-hBN	Titanium Alloy	MMW-1 type pin/disc tribological test rig	10	1600	Artificial seawater	0.6-0.8	5.50E-06	(Chen et al., 2018)
6.	Si_3N_4	CoCrMo Alloy	Ball-on-disc tribometer	2.44, 2.45		Bovine serum, Sodium azide, EDTA	0.33-0.78		(Schmidt, Leifer, et al., 2019)
7.	Si_3N_4	Si_3N_4 Ball	Ball-on-disc tribometer	15	40	Simulated body fluid	0.366	1.09E-06, 3.75E-08	(Das et al., 2018)
8.	UHMWPE	Si_3N_4	Ball-on-disc tribometer	20,25		Plasma solution			(Ge et al., 2008)
9.	Si_3N_4-hBN	Al_2O_3	Pin-on-disc tribometer	15			0.19		(Ghalme et al., 2016)
10.	Si_3N_4	Si_3N_4	Pin-on-disc tribometer	1	50	PBS & Bovine serum	0.2-0.4		(Olofsson, Grehk, et al., 2012)

11.	$Si_xC_yN_z$	Si_xN_y	Pin-on-disc tribometer	1	40	Serum Solution	0.2-0.3	1.00E-05	(Pettersson, Tkachenko, et al., 2013)
12.	Si_3N_4 Coated CoCrMo	UHMWPE	Multidirectional wear test	150	56	Bovine serum solution	0.11-0.12		(Correa Filho et al., 2020)
13.	SiN_x	UHMWPE	Custom-made tribometer	0-100		Fetal bovine serum solution	0.11-0.20	6.00E-04	(Schmidt, López, et al., 2019)
14.	Coated Si_3N_4 on CoCr	Si_3N_4 Ball	Ball-on-disc tribometer	15		Bovine serum solution			(Olofsson, Pettersson, et al., 2012)
15.	SiN_x coated CoCr alloy	Al_2O_3	Ball-on-disc tribometer			Bovine serum solution			(Pettersson, Skjöldebrand, et al., 2016)
16.	DLC coated Si_3N_4	Si_3N_4 Ball	Pin-on-disc tribometer	1	40	Dry sliding	0.1-0.2		(Bhattacharya et al., 1991)
17.	Si_3N_4-hBN	GCr15 Steel	Pin-on-disc tribometer	10	1730	Dry, seawater, freshwater	0.5, 0.03, 0.07	0.03E-06, 0.06E-06	(Han et al., 2020)
18.	Si_3N_4	Aluminium (AA8011) alloy	Universal tribometer	20,30, 40		Dry sliding		6.00E-03	(Fayomi et al., 2020)
19.	Ni-Si_3N_4		Pin-on-disc tribometer	5	20		0.9444		(Sajjadnejad et al., 2020)
20.	Si_3N_4	Stainless Steel and PEEK	Pin-on-disc tribometer	10,30	104719.7	Artificial seawater	0.48-0.72, 0.27-0.07	5.00E-06	(J. Zhang et al., 2020)
21.	Si_3N_4	Si_3N_4	Pin-on-disc tribometer	9.8	1	Humid air, water, hexadecane & stearic acid	0.1, 0.12, 0.65, 0.75	5.00E-11	(Jahanmir and Fischer, 1988)
22.	Si_3N_4	SiC	Pin-on-disc apparatus	5or10	1-200	Water	0.2,0.7	1.25E-05	(Tomizawa and Fischer, 1987)
23.	TiN-Si_3N_4	PEEK &S.Steel	Pin-on-Disc tribometer	16.3			0.2-0.25		(Mitchell and Stott, 1992)
24.	Si_3N_4	Ti6Al4V	Ball-on-disc Tribometer	20	710	PBS,ringer,distilledwater saline solution & sesame Oil	0.22-0.41	3.33E-06 to 2.11E-05	(Shankar, Nithyaprakash, Santhosh, et al., 2020)
25.	Si_3N_4	Si_3N_4	CSEM pin-on-disk system	3,5	60,120	Purified water	0.002	6.50E-06	(Özmen, 2016)
26.	Si_3N_4	Si_3N_4	Ring-on-ring Rolling contact system	980, 1470, 1960, 2940	83770			0.43E-08 to 3.56E-08	(Akazawa et al., 1986)
27.	Si_3N_4	Hardened Steel	Twin-disk tribometer	500		Deionized water	0.28	2.56E-06	(Khader et al., 2012)
28.	Si_3N_4-hBN	Ti6Al4V	Pin-on-disc tribometer	10	1670	seawater & saltwater	0.15–0.24	9.00E-09	(Chen et al., 2018)
29.	Si_3N_4	Si_3N_4	Pin-on-plate machine	0.5,30	1	Dry, liquid & gas	0.80, 0.85	4.00E-11	(Fischer and Tomizawa, 1985)
30.	Si_3N_4	Si_3N_4	Ball-on-block machine.	9.8	2.4	Water, alcohol	0.14, 0.78		(Hibi and Enomoto, 1989)
31.	Si_3N_4	GH2132, GH4169& GH605 - Fe,Co&Ni	Ball-on-disc tribometer	10,15, 20	2083.33		0.43, 0.47, 0.51	6.20E-06	(Huang et al., 2016)
32.	Si_3N_4	Sinter PCD	Ball-on-disk tribometer	5	83.8	(NaOH) solution	7-11.5		(Sha et al., 2020)
33.	Si_3N_4	Bearing Steel	Pin-on-disc tribometer	60,12	7000	Mobil jet II oil	0.04, 0.09	1.00E-06	(Wang et al., 2003)
34.	Si_3N_4	Si_3N_4	Pin-on-disc tribometer	3,5	60, 120, 300	Water	0.6		(Xu et al., 1997)
35.	Si_3N_4	AISI 321 Steel	Pin-on-disc tester	58.8 - 235.2	0.8 -3.2	Dry sliding	0.41 to 0.43	6E-14 to 21E-14	(X. Zhao et al., 1997)
36.	Si_3N_4	Inconel 718	Pin-on-disc tribometer	100	1000 to 20000	Dry sliding	0.2 , 0.57		(B. Zhao et al., 2020)
37.	Si_3N_4	Al_2O_3	Ball-on-disc tribometer	15,20 25,	700	NaCl (Saline solution)	0.077, 0.072, 0.071	5.16E-07	(Shankar, Nithyaprakash, Sugunesh, et al., 2020)

4.0 CONCLUSIONS

Silicon nitride has gradually found its applications in major fields with its remarkable mechanical and biocompatible properties. Several studies reported in this review article highlight the improvements in mechanical, tribological and biocompatible properties of silicon nitride by adding additives to form composites. Recently developed Si_3N_4 composite with titania and calcia proved to be excellent biocompatible material for joint replacement. Also, silicon nitride-based coatings showed improved wear rate. Studies like these continue to explore Si_3N_4 in all possible ways to use it in better way in medical as well as industrial fields. The alternative ceramics which are currently in use like Al_2O_3 and ZrO_2 have less significant effect in hip joint replacement based on current scenario when compared with Si_3N_4 based biomaterial showing improved tribological behavior. Though the Si_3N_4 was mainly used for industrial applications, with these improved developments in tribological study, the potential use of Si_3N_4 in biomedical field still needs to be explored in terms of processing, manufacturing and cost reduction.

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