APPLICATION OF SILICON NITRIDE (Si_3N_4) CERAMICS IN BALL BEARINGS

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ABSTRACT

This paper is discus about silicon nitride ceramics in application to ball bearing. Silicon nitride (Si_3N_4) have advance properties such as consistent at temperature operation up to 1000°C, greater thermal shock resistance, lower density and low thermal expansion. This properties gives some benefit for ball bearing material such as higher running speed, reduce vibration of the shaft, will improve the life time and maintenance cost, lower heat generated, less energy consumption, lower wear rate, reducing noise level and reduce of using lubricant.

The sintering methods are used to produce ball bearing from silicon nitride. Some techniques can be applied to increase ceramics strength which are reduce porosity, reduce grain size, reduce surface flaw and proof stressing.

The surface finishing of the ceramic bearing is very important because silicon nitride as a brittle material, its strength is limited to the flaw sizes especially the flaw at the surface.

Key words: *Silicon nitride (Si_3N_4), Ball Bearing, Sintering*

INTRODUCTION

In the machinery system, bearing is very important to support of motion. A bearing is an engineering component that allows relative motion between two parts. Bearing also uses to support loads from the component and secures the component position. Bearings are classified in two major types which are radial bearings and axial bearings. A radial bearing allows the motion about the center for example: a bearing that permits the relative radial motion between a shaft and housing. However, an axial bearing allows the motion in the axial direction. Bearing also can be classified base on their relative motion and the main component. They are ball bearings, roller bearings, ball thrust bearings, roller thrust bearings and tapered roller bearings.

In addition, bearing materials can be classified into two groups which are through-hardened materials and case-hardened materials. The through-hardened materials usually contain alloying elements such as molybdenum, tungsten, chromium, vanadium, aluminum and silicon (http://www.machinedesign.com). They are used to produce hardness at high temperature. The common grades in this group are SEA52100 steels, M series steels, 440C stainless steel and WB49. SAE52100 steels contain high carbon chromium and small amounts of manganese and silicon. However, SAE 52100 steels are operated only at temperature up to 177C. On the other hand, M series steels can be operated at the range temperature from 315°C to 538°C. The M series includes M50, M10, M1 and M2.

The next bearing material group is case-hardened materials. These sort of steels are characterized a hardened surface and a soft core. The common grades for this group include M50-NIL, AISI4320, AISI931, CBS600 and CBS 1000. They have a surface hardness range from Rc 58 to 63 and operation limit temperature from below 177°C to 315°C (Zaretsky 1990, p. 7).

From both groups, the materials that are commonly used for ball bearings are SAE52100 steel, M50 steel, M50-NIL steel, 440C stainless steel and silicon nitride (http://www.mrcbearing services.com). Among these materials, only silicon nitride (Si_3N_4) is a non-metallic material or a ceramic material.

Silicon Nitride Ceramic Ball Bearings

Silicon nitride (Si_3N_4) has some properties that make this ceramic becomes a candidate of bearing material. The advance properties include: the strength is consistent at temperature operation up to 1000°C, greater thermal shock resistance, lower density and low thermal expansion (Budinski 1989, p. 200). The structure of silicon nitride (Si_3N_4) is made of sintered crystal of hexagonal alpha and beta forms.

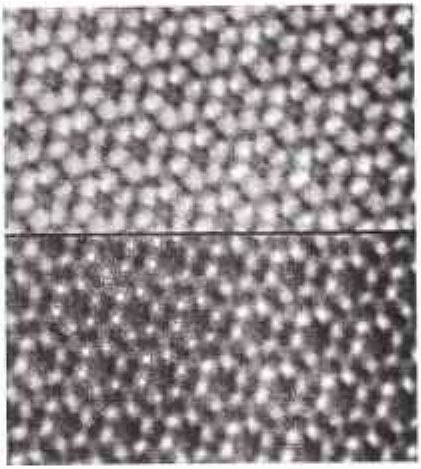

Figure 1 Crystal structure of silicon nitride (http://www.iatia.com.au)

Figure 1 shows the crystal structure of silicon nitride, where silicon atoms (red) and nitrogen (green) form hexagonal crystal structures.

The typical chemical composition of silicon nitride is shown in Table 1

Table 1. Chemical composition of Si_3N_4 in wt %

Al	C	Ca	Fe	Mg	O	Si_3N_4
≤0.5 %	≤0.88	≤0.04	≤0.17	0.6 - 1.0	2.3-3.3	97.1 - 94.1

(Jiang & Komanduri 1998, p. 270)

The use of silicon nitride ceramic for ball bearings can be divided into two types that are ceramic ball bearings and ceramic hybrid ball bearings. The sort of bearing can be seen in figure 2.

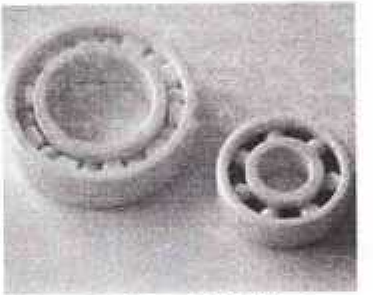

Figure 2 (a) Ceramic ball bearings (http://www.lily-bearings.com)

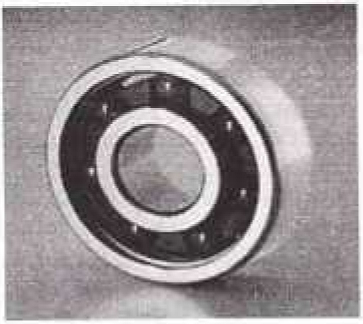

Figure 2 (b) Ceramic hybrid ball bearing (http://www.ferrovac.ch)

The main deference between both bearings is that in full ceramic ball bearings all the bearing components are made of silicon nitride ceramic. However, in ceramic hybrid ball bearing only balls are made of silicon nitride ceramic and the inner race and outer race are made of steel.

Over the past two decades, ceramic bearings have been used in a wide range of applications such as machine tool spindles, dental drills, motor racing, aerospace, high speed air turbine bearing and biotechnology industry. Typically, silicon nitride ball bearings are used for high temperature applications and for high running speed applications (Ling & Yang 2005, p.31).

Comparison Between Candidate Bearing Materials

As mentioned before that ball bearings generally uses 52100 steel, M50 steel, M50-NIL steel, 440C stainless steel and silicon nitride (Si_3N_4). Table 2 shows the mechanical properties of silicon nitride and two metallic materials for bearings which are M50 steels and 440C stainless steels.

Table 2. Properties of silicon nitride (Si_3N_4), M50 steels and 440C stainless steels

Properties	unit	Si_3N_4	M50	440C
Metallic/ non metallic		Ceramic	Tool steel	Stainless steel
Density	kg/m^3	3190	7850	7800
Bending strength	MPa	867	2400	2400
Tensile strength	Mpa	414-1000	1720	1790
Working teemperature	°C	800	538	300
Weibull modulus		14		
Fracture toughness	$MPa\ m^{1/2}$	41-53		
Young's modulus	GPa	303	208	200
Poisson ratio		0.28	0.30	0.30
Hardness (Rc)		75-80	62	66
Thermal shock resistance	ΔTK	500/700		
Thermal conductivity	W/mK	26	26	24.2
Thermal expansion	$10^{-6}/K$	2.7	12.5	10.2
Specific heat	kJ/kgK	0.76	0.48	0.46

(Lube & Dusza 2006, p. 3), (Budinski 1989, p.189) & (Callister 2003, pp.737-770)

Advantages And Disadvantage Of Silicon Nitride Ceramic Ball Bearings.

The advantages of silicon nitride ball bearings if compared to steel ball bearings are come from some advanced properties of silicon nitride. By evaluation some features such as density, modulus elasticity, coefficient of linear expansion, hardness, coefficient of friction, wear resistance and thermal resistance the benefits of using silicon nitride for ball bearings can be known.

Density: Table 2 shows the density of Si_3N_4 is about 3.2 g/cm³ and 7.9 g/cm³ for steels, the resulting of the lighter weight produces the smaller centrifugal force then reduces slipping and the higher running speed can be achieved.

Modulus elasticity: the higher modulus elasticity of silicon nitride tells that silicon nitride is more rigid that steel, this property will produce the higher ball accuracy and it will reduce vibration of the shaft/ spindle and allowing higher speed.

Thermal expansion: the low thermal expansion coefficient of silicon nitride allows the ceramic balls experience smaller change of contact angle then it will improve the life time and maintenance cost (http://www.bearingworks.com).

Linear friction coefficient: the coefficient of friction for the oil lubricated Si_3N_4 on steels are from 0.04 to 0.09, while for M50 steels on steels are between 0.10 and 0.17 (Wang et al 2003, p. 662). The lower coefficient of friction of silicon nitride affects on the lower heat generated, less energy consumption, lower wear rate, reducing noise level and reduce of using lubricant.

Working temperature: as can be seen in Table 2, the working temperature of silicon nitride is higher than steels have. So silicon nitride ball bearings can be used in higher temperature environment.

Wear resistance: the wear resistance of silicon nitride that was evaluated by Wang shows the wear rate of Si_3N_4 at least two times less than M50 steels (Wang et al 2003, p. 667). This property leads the silicon nitride ball bearings have a longer life time than steel ball bearings.

Corrosion resistance: silicon nitride ball bearings also show the greater corrosion resistance compared to steel ball bearing.

However, the main disadvantage of using silicon nitride for ball bearings is their price is relatively high if compared to steel ball bearings. The reason of high cost of silicon nitride ball bearings is because of surface condition is one of the major factors of silicon nitride strength but the surface finishing process in ceramic bearing manufacturing is cost up to 50% (Wang 2000, p 162). As a consequence, the silicon nitride ball bearings remain more expensive than steel ball bearings. In the market, finished silicon nitride balls price is from 2000-4000 US$/kg (Callister 2003, p.768).

Manufacture Of Silicon Nitride Ceramic Ball Bearings.

Silicon nitride ceramics like other most ceramics are produced by sintering process. Sintering process is a thermal treatment of a compacted ceramic powder at a temperature below the melting point of the main component so it will bond together and its strength increases. The sintering methods for silicon nitride ball bearing include reaction sintering, hot pressing and standard pressure sintering or pressureless sintering. However, the hot isostatically pressed (HIP) is the most commonly used for sintering process of the silicon nitride ball bearing (Thoma et al. 2004, p. 461). The typical manufacturing process of silicon nitride is illustrated in Figure 3 (Davies 2006).

As can be seen in Figure 3, Y_2O_3 and Al_2O_3 are sintering aid components then they mix with main component. After that the mixture is added by binder additive such as a kind of polymer. The forming and sintering process are depended on the type of sintering. At hot pressing, the mixture pressing and heating at the same time.

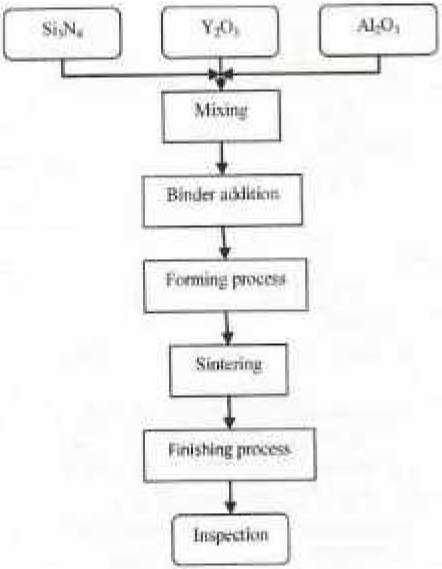

Figure 3 Schematic diagram of silicon nitride production.

In addition, to help the formation of a liquid phase during sintering process in elevated temperature, the process needs sintering aid components. Sintering aids that produce a liquid phase at high temperature allow mass transfer by rearrangement and solution-reprecipitation processes then producing the phase transformation and densification of Si_3N_4 (Vuckovic et al 2006, p. 303). Also, sintering aids is used to improve mechanical properties of the ceramics because they will help in reducing porosity. Sintering aid components or sintering additives may in form of oxide additives such as yttria (Y_2O_3), alumina (Al_2O_3), magnesia (MgO) and Lithia (Li_2O). For a low temperature sintering uses sodium oxide (Na_2O). Sintering aids such as MgO, Y_2O_3 during sintering process react with SiO2 on silicon nitride particle to form silicate liquid phase and then transform into glassy phase after cooling down at triple junction points and between grain boundaries (Ling & Yang 2005, p. 33). This glassy phase or second phase has a great effect on the properties of the ceramics.

Finishing Process Of Silicon Ni-tride Balls.

In addition, the reducing of porosity and grain size process are included in manufacturing process, however, the reducing surface flaw or surface finishing of the ceramic bearing is final process that determines the ceramic ball bearing quality.

The surface finishing of the ceramic bearing is very important process because silicon nitride as a brittle material, its strength is limited to the flaw sizes especially the flaw at the surface or follows the theorem of 'weakest link hypothesis'. This theorem states that the strength is determined by the largest flaw size or in other word that ceramic components will fail due to the largest flaw size at the surface. If the surface flaw size can be reduced the strength will be increase.

Finishing process of silicon nitride balls consist of two techniques which are the conventional technique and magnetic float polishing technique (Jiang & Komanduri 1998, p. 267). The conventional plate grinding technique comprises grinding and lapping process using diamond abrasive with low speeds and higher loads. This technique needs a long time to finish and generally more expensive. Defects such as flaws, scratches, micro-cracks and pits generally still present on ball bearing surface in conventional finishing process.

The next finishing technique is magnetic float polishing. Generally, the magnetic float polishing provides higher quality of silicon nitride balls. Figure 4 (a) shows the conventional plate grinding and magnetic fluid float polishing (b).

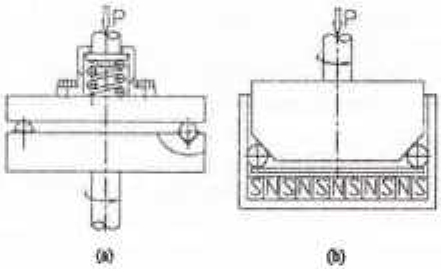

Figure 4 Silicon nitride grinding techniques (Wang et al 2000, p. 162).

The magnetic float polishing technique is based on magneto hydrodynamic action that able to float non-magnetic float and abrasive suspended by magnetic field. The main difference between these techniques on the force applied between abrasive and balls. In the magnetic float polishing technique, the force applied by abrasive to the ball (3-point contacts) is quite small and controllable. The force is come from magnetic buoyancy force when a magnetic field is applied. But, in conventional technique the force is come from spring force.

Porosity And Surface Flaws In Silicon Nitride Balls.

Some techniques can be applied to increase ceramics strength which are reduce porosity, reduce grain size, reduce surface flaw and proof stressing.

In order to reduce surface flaw size, the finishing process is done step by step from the coarser grinding then the finer grinding and polishing but unfortunately the fine polishing can not remove the flaws that initiated by the coarse grinding steps. But it should be noted that for any finishing methods that applied, surface defects/ flaws are still introduced by sharp contact of abrasive finishing process. The micro-cracks especially subsurface cracks are still present in the silicon nitride ceramics ball (Swab & Sweeney 1995, p.188). The micro-cracks or flaws are reported lead to spalling formation in silicon nitride balls and decrease the life of the bearing (Swab & Sweeney 1995, p.188). Hence, for these reasons it is recommended that the material removal rate during grinding process should be reduced and eliminates grinding with coarse grid wheels.

As mention earlier that sintering aids will improve mechanical properties by decreasing the amount of porosity. The density of the ceramics also will increase as porosity decrease. One of methods to make the higher density of the silicon nitride was introduced by Vuckovic et al. Their research was based on introducing the prepared b-Si_3N_4 seeds into a mixture of a-Si_3N_4 and 10wt % sintering additive. With 0-3% b-Si_3N_4 seeds the full densification can be achieved after gas pressure sintering at 1800°C for 4 hours (Vuckovic et al 2006, p. 303).

The pressureless sintering also can produce silicon nitride with a low porosity. The composition of a-Si_3N_4 and 9% wt sintering aids (4wt % Y_2O_3 and 5wt % MgO) then sintered with standard pressure at 1700°C for 60 min will produce 99% of theoretical density (Ling & Yang 2005, p.33).

Moreover, another technique on reducing porosity is recently done by Tatli and Thompson. Densification of silicon nitride at relatively low temperature was introduced by hot pressing of Si_3N_4 with Na_2O as the sintering aid. Powder with the composition of a-Si_3N_4 and 5wt.% Na_2O was hot press sintered at 1500°C for 20 min produced silicon nitride with 97% of theoretical density (Tatli & Thompson 2006, p. 4).

Fracture Mechanism Of Silicon Nitride Ceramic Bearings.

The flaws are the important phenomenon in discussion of the fracture mechanism of the ceramics. The flaws can be divided into intrinsic and extrinsic flaws (Kutz 2002, p. 789). Intrinsic flaws are produced during manufacturing process. They can be in form of pores, shrinkage cracks or area with low density. However, extrinsic flaws are caused by surface treatment such as machining and grinding. The flaws size has a correlation with the fracture strength of the ceramics. Its relation is formulated as: (Kutz 2002, p. 790)

$$\sigma_c = \frac{K_{IC}}{Y\sqrt{a}} \qquad (1)$$

Where s_c is the fracture strength, a is the flaw size, K_{IC} is the fracture toughness and Y is a constant that depends on the shape of the flaw. For example Y value for a semicircular surface flaw is 1.28 with the flaw size is 50mm and from Table 1 the fracture toughness of silicon nitride is 4.9 MPa $m^{1/2}$, the strength of silicon nitride can be calculated as:

$$\sigma_c = \frac{4.9}{1.28\sqrt{0.00005}} = 541MPa$$

If the flaw size is 100mm, the silicon nitride strength becomes:

$$\sigma_c = \frac{4.9}{1.28\sqrt{0.0001}} = 382MPa$$

The comparison of two calculations above shows that flow size has a significant effect to the strength of silicon nitride, with two times of flaw size the fracture strength decreases about 29%.

The intrinsic flaws such as pores also present in the silicon nitride balls because the sintering process may not produce fully density ceramics. The example, the pore that initiates a fracture on the silicon nitride is shown in Figure 5 below (O'Brien et al 2003, p.464).

Figure 5 (a) shows the point C is the junction of three cracks (D, F, G) and Figure 5 (b) shows the magnification of point C that indicates the fracture of silicon nitride ball that initiated by a 2mm pore.

In addition, the wear mechanism in silicon nitride (Si_3N_4) ball bearings can be explained by the following stages. The research that was conducted by Chen, concluded that contact stress fatigue is the main cause of wear mechanism (Chen et al 1996, p. 205). As a consequence, the wear mechanism in silicon nitride balls also produces Si_3N_4 debris which then deposit in the lubricant. The debris in the lubricant can create other scratches in silicon nitride balls. This stage shows the second wear mechanism is occurred. The process could be repeated with the larger debris will produce more scratches and flaws as multiple wear mechanisms. Then finally fractures in silicon nitride balls such as spallings clearly appear on the surface.

The location of fractures can be seen by the fractographic analysis. The initial fracture is located in the raceway of inner race (Swab & Sweeney 1995, p.186). The fracture at the inner race is caused by the stress created by a ball. The compressive forces are perpendicular to the ball-raceway contact area. But the contact area of the inner race is smaller than contact area of the outer race, so the inner race experiences a higher stress than the outer race does.

CONCLUSION

a. The advance properties of silicon nitride (Si_3N_4) that make this ceramic becomes a candidate of bearing material are the strength is consistent at temperature operation up to 1000C, greater thermal shock resistance, lower density and low thermal expansion.
b. The advance properties of silicon nitride give some benefit for ball bearings include the higher running speed, reduce vibration of the shaft, will improve the life time and maintenance cost, lower heat generated, less energy consumption, lower wear rate, reducing noise level and reduce of using lubricant.
c. The sintering methods for silicon nitride ball bearing include reaction sintering, hot pressing and standard pressure sintering or pressureless sintering. However, the hot isostatically pressed (HIP) is the most commonly used for sintering process of the silicon nitride ball bearing.
d. Sintering aid components or sintering additives that used in manufacturing of silicon nitride may in form of oxide such as yttria (Y_2O_3), alumina (Al_2O_3), magnesia (MgO), Lithia (Li_2O) and sodium oxide (Na_2O).
e. Some techniques can be applied to increase ceramics strength which are reduce porosity, reduce grain size, reduce surface flaw and proof stressing.
f. The surface finishing of the ceramic bearing is very important because silicon nitride as a brittle material, its strength is limited to the flaw sizes especially the flaw at the surface.
g. In order to minimize the surface flaws that caused by coarse grinding process, it is suggested that the material removal rate during grinding process should be reduced and eliminates grinding with coarse grid wheels.
h. The sintering methods, sintering aids used, sintering temperature and soaking time in silicon nitride manufacturing are the factor on obtaining the desire porosity of silicon nitride.
i. The pores and surface flaws are the cause of the fracture initiation on the silicon nitride ball bearings.

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