Trends of Technological Development of Special Environment Bearings for Semiconductor Manufacturing Equipment

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In line with technological progress of recent years, the environment and conditions in which rolling bearings are used are becoming increasingly advanced and diversified year by year. Bearings are being required to perform in more severe operating conditions, such as special environments with high temperature, vacuum, cleanliness, and corrosiveness.

Since developing vacuum bearings (silver ion plate bearings) in 1978, JTEKT has studied lubricants and bearing materials while promoting the development of the EXSEV (Extreme Special Environment) bearing series that supports various special environments in order to keep pace with cutting-edge technical fields.

Many bearings are exposed to diverse and severe special environments during the semiconductor manufacturing process in particular. This paper will highlight the needs of each operating environment for the main manufacturing processes and the JTEKT bearings that support such needs.

***Key Words**: semiconductors, vacuum, clean, high temperatures, corrosive, solid lubricant, EXSEV*

1. Introduction

With recent technological advances, the environments and conditions where rolling bearings are used have become increasingly severe and diversified over the years, and the conditions where special environment bearings are used have become increasingly severe as well. The semiconductor market, in particular, is experiencing rapid growth in demand due to improved functionality in smartphones and the spread of the Internet of Things (IoT), artificial intelligence (AI), and automated driving, and this has led to calls for even higher reliability and durability in manufacturing equipment.

Since developing bearings for vacuum environments (silver ion plate bearings) in 1978, JTEKT has developed a variety of products, including a series of EXSEV (Extreme Special Environment) bearings which are suitable for special environments and have been widely used in equipment for manufacturing cutting-edge devices. As shown in **Table 1**, the bearings used in semiconductor manufacturing equipment are being required to perform in processes for a wide array of operating environments including vacuum, clean, high-temperature, and corrosive environments.

In addition to providing an overview of the JTEKT special environment bearings, this paper introduces

Table 1 Semiconductor manufacturing processes and main bearing operating environments

Semiconductor manufacturing process		Oxidation	Exposure	Etching	Thin film deposition	Planarization (CMP)	Electrode	Cleaning	Inspection	Transport	Vacuum pump
Bearing usage environment	Vacuum	○	–	○	○	–	○	–	○	○	○
	Clean	–	○	–	○	–	○	○	○	○	–
	High-temperature	○	–	–	–	–	○	–	–	○	–
	Corrosive	○	–	○	–	○	–	○	–	–	–
Applied products	EXSEV-EX : Section 2.1	○	–	○	○	○	–	–	○	○	–
	New Clean Pro Bearing-PR : Section 2.2	–	○	–	–	–	–	○	–	–	–
	MV Coating : Section 2.3	–	–	–	–	–	–	–	–	–	○
	EXSEV-XT : Section 3.1	–	–	–	–	○	–	–	–	–	–
	Ceramic Bearings : Section 4.2	○	–	○	–	–	○	○	–	–	–

the features of the bearings used in semiconductor manufacturing equipment.

2. Vacuum and Clean Environments

2. 1 EXSEV-EX (Fluorinated Grease for Vacuum and Clean Environments)

General bearings typically use greases comprising mineral oil-based lubricants. However, in many cases, grease cannot be used for semiconductor manufacturing equipment because of problems such as oil evaporation and grease decomposition. Therefore, in high-temperature environments exceeding 200℃ or in vacuum or clean environments where oil evaporation or contamination can pose a problem, a grease with a base oil of perfluoropolyether (PFPE), which has low vapor pressure and is chemically stable, and a thickener of polytetrafluoroethylene (PTFE) is used. This is also known as a fluorinated grease.

In recent years, international regulations have become stricter on environmentally hazardous substances, and perfluorooctanoic acid (PFOA) and its salts contained in PTFE have been subject to regulation under the Stockholm Convention. As a result, the semiconductor industry, where fluorinated grease is widely used, has been required to take immediate measures for environmental safety. In response to these environmental regulatory trends, in 2019, we developed EXSEV-EX (**Fig. 1**) as a PFOA-free product to replace the fluorinated grease (KDL Grease) that we had been providing. The results when evaluating the particle emission and outgas volume of the developed product in comparison with the conventional KDL Grease are shown below. The particle emission evaluation apparatus is shown in **Fig. 2**, and the evaluation conditions are shown in **Table 2**. Two bearings were placed in a clean bench where clean air was supplied, and the amount of particle emitted from the bearings was measured with a particle counter while they were rotated under an axial load applied by a spring. As shown in **Fig. 3**, the amount of dust generated by the developed product was less than that of the conventional product. Also, the amount of outgas was measured by gas chromatography-mass spectrometry (“GC/MS” below) under the conditions shown in **Table 3**. As shown in **Fig. 4**, the amount of outgas was lower than that of the conventional product. And so, we were successful in developing a product where the particle emission and outgas were less than those of the conventional product. Also, compared to the conventional product, the developed product has the same or better performance in terms of starting torque, running torque, noise, and service life, and it also complies with environmental regulations, thus contributing to broad compliance with environmental regulations by our customers, the makers of semiconductor manufacturing equipment.

Fig. 1 EXSEV-EX (grease)

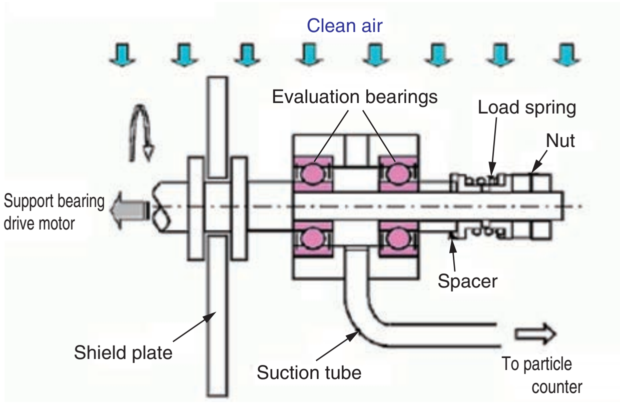

Fig. 2 Testing equipment

Table 2 Test conditions

Test bearings		6000ZZ (ϕ10×ϕ26×8mm)
Material	Bearing race and ball	SUS440C
	Cage and shield	SUS304
Rotation speed		1 000 min^{-1}
Axial load		50 N
Temperature		Room temperature
Atmosphere		Open air and inside clean bench (Class 10)
Test time		20 h
Test items		Amount of particle emitted with particle diameter 0.1 μm or larger

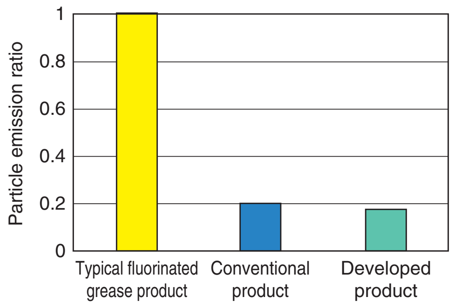

Fig. 3 Comparison of bearing particle emission amount

Table 3 Test conditions

Sample	Grease
Measurement method	GC/MS
Temperature	160℃
Test time	0.75 h

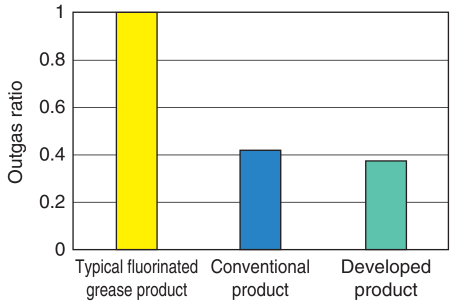

Fig. 4 Comparison of outgassing amount

2. 2 New Clean Pro Bearing-PR (Special Fluorinated Solid Lubricant Coating for Vacuum and Clean Environments)

In some semiconductor manufacturing processes such as those using lithography equipment, a higher level of cleanliness than that of fluorinated grease is required. Clean Pro bearings are used as bearings that can meet the strict requirements of these clean environments. This product features a solid lubricating film made of a special fluoropolymer that is applied over the entire bearing surface so it can be used in ISO Class 4 (Class 10 based on FED-STD-209D) clean environments. In 2017, JTEKT developed the new Clean Pro Bearing-PR (**Fig. 5**), an improved version of this special fluoropolymer solid lubricant coating. When the particle emission was evaluated in the same way as grease, the results showed that particle emission during bearing rotation was reduced by 50% compared to the conventional product. When the bearing was rotated for an extended period of time to evaluate the particle emission life, which is the time until the amount of particle emission exceeds the ISO Class 4 level, the results found that the particle emission life was increased by a factor of at least 10 as shown in **Fig. 6**. Also, the amount of outgas was lower than that of the conventional product when measured by GC/MS at temperatures ranging from room temperature to 200℃. Consequently, the new Clean Pro Bearing-PR provides significantly improved performance in terms of particle emission and particle emission life, contributing to higher reliability and lower running costs for semiconductor manufacturing equipment.

Fig. 5 New Clean Pro-PR

Table 4 Test conditions

Test bearings		6000ZZ (ϕ10×ϕ26×8mm)
Material	Bearing race and ball	SUS440C
	Cage and shield	SUS304
Rotation speed		200 min^{-1}
Axial load		50 N
Temperature		Room temperature
Atmosphere		Open air and inside clean bench (ISO class 4)
Test items		Amount of particle emitted with particle diameter 0.1 μm or larger

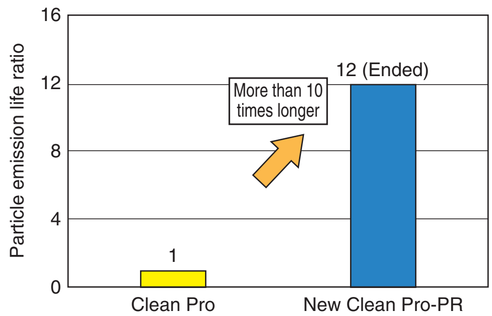

Fig. 6 Comparison of particle emission life

2. 3 MV Coating (Solid Lubricant Coating for Vacuum Environments)

Magnetic bearing turbomolecular pumps (**Fig. 7**) are widely used in many semiconductor manufacturing processes because of the high vacuum level required. If the magnetic bearing failed, the rotor cannot be supported, causing the rotor and stator to come into contact, which could damage the pump. Touchdown bearings are used to prevent such contact between parts and to stop the rotor safely. To ensure pump reliability, the touchdown bearing must have high durability. Because touchdown bearings are used in a high vacuum, grease cannot be used because of outgassing and other problems, and so solid lubricants are used. Under such severe lubrication conditions, extending the service life has presented numerous challenges. This led JTEKT to re-examine the binder of the molybdenum disulfide film to develop MV Coating, which features higher adhesiveness. Service life comparison tests were conducted using a touchdown test equipment that simulated an actual machine. The rotor was run to reach the rated rotational speed, and then the power to the magnetic bearing was turned off, and the rotor was dropped and supported by the touchdown bearing until the rotor came to a stop. After the rotor stopped, the magnetic bearing was restarted, and if the rotor floated normally, the touchdown was considered successful. And this cycle was repeated to evaluate the durability performance. The test conditions are shown in **Table 5**, and the test results are shown in **Fig. 8**. It was found that the durability of MV Coating products was four times higher than that of conventional products (based on JTEKT evaluation standards) for enabling higher reliability in turbomolecular pumps.

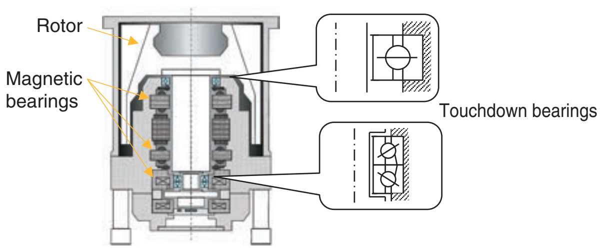

Fig. 7 Turbomolecular pump

Table 5 Test conditions

Bearing size		6909 (ϕ45×ϕ68×12mm) 7904DF (ϕ20×ϕ37×18mm)
Material	Bearing race	SUS440C
	Ball	Si_3N_4
Lubricant		MV Coating on inner and outer rings
Rotor weight		6.6 kg
Rotation speed		34 000 min^{-1}
Temperature		Room temperature
Vacuum level		10^{-4} Pa

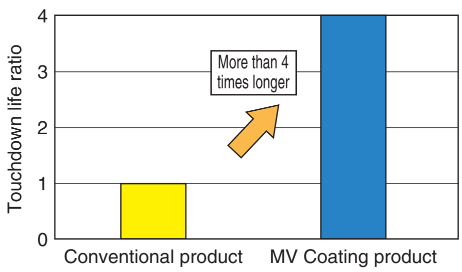

Fig. 8 Touchdown life ratio

3. High-temperature Environments

3. 1 EXSEV-XT (Fluorinated Grease for Vacuum and High-temperature Environments)

Generally, solid lubricants are used in environments where grease cannot be used. Grease undergoes accelerated oxidation, decomposition, and evaporation in high-temperature and under vacuum[1]. However, solid lubricants can be used at high temperatures and in ultra-high vacuums due to their superior heat resistance and other features. Typical solid lubricants that can be used in high-temperature environments are molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2), which are layered crystalline structure materials. Solid lubricants are primarily coated on cages and bearing races by sputtering or baking methods, and MoS_2 and WS_2 are used in high-temperature environments at 300℃ and 350℃, respectively. However, depending on the operating conditions, solid lubricants also have disadvantages such as particle emission from the lubricant and shorter service life compared to grease[2].

On the other hand, in high-temperature environments, fluorinated grease is limited to usage up to about 260℃, which is the thermal decomposition temperature of PTFE, the thickener. This is what led us, in 2017, to develop the EXSEV-XT as a bearing that combines the features of 350℃ heat resistance and a long service life. To enable compatibility with high-temperature environments at 350℃, a grease containing a combination of a base oil that does not easily evaporate and a thickener that is resistant to thermal decomposition was used. This grease was subjected to thermogravimetric analysis under the test conditions in **Table 6**, and the results are shown in **Fig. 9**. The temperature where the weight drops by 5% is 397℃, indicating that the grease has an extremely high heat resistance. The durability performance under high temperature conditions of EXSEV-XT was compared with that of conventional bearings with solid lubricant. The test method was as shown in **Fig. 10**, where the bearing was installed in the furnace and an axial load was applied by pressing the shaft from outside the furnace, causing the bearing to rotate. The test conditions are shown in **Table 7**. The results found, as shown in **Fig. 11**, that the EXSEV-XT bearing life at high temperatures was more than six times longer than that of conventional bearings with solid lubricant. Consequently, this enables higher temperatures in the manufacturing process and lower maintenance costs for equipment.

Table 6 Test conditions

Sample amount	10 mg
Temperature increase	5℃/min

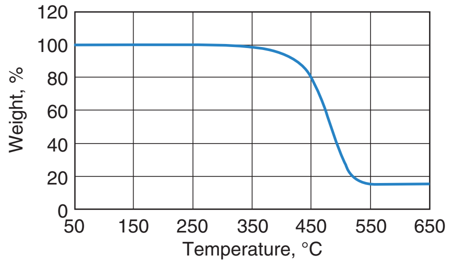

Fig. 9 Thermogravimetric analysis results

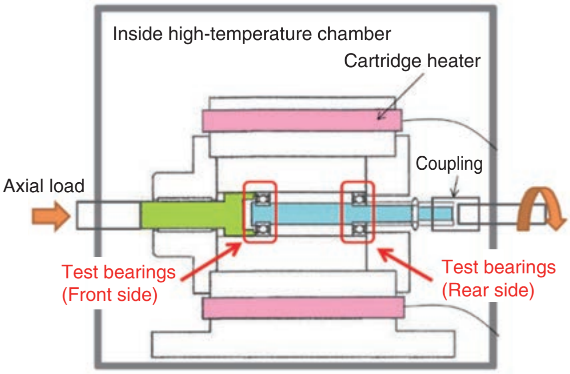

Fig. 10 High temperature endurance evaluation unit

Table 7 Test conditions

Test bearings		6000ZZ (ϕ10×ϕ26×8mm)
Material	Bearing race and ball	SUS440C
	Cage	Bearings with solid lubricant: PEEK resin EXSEV-XT: SUS 304
	Shield	SUS304
Rotation speed		500 min^{-1}
Axial load		185 N
Temperature		300℃

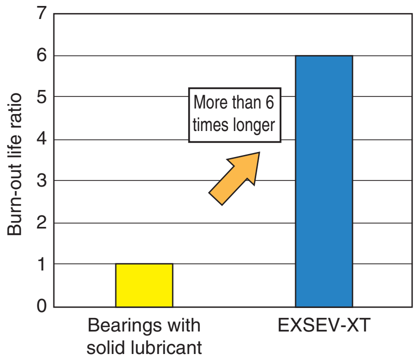

Fig. 11 Endurance test results

4. Corrosive Environments

4. 1 Corrosion Guard Pro Bearing-MD (Precipitation Hardening Stainless Steel Bearing)

The main materials used for the bearings in semiconductor manufacturing are high carbon chrome bearing steel (SUJ 2) and martensitic stainless steel (SUS 440C). However, precipitation hardening stainless steel is used for the bearings in semiconductor manufacturing equipment used in corrosive environments because corrosive liquids and gases can lead to shorter bearing life. This bearing, which uses precipitation hardening stainless steel for the bearing races and ceramics for the balls, is called Corrosion Guard Pro Bearing-MD. The mechanical properties of the various materials used in bearing races are shown in **Table 8**.

To compare the corrosion resistance of these steel types, a CASS test was conducted based on the salt spray test method in JIS Z 2371. The test conditions are shown in **Table 9**. The results of the CASS tests on general bearings (SUJ 2), stainless steel bearings (SUS 440C), and Corrosion Guard Pro Bearing-MD are shown in **Fig. 12**. These results show that the corrosion resistance was, from best to worst, Corrosion Guard Pro Bearing-MD > Stainless steel bearing > General bearing, in that order.

Table 8 Material properties of various steel

	Hardness HRC	Young's modulus GPa	Linear expansion coefficient 10^{-6}, K^{-1}	Corrosion resistance
General bearing	61	208	12.5	×
Stainless-steel bearing	60	208	10.5	△
Corrosion Guard Pro Bearing-MD	40	196	11	○

○: Superior, △: Slightly inferior, ×: Inferior

Table 9 CASS test conditions

Solution used	Sodium chloride: 50 ± 5 g/l Copper chloride (II): 0.26 ± 0.02 g/l
pH	3.0～3.2
Temperature	50 ± 2℃
Test time	4 h

General bearing SUJ2 | Stainless-steel bearing SUS440C | Corrosion Guard Pro Bearing-MD

Fig. 12 CASS test results

4. 2 Ceramic Bearings

Compared to metallic materials, ceramics have lower toughness and poor workability, but on the other hand, they also have excellent properties such as a light weight, heat resistance, and corrosion resistance[1)]. **Table 10** shows the mechanical properties of various ceramics[2)]. Ceramics, such as silicon nitride (Si_3N_4), zirconia (ZrO_2), and silicon carbide (SiC), can be used in severe environments where conventional metal materials cannot. And so, the rolling characteristics of various ceramics were confirmed by the thrust rolling life test shown in **Fig. 13**. Raceways (flat plates) were fabricated from various ceramics and used as samples for applying thrust loads. The balls were made of bearing steel in the case of oil lubrication and made of ceramics in the case of water lubrication. The test results are shown in **Fig. 14**[3)]. The vertical axis shows the load acting on each ball, and the horizontal axis shows the number of stress loading cycles. The applied load is increased in stages, and the time when the test was stopped due to separation occurring on each raceway (flat plate) was plotted. The results confirmed that silicon nitride was the most suitable material for rolling bearings. By conducting these evaluations, JTEKT became the first company in the world to develop ceramic bearing products that use silicon nitride.

Next, we will explain the corrosion resistance of ceramics. Ceramics have a much higher corrosion resistance than bearing steel and stainless steel, and ceramics can be used in a variety of corrosive environments. The resistance of various ceramics to corrosion by typical chemical solutions is shown in **Table 11**[4)]. As indicated in the table, the corrosion resistance for different types of ceramics varies, and so it

Table 10 Mechanical properties of various ceramic materials

Property, units \ Ceramic material	Silicon nitride Si_3N_4	Zirconia ZrO_2	Silicon carbide SiC
Density, g/cm^3	3.2	6.0	3.1
Linear expansion coefficient, K^{-1}	3.2×10^{-6}	10.5×10^{-6}	3.9×10^{-6}
Vickers hardness, HV	1 500	1 200	2 200
Young's modulus, GPa	320	220	380
Poisson's ratio	0.29	0.31	0.16
Three-point bending strength, MPa	1 100	1 400	500
Fracture toughness, MPa·m$^{1/2}$	6	5	4
Heat resistance (in air) , ℃	800	200	1 000 min.
Thermal shock resistance, ℃	750 min.	350	350
Thermal conductivity coefficient, W/(m·K)	20	3	70
Specific heat, J/(kg·K)	680	460	670

Test conditions

	Oil lubrication	Water lubrication
Lubricant	Spindle oil	Tap water
Ball	Bearing steel	Ceramic material
Load	Increased in stages at every 1.08×10^7 stress loading cycles	
Rotation speed	1 200 min^{-1}	

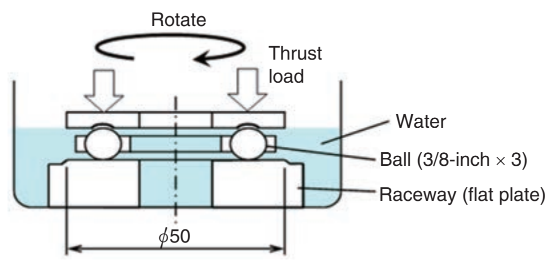

Fig. 13 Thrust rolling life test

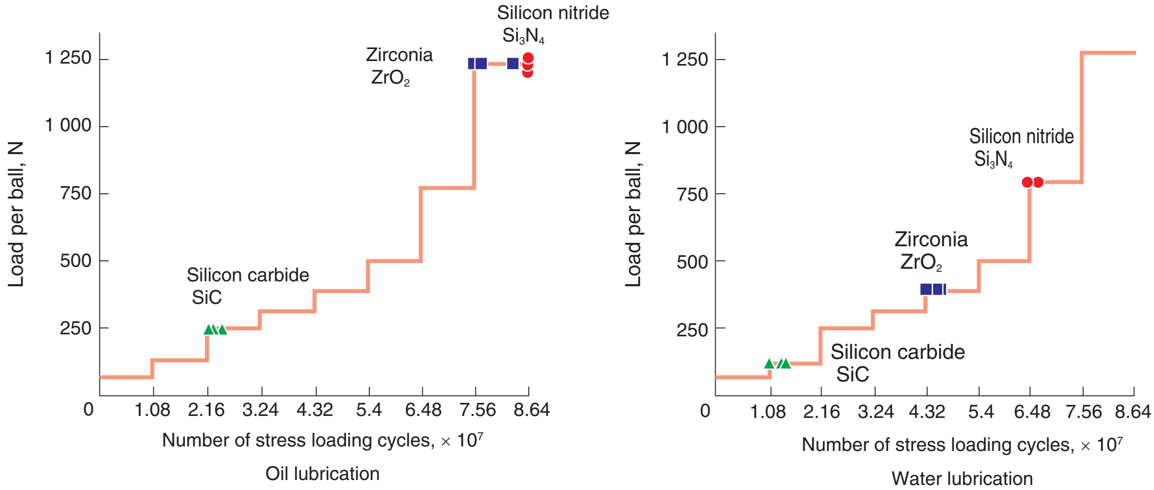

Fig. 14 Thrust rolling life test results

Table 11 Comparison of anti-corrosiveness of each ceramic type

Chemical	Concentration	Temperature	Time	Silicon nitride Si_3N_4	Zirconia ZrO_2	Silicon carbide SiC
HCl	35%	Boiling	30 min	A	B	A
HNO_3	70%	Boiling	30 min	A	B	A
H_2SO_4	98%	Boiling	30 min	A	C	A
H_3PO_4	90%	Boiling	30 min	A	B	B
HF	60%	20℃	24 h	C	B	A
KOH	10%	80℃	7 days	A	A	C
KOH	100%	Boiling	24 h	C	C	C
NaOH	100%	500℃	24 h	C	–	C
Na_2CO_3	100%	900℃	24 h	C	C	C
Na_2SO_4	100%	Melting	–	C	B	C
KNO_3	100%	Melting	–	A	–	A

A: No erosion observed, B: Minor erosion, C: Major erosion

is necessary to select the ceramics that provide the proper resistance to the various corrosive chemicals and gases in the specific semiconductor manufacturing process.

For example, in some semiconductor manufacturing processes, hydrofluoric acid (HF) comes into contact with the bearing. In these types of environments, bearings made of silicon nitride can be corroded (C in **Table 11**). JTEKT offers highly corrosion-resistant ceramic bearings made of silicon carbide (A in **Table 11**, **Fig. 15**) for extending the service life of bearings and enabling long-term use of bearings in acidic environments that previously presented serious challenges.

Also, to better support the diversified corrosive environments in semiconductor manufacturing processes, JTEKT developed the Corrosion Guard Pro Bearing-AZ, where a new ceramic material, alumina-zirconia composite (Al_2O_3-ZrO_2), was applied to the bearing. The key feature of this material is that it has the advantages of alumina, which has excellent corrosion resistance, and zirconia, which has excellent load resistance. Because the material does not contain silicon, it can avoid the adverse effects of silicon reaction products in some semiconductor manufacturing equipment, and so it is expected to lead to improved productivity for semiconductors.

Fig. 15 High anti-corrosive ceramic bearing (silicon carbide)

The range of application of ceramics under various corrosion environments is shown in **Fig. 16**. The vertical

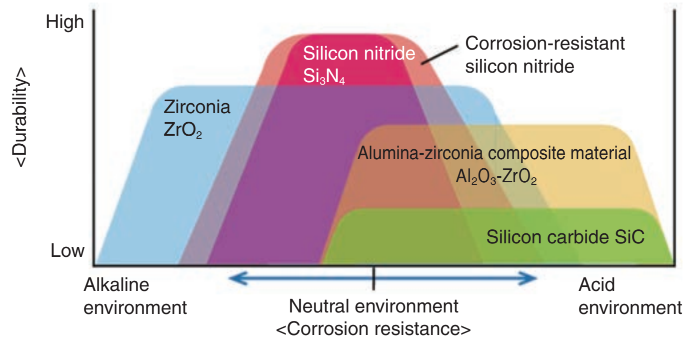

Fig. 16 Application of ceramics under various corrosion environments

axis shows the load resistance, and the horizontal axis shows the environment type. These products enable the selection of materials capable of covering a wider range of corrosive environments, which are expected to diversify in the future.

5. Conclusion

The environments where special environment bearings are used are changing dramatically and becoming more diverse. There is no single bearing specification that can meet the operating conditions of all semiconductor manufacturing equipment. Therefore, when selecting bearings, it is necessary to consider not only the dimensional accuracy, but also the materials, lubrication, and many other factors. The performance, durability, and reliability of the equipment will be improved by using bearing specifications that match the operating conditions and performance required for various types of semiconductor manufacturing equipment. Looking forward, we will continue to develop bearings with a focus on both further upgrading the performance requirements and improving productivity in the semiconductor industry for making our own small contribution to delivering a more stable supply of cutting-edge devices with even higher performance.

*1 EXSEV is a registered trademark of JTEKT Corporation.

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