

Rolling Bearings for Extreme Special Environments

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As a result of recent advances in technology, bearings have come to be used in severer environments and under extreme conditions. Specifically, highly advanced technology requires bearings that can be used in special environments, such as in vacuum, clean, high-temperature, and corrosive environments. It is extremely difficult for conventional bearings made of bearing steel and lubricated with ordinary oil or grease to meet these requirements. JTEKT has developed and commercialized various types of bearings for extreme special environments in order to meet such needs. In this paper, the materials, lubricants and configurations of bearings for extreme special environments are presented.

Key Words: special environment, solid lubricant, ceramics, vacuum, cleanliness

1. Introduction

With recent technological improvement, performance required for rolling bearings, which are getting severer and severer, are diversifying year by year.

Especially, in the cutting edge fields of semiconductor, flat panel display such as liquid crystal display, storage device and medical device, bearings are sometimes used under extreme special environments such as vacuum, clean and high temperature environments. **Figure 1** shows the relationship between extreme special environments and industries.

The extreme special environments do not sometimes enable bearings made of conventional bearing steels, oils

and greases being used under general environments to be applied.

JTEKT has developed various extreme special environment bearings that can satisfy various needs, and has commercialized them as the EXSEV (Extreme Special Environment) bearing series. In terms of bearings applied to the special environments, the key issue is how appropriate bearings are chosen and what combination of the bearing material and the lubricant are investigated in accordance with environments and requirements for bearing performances.

This report represents bearing materials and lubricants used under extreme special environments, bearings to be applied, and examples of bearing configurations.

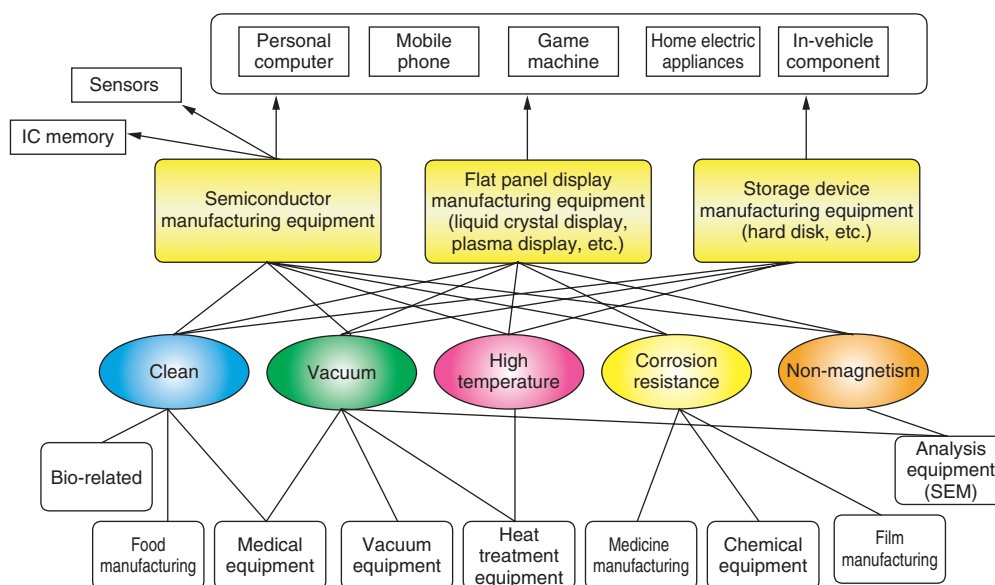


Fig. 1 Relationship between extreme special environments and industries

2. Bearing Material

2.1 Metallic Material

Table 1 shows typical ferrous alloys applying to inner rings, outer rings and rolling elements^{1), 2)}.

The inner rings, the outer rings and the rolling elements are usually made of high-carbon chromium bearing steel (SUJ2) that is resistant to rolling fatigue. However, in such extreme special environments as vacuum, clean and high temperature, rust preventive oil frequently cannot be used, and SUJ2 may have a problem of corrosion. Thus, martensitic stainless steel (SUS440C) having superior corrosion resistance is used as the standard material for extreme special environments. SUS440C possesses not only high temperature resistance but also the hardness of about HRC55 even at 300°C, which can be used as standard material for semi-high temperature up to 300°C.

As for high temperature environment exceeding 300°C, high-speed tool steel (SKH4) is used. In addition, in highly corrosive environments, precipitation hardening stainless steel (SUS630) having superior corrosion resistance is used. Moreover, in non-magnetic applications, austenitic non-magnetic stainless steel is sometimes used because the steel obtains the hardness of about HRC43 by age hardening treatment³⁾. As for

nonferrous metals, there are non-magnetic beryllium copper, cobalt alloy having superior heat resistance, and titanium alloy and nickel alloy having superior corrosion resistance. However, the nonferrous metals have not been used except for few applications since ceramics were getting more and more practical.

2.2 Ceramic Material

Ceramics, which has various superior characteristics such as heat resistance, corrosion resistance, light weight, non-magnetism, and wear resistance, is used for various extreme special environments. Main characteristics of ceramics are also shown in **Table 2**^{1), 2)}. From the viewpoint of load carrying capacity and rolling life, silicon nitride (Si₃N₄) is used as the standard ceramic material for bearings.

Ceramics not only have well-known characteristics such as heat resistance, corrosion resistance, light weight and non-magnetism, but also a property that adhesion is unlikely to occur due to its covalent bond structure, whereas adhesion is often observed on metallic materials. Thus, ceramic bearings can be sometimes used without lubricant in such extreme special environments as high temperature exceeding 500°C, or in vacuum where any solid lubricant cannot be used.

Table 1 Typical ferrous alloy for EXSEV bearings

	Hardness (HRC)	Young's modulus (GPa)	Linear expansion coefficient ($\times 10^{-6} K^{-1}$)	Load carrying capacity	Outgas	Corrosion resistance	Delivery record of bearing materials		Remarks
							Inner ring/outer ring	Ball	
High-carbon chromium bearing steel (SUJ2)	61	208	12.5	◎	◎	×	Yes	Yes	Standard material for conventional bearing
Martensitic stainless steel (SUS440C)	60	208	10.5	◎	◎	△	Yes	Yes	Standard material for extreme special environment bearing
High-speed tool steel (SKH4)	64	207	12.0	◎	◎	×	Yes	Yes	For high temperature
Precipitation hardening stainless steel (SUS630)	40	196	11.0	○	◎	○	Yes	No	For corrosion resistance
Nonmagnetic stainless steel	43	200	18.0	○	◎	△	Yes	No	For nonmagnetic

◎: Excellent, ○: Good, △: Acceptable, ×: Not good

Table 2 Characteristics of ceramics

	Silicon nitride Si ₃ N ₄	Zirconia ZrO ₂	Silicon carbide SiC	Alumina Al ₂ O ₃	Bearing steel SUJ2 (for reference and comparison)
Hardness, HV	1 500	1 200	2 200	1 600	750
Density, g/cm ³	3.2	6	3.1	3.8	7.8
Young's modulus, GPa	320	220	380	350	208
Linear heat expansion coefficient, K ⁻¹	3.2 × 10 ⁻⁶	10.5 × 10 ⁻⁶	3.9 × 10 ⁻⁶	7.1 × 10 ⁻⁶	12.5 × 10 ⁻⁶
Load carrying capacity	◎	○	○	△	◎
Wear resistance	◎	◎	◎	◎	◎
Heat resistance	800	200	Over 1 000	←	180
Remarks	Standard material for ceramic bearing	–	For high corrosion resistance	Smaller load capacity Not applicable to bearing	–

◎: Excellent, ○: Good, △: Acceptable

The test result on the effect of ceramics for suppressing adhesion is shown herein under. In this test, bearings with balls made of SUS440C and Si₃N₄ were rotated without lubricant, and particle emissions from each bearing were measured^{1), 4)}. The test apparatus, the test conditions and the result are shown in **Fig. 2**, **Table 3** and **Fig. 3** respectively. The particle emissions from the bearing B with Si₃N₄ balls showed 1/100 as small as the bearing A with SUS440C balls. As a result of analysis of emitted particles from the bearings A and B, it was confirmed that the bearing B with Si₃N₄ balls showed less wear at the rolling contact surface than the bearing A with SUS440C balls.

	Inner ring/ outer ring	Ball	Retainer	Lubricant
A	SUS440C	SUS440C	SUS304	No lubrication (dry)
B		Si ₃ N ₄		

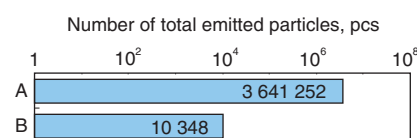


Fig. 3 Comparison of particle emission between hybrid ceramic bearing and steel bearing

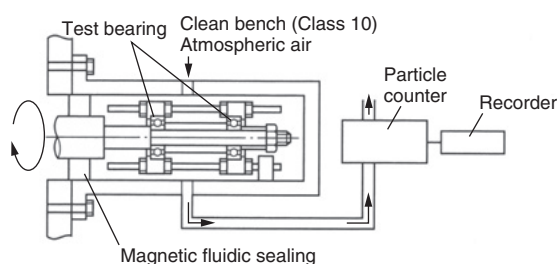


Fig. 2 Test equipment

Table 3 Test conditions

Bearing size	φ6mm × φ12mm × 3mm
Load	Radial 2.9 N/two bearings
Rotational speed	200 min ⁻¹
Test time	20 h
Measured particle size	Over 0.3 μm

3. Lubricants

Greases or solid lubricants are mainly used as lubricants.

Since greases have far better lubricity than that of solid lubricants they are applied as much as possible if they are allowed. The main grease for extreme special environments is fluorinated grease which has features of low evaporation pressure and chemical stability at temperatures up to 200°C.

As for environments where the grease cannot be used due to higher temperature or lower outgassing, etc., solid lubricants are mainly used instead. The solid lubricants are basically classified into three types, which are soft metals, layer lattice materials and polymers. Typical solid lubricants and application examples for bearings are shown in **Table 4**^{1), 2), 5)}.

The soft metals such as silver (Ag) or lead (Pb) are used in ultra high vacuum condition where outgassing from the bearing is critical. Such metals are coated on rolling elements (balls) with ion plating. However, when Ag is used in air, it should be concerned that durability rapidly decreases due to oxidation of Ag.

Table 4 Typical solid lubricants for EXSEV bearings

Solid lubricant		Major characteristics						Implementation to bearing	
		Thermal stability, °C		Friction coefficient		Particle emissions	Outgas	How to be applied	Main applications
		Air	In vacuum	Air	In vacuum				
Soft metal	Silver (Ag)	–	600	–	0.2~0.3	△	◎	Coating on balls	Ultra high vacuum
	Lead (Pb)	–	300	0.05~0.5	0.1~0.15	△	◎		
Layer lattice structure material	Molybdenum disulfide (MoS ₂)	350	400	0.01~0.25	0.001~0.25	△	○	Coating on retainer, inner ring and outer ring	Vacuum, high temperature
	Tungsten disulfide (WS ₂)	425	400	0.05~0.28	0.01~0.2	△	○		
	Graphite (C)	500	–	0.05~0.3	0.4~1.0	△	○		High temperature
Polymer	Polytetrafluoroethylene (PTFE)	260	200	0.04~0.2	0.04~0.2	◎	△	Retainer material	Clean Vacuum, corrosion resistance
	Polyimide (PI)	300	200	0.05~0.6	0.05~0.6	○	△		

◎: Excellent, ○: Good, △: Acceptable

The layer lattice materials are mainly used for high temperature applications. Molybdenum disulfide (MoS₂) or tungsten disulfide (WS₂) can be also used even in vacuum. The materials are coated on retainers or raceway rings with sputtering or baking, or mixed with retainer materials as an additive for composite materials.

The polymers are used when cleanliness or anti-corrosion is required. Furthermore, the polymers can be used for bearings in repetitive conditions of air and vacuum since they are less dependent on pressure than any solid lubricants. The polymers are generally coated on retainers or raceway rings, or is directly implemented to retainer materials.

oil is allowed, the fluorinated grease can be used due to smaller particle emissions and longer life than any solid lubricants.

4. Specifications of Rolling Bearing for Various Extreme Special Environments

4.1 Clean Environment

Particle emissions from bearings are significantly critical in clean environment. **Figure 4** shows the result of comparison tests on particle emissions from bearings with various lubricants^{1), 4)}.

While the bearing lubricated with silver or molybdenum disulfide showed over 10 000 particle emissions, three types of bearings using solid lubricants of fluorinated polymers showed a thousandth as small emissions as any others (E, F, and G in **Fig. 4**). As a result, bearings lubricated with fluorinated polymers are often used in clean environment.

The fluorinated grease also emits only fewer particles in which the main substance is fluorine base oil (perfluoropolyether). If the scattering of small fluorine

	Configurations of bearing materials			Lubrication method	
	Inner ring/ outer ring	Ball	Retainer	Applied position	Lubricant
C	SUS440C	SUS440C	SUS304	Ball	Ag ion plating
D				Retainer	MoS ₂ baking layer
E				Retainer	PTFE baking layer
F			Fluorine resin	Retainer	Fluorine resin
G			SUS304	All surface	Fluorinated polymer film
H				Filled	Fluorinated grease

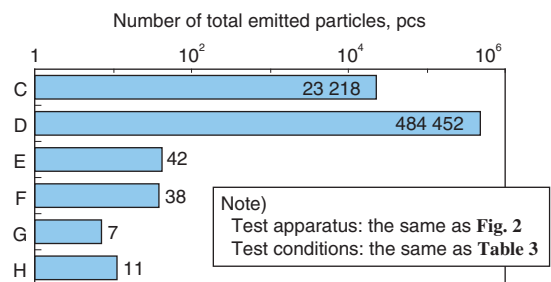


Fig. 4 Test result (comparison of total emitted particles in 20-hour test)

4.2 Vacuum Environment

Figure 5 shows general application ranges based on the pressure and the temperature about various lubricants used in vacuum^{5), 6)}. The lower pressure limit where fluorinated grease can be used is about 10⁻⁵ Pa at room temperature. However, as oil in fluorinated grease

gradually evaporates, it should be concerned that the grease might contaminate the environment.

When solid lubricants as polymers and layer lattice materials are used in the same pressure range, they are applicable at higher temperature than the fluorinated grease. In ultra high vacuum range, which equals to or lower than 10^{-5} Pa, outgassing is critical so that soft metals should be selected.

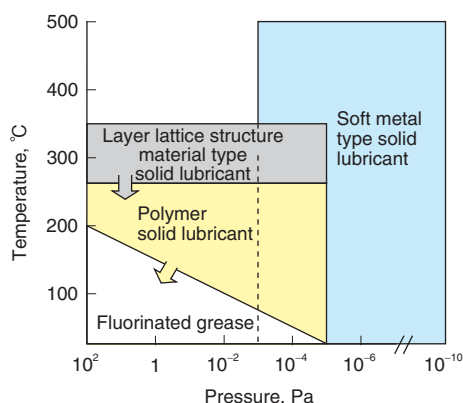


Fig. 5 Application range of each lubricant in vacuum environments

4.3 High Temperature Environment

As for high temperature environments, not only bearing materials but also lubricants must be investigated although they depend on temperature range. **Figure 6** shows the general application range of each bearing material and lubricant^{5), 6)}.

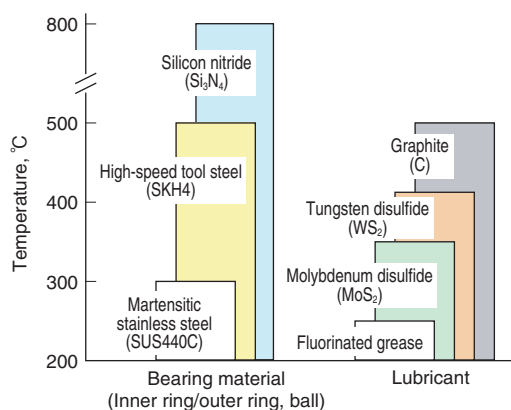


Fig. 6 Application range of each lubricant and bearing material at high temperature environments

As for bearing materials, martensitic stainless steel is used up to about 300°C, and high-speed tool steel is used in the range from about 300°C to about 500°C. Moreover, silicon nitride can be used up to about 800°C.

As for lubricants, fluorinated grease can be used up to about 250°C. At the temperature exceeding 250°C, layer lattice solid lubricants such as molybdenum disulfide,

tungsten disulfide, and graphite can be used. The graphite can be used up to about 500°C, however, it cannot be used in vacuum because of no lubricity in vacuum. There has been no lubricant that can be stably used over 500°C. In this range, full ceramic bearings which consist of all components (inner rings, outer rings, and balls) made of ceramic are sometimes used without lubricant.

4.4 Corrosive Environment

There are various corrosive environments such as corrosive liquid immersion or scattering, and corrosive gas environments depending on both constitutions and concentration of liquid or gas, and the temperature. For the environments, either precipitation hardening stainless steel or ceramics are selected as a material of an inner ring and an outer ring according to conditions. In addition, rolling elements are made of ceramics, and retainers are made of fluorine resins.

As for ceramic materials, silicon nitride with Al_2O_3 - Y_2O_3 as a sintering additive, which has far better corrosion resistance than metallic materials, are often applied. However, in some corrosive conditions such as liquid constitutions or temperature ranges, the ceramics sometimes shows corrosion due to dissolution of the sintering additives. In the conditions, silicon nitride with spinel $MgAl_2O_4$ as the sintering additive to improve the corrosion resistance⁷⁾, or silicon carbide (SiC) is sometimes used.

4.5 Non-magnetism

In non-magnetic application, ceramics or non-magnetic stainless steel³⁾ are often applied to inner rings and outer rings according to the usage purpose. In addition, the rolling element is made of ceramics and the retainer is mainly made of fluorinated resin.

5. Examples of Bearing Configurations

In extreme special environments where bearings are operated in the field, there are some combinations of the environments such as "vacuum + clean" or "vacuum + high temperature." As a result, the key issue is to prioritize requirements when the bearing configurations are investigated.

Some configurations of JTEKT extreme special environment bearings are shown in **Table 5**¹⁾. A combination of the above-described materials and lubricants with fulfilling JTEKT engineering enables JTEKT extreme special environment bearings to satisfy various complex environments.

One of the most extreme special environments is the Front End process in the semiconductor fabrication where semiconductors are processed on wafers. **Table 6** also shows requirements for the Front End process in the

semiconductor fabrication and the bearing configurations. Consequently, it is obvious that JTEKT extreme special

environment bearings are applied to all Front End processes.

Table 5 Typical configuration of JTEKT EXSEV bearings

Products	Configuration				Lubrication		Applicable environments					
	Inner ring/ outer ring	Ball	Retainer	Shield	Lubricant	Applied position	Clean	Vacuum (pressure, Pa)	High temperature (temperature, ℃)	Corrosion resistance	Nonmagnetic	
Clean Pro Bearing	Martensitic stainless steel		Austenitic stainless steel		Fluorinated polymer	Coating on all surface	○	~10 ⁻⁵	200	△	-	
High Temperature Clean Pro Bearing					Fluorine resin	Coating on raceway surface and balls	○	~10 ⁻⁵	260	△	-	
DL Bearing					Fluorinated grease	Filled	○	~10 ⁻⁵	200	△	-	
MG Bearing					Silver	Coating on balls	-	10 ⁻³ ~10 ⁻¹⁰	300	△	-	
MO Bearing					Molybdenum disulfide	Coating on retainer	-	~10 ⁻⁵	300	△	-	
PN Bearing					PEEK resin	Molybdenum disulfide, etc.	Compounded in retainer	-	~10 ⁻⁵	300	△	-
WS Bearing					Sintered separator	Tungsten disulfide	Compounded in separator	-	~10 ⁻⁵	350	△	-
Corrosion Resistant Hybrid Ceramic Bearing	Precipitation hardening stainless steel	Fluorine resin	Not applicable		Fluorine resin	Retainer material	○	~10 ⁻⁵	200	○	-	
Ceramic Bearing	Silicon nitride						○	~10 ⁻⁵	200	○	○	
Corrosion Resistant Ceramic Bearing	Silicon nitride with corrosion resistance specification						○	~10 ⁻⁵	200	○	○	
High Corrosion Resistant Ceramic Bearing	Silicon carbide						○	~10 ⁻⁵	200	○	○	
Non-magnetic Hybrid Ceramic Bearing	Nonmagnetic stainless steel						○	~10 ⁻⁵	200	△	○	
High Temperature Hybrid Ceramic Bearing	High-speed tool steel						-	-	500	-	-	
Full Complement Ceramic Ball Bearing	Silicon nitride						Not applicable (full complement ball)			Not applicable	Not applicable	-

○: Applicable, △: Applicable depending on conditions

Table 6 Required of bearings for semiconductor manufacturing equipments

Main semiconductor manufacturing processes	Requirements for bearing*					JTEKT products**
	Outgas (vacuum)	Clean	Corrosion resistance	Non-magnetism	High temperature	
Oxidation	B	D	A	D	A	WS Bearing, MO Bearing
Photolithography	A	B	D	D	D	Clean Pro Bearing
Etching	D	C	A	D	D	Ceramic Bearing, Corrosion Resistant Hybrid Ceramic Bearing
Ion implantation	B	B	D	D	D	DL Bearing
Sputtering, CVD	B	A	D	D	A	Clean Pro Bearing, High Temperature Clean Pro Bearing
Flattening (CMP)	D	B	A	D	D	Ceramic Bearing, Corrosion Resistant Ceramic Bearing
Inspection (SEM)	C	B	D	A	D	Ceramic Bearing, Non-magnetic Hybrid Ceramic Bearing
Transportation	B	B	B	D	B	Clean Pro Bearing, DL Bearing
Cleaning	D	B	A	D	D	Clean Pro Bearing, Ceramic Bearing

* Characteristics requirement: (Highest) A ← Required level → D (Lowest)

** Detailed bearing specifications referring to **Table 5**.

6. Conclusion

Materials and lubrications for JTEKT extreme special environment bearings as well as bearings for each environment have been introduced.

Environments in which bearings are used are likely to not only get severer and severer but also be diversified. For example, the circuit lines of semiconductor devices become finer year by year and it is expected that requirements for the cleanliness and outgassing of the bearings in the semiconductor fabrication will be more critical than at present.

JTEKT keeps considering higher-performed bearings for extreme special environments to the market by developing various engineering such as material, surface treatment, lubricant and optimal design.

References

- 1) JTEKT Corporation: CERAMIC BEARINGS AND EXSEV BEARINGS FOR EXTREME SPECIAL ENVIRONMENTS, CAT. no. B2004E (2006).
- 2) H. Takebayashi: Koyo Engineering Journal, 156E (2000) 52.
- 3) T. Hattori, K. Kitamura, K. Hayashida: Koyo Engineering Journal, 156E (2000) 30.
- 4) H. Takebayashi: Koyo Engineering Journal, 157E (2000) 58.
- 5) Y. Fujii, H. Takebayashi: Journal of Japan Society for Design Engineering, 38, 3 (2003) 115.

- 6) Y. Fujii, H. Ono: Koyo Engineering Journal, 164E (2004) 24.
- 7) H. Takebayashi, K. Hayashida: Koyo Engineering Journal, 145 (1994) 132.



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