10. Bearing materials

10.1 Comparison of national standards of rolling bearing steel

The dimension series of rolling bearings as mechanical elements have been standardized internationally, and the material to be used for them specified in ISO 683/17 (heat treatment, alloy, and free cutting steels / Part 17 ball and roller bearing steels). However, materials are also standardized according to standards of individual countries and, in some cases, makers are even making their own modifications.

As internationalization of products incorporating bearings and references to the standards of these kinds of steels are increasing nowadays, applicable standards are compared and their features described for some representative bearing steels.

Table 1 Applicable national standards and chemical composition of high-carbon chrome bearing steel

JIS G 4805	ASTM	Other major national standards	Chemical composition (%)						Application	Remarks
			C	Si	Mn	Cr	Mo	Others		
SUJ1	—	—	0.95 to 1.10	0.15 to 0.35	≦0.50	0.90 to 1.20	—	*1	Not used generally	Equivalent to each other though there are slight differences in the ranges.
—	51100	—	0.98 to 1.10	0.15 to 0.35	0.25 to 0.45	0.90 to 1.15	≦0.10	*1		
SUJ2	—	—	0.95 to 1.10	0.15 to 0.35	≦0.50	1.30 to 1.60	—	*1	Typical steel type for small and medium size bearings	Equivalent to each other though there are slight differences in the ranges.
—	A 295-89 52100	—	0.93 to 1.05	0.15 to 0.35	0.25 to 0.45	1.35 to 1.60	≦0.10	P≦0.025 S≦0.015		
—	—	100Cr6 (DIN)	0.90 to 1.05	0.15 to 0.35	0.25 to 0.40	1.40 to 1.65	—	—		
—	—	100C6 (NF)	0.95 to 1.10	0.15 to 0.35	0.20 to 0.40	1.35 to 1.60	≦0.08	P≦0.030 S≦0.025		
—	—	535A99 (BS)	0.95 to 1.10	0.10 to 0.35	0.40 to 0.70	1.20 to 1.60	—	*1		
SUJ3	—	—	0.95 to 1.10	0.40 to 0.70	0.90 to 1.15	0.90 to 1.20	—	*1	For large size bearings	SUJ3 is equivalent to Grade 1. Grade 2 has better quenching capability
—	A 485-03 Grade 1	—	0.90 to 1.05	0.45 to 0.75	0.90 to 1.20	0.90 to 1.20	≦0.10	P≦0.025 S≦0.015		
—	A 485-03 Grade 2	—	0.85 to 1.00	0.50 to 0.80	1.40 to 1.70	1.40 to 1.80	≦0.10	P≦0.025 S≦0.015		
SUJ4	—	—	0.95 to 1.10	0.15 to 0.35	≦0.50	1.30 to 1.60	0.10 to 0.25	*1	Scarcely used	Better quenching capability than SUJ2
SUJ5	—	—	0.95 to 1.10	0.40 to 0.70	0.90 to 1.15	0.90 to 1.20	0.10 to 0.25	*1	For ultralarge size bearings	Though Grade 3 is equivalent to SUJ5, quenching capability of Grade 3 is better than SUJ5.
—	A 485-03 Grade 3	—	0.95 to 1.10	0.15 to 0.35	0.65 to 0.90	1.10 to 1.50	0.20 to 0.30	P≦0.025 S≦0.015		

Notes *1: P≦0.025, S≦0.025
Remarks ASTM: Standard of American Society of Testing Materials, DIN: German Standard, NF: French Standard, BS: British Standard

Table 2 JIS and ASTM standards and chemical composition of carburizing bearing steel

JIS G 4052 G 4053	ASTM A 534-90	Chemical composition (%)							Application	Remarks
		C	Si	Mn	Ni	Cr	Mo	Others		
SCr420H	—	0.17 to 0.23	0.15 to 0.35	0.55 to 0.95	≦0.25	0.85 to 1.25	—	*2	For small bearings	Similar steel type
—	5120H	0.17 to 0.23	0.15 to 0.35	0.60 to 1.00	—	0.60 to 1.00	—	*3		
SCM420H	—	0.17 to 0.23	0.15 to 0.35	0.55 to 0.95	≦0.25	0.85 to 1.25	0.15 to 0.35	*2	For small bearings	Similar steel type, though quenching capability of 4118H is inferior to SCM420H
—	4118H	0.17 to 0.23	0.15 to 0.35	0.60 to 1.00	—	0.30 to 0.70	0.08 to 0.15	*3		
SNCM220H	—	0.17 to 0.23	0.15 to 0.35	0.60 to 0.95	0.35 to 0.75	0.35 to 0.65	0.15 to 0.30	*2	For small bearings	Equivalent, though there are slight differences
—	8620H	0.17 to 0.23	0.15 to 0.35	0.60 to 0.95	0.35 to 0.75	0.35 to 0.65	0.15 to 0.25	*3		
SNCM420H	—	0.17 to 0.23	0.15 to 0.35	0.40 to 0.70	1.55 to 2.00	0.35 to 0.65	0.15 to 0.30	*2	For medium bearings	Equivalent, though there are slight differences
—	4320H	0.17 to 0.23	0.15 to 0.35	0.40 to 0.70	1.55 to 2.00	0.35 to 0.65	0.20 to 0.30	*3		
SNCM815	—	0.12 to 0.18	0.15 to 0.35	0.30 to 0.60	4.00 to 4.50	0.70 to 1.00	0.15 to 0.30	*2	For large bearings	Similar steel type
—	9310H	0.07 to 0.13	0.15 to 0.35	0.40 to 0.70	2.95 to 3.55	1.00 to 1.45	0.08 to 0.15	*3		

Notes *2: P≦0.030, S≦0.030 *3: P≦0.025, S≦0.015

10.2 Long life bearing steel (NSK Z steel)

It is well known that the rolling fatigue life of high-carbon chrome bearing steel (SUJ2, SAE52100) used for rolling bearings is greatly affected by non-metallic inclusions.

Non-metallic inclusions are roughly divided into three-types: sulfide, oxide, and nitride. The life test executed for long periods showed that oxide non-metallic inclusions exert a particularly adverse effect on the rolling fatigue life.

Fig. 1 shows the parameter (oxygen content) indicating the amount of oxide non-metallic inclusions vs. life.

The oxygen amount in steel was minimized as much as possible by reducing impurities (Ti, S) substantially, thereby achieving a decrease in the oxide non-metallic inclusions. The resulting long-life steel is the Z steel.

The Z steel is an achievement of improved steelmaking facility and operating conditions made possible by cooperation with a steel maker on the basis of numerous life test data.

A graph of the oxygen content in steel over the last 25 years is shown in Fig. 2.

The result of the life test with sample material in Fig. 2 is shown in Fig. 3. The life tends to become longer with decreasing oxygen content in steel. The high-quality Z steel has a life span which is about 1.8 times longer than that of conventional degassed steel.

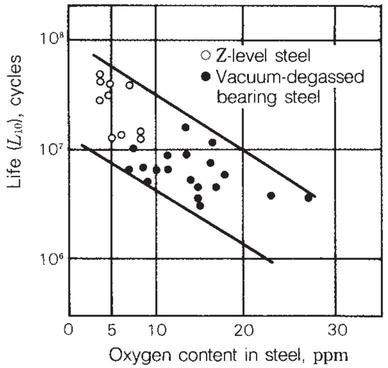


Fig. 1 Oxygen content in steel and life of bearing steel

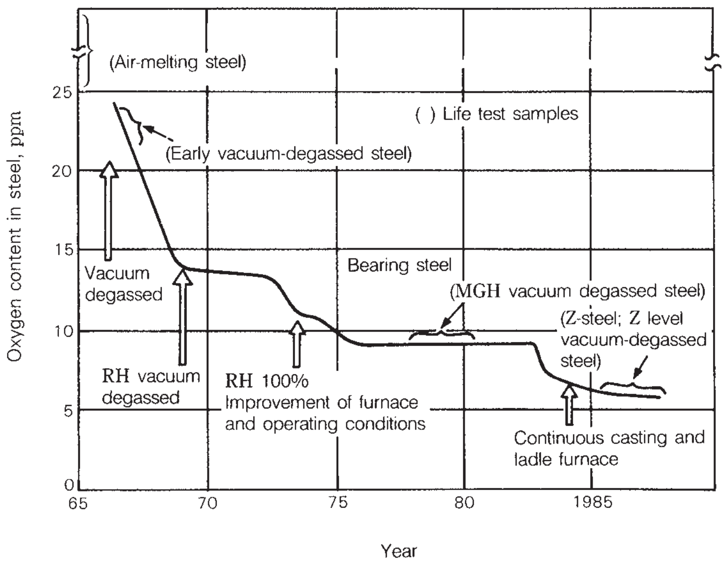
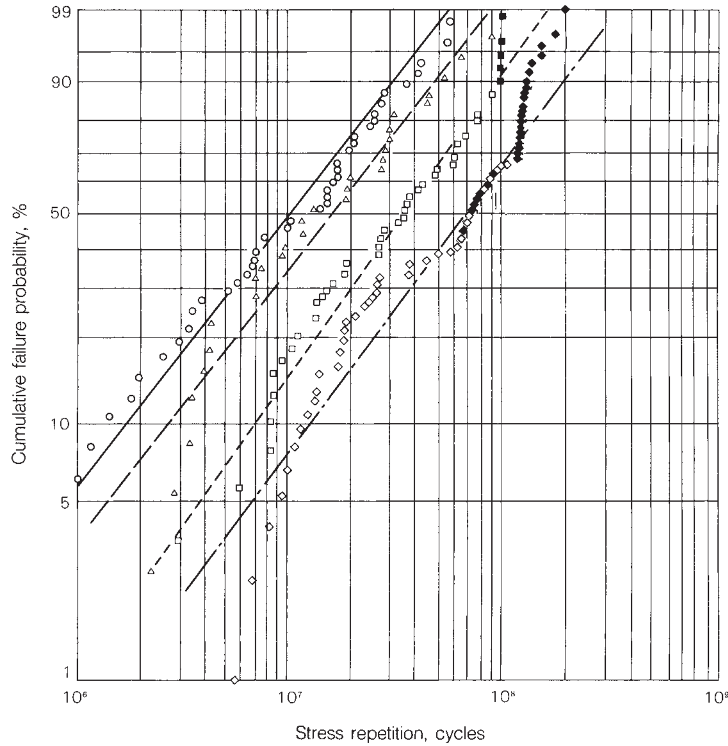


Fig. 2 Transition of oxygen content in NSK bearing steels



Classification	Test quantity	Failured quantity	Weibull slope	L_{10}	L_{50}
○ Air-melting steel	44	44	1.02	1.67×10^6	1.06×10^7
△ Vacuum degassed steel	30	30	1.10	2.82×10^6	1.55×10^7
□ MGH vacuum degassed steel	46	41	1.16	6.92×10^6	3.47×10^7
◇ Z steel	70	39	1.11	1.26×10^7	6.89×10^7

Remarks Testing of bearings marked dark ■ and ◆ has not been finished testing yet.

Fig. 3 Result of thrust life test of bearing steel

10.3 High temperature bearing materials

Even for rolling bearings with countermeasures against high-temperature, the upper limit of the operating temperature is a maximum of about 400°C because of constraints of lubricant. This kind of bearing may be used in certain cases at around 500 to 600°C if the durable time, running speed, and load are restricted. Materials used for high-temperature bearings should be at a level appropriate to the application purpose in terms of hardness, fatigue strength, structural change, and dimensional stability at the operating temperature. In particular, the hardness is important.

Ferrous materials generally selected for high temperature applications include high-speed steel (SKH4) and AISI M50 of Cr-Mo-V steel. Where heat and corrosion resistances are required, martensitic stainless steel SUS 440C may be used. Chemical components of these materials are shown along with bearings steel SUJ2 in Table 1. Their hardness at high temperature is shown in Fig. 1.

The high-temperature hardness of bearing steel diminishes sharply when the tempering temperature is exceeded. The upper limit of the bearing's operating temperature for a bearing having been subjected to normal tempering (160 to 200°C) is around 120°C. If high-temperature tempering (230 to 280°C) is made, then the bearing may be used up to around 200°C as long as the load is small.

SKH4 has been used with success as a bearing material for X-ray tube and can resist well at 450°C when operated with solid lubricant. M50 is used mostly for high-temperature and high-speed bearings of aircraft, and the upper limit of operating temperature is around 320°C.

Where hardness and corrosion resistance at high temperature are required, SUS 440C, having been subjected to high temperature tempering (470 to 480°C), can have a hardness between SUJ2 and M50. Accordingly, this steel can be used reliably at a maximum temperature of 200°C. In high temperature environments at 600°C or more, even high-speed steel is not sufficient in hardness. Accordingly, hastealloy of Ni alloy or stellite of Co alloy is used.

At a temperature exceeding the above level, fine ceramics may be used such as silicon nitride (Si_3N_4) or silicon carbonate (SiC) which are currently highlighted as high-temperature corrosion resistant materials. Though not yet satisfactory in workability and cost, these materials may eventually be used in increasing quantity.

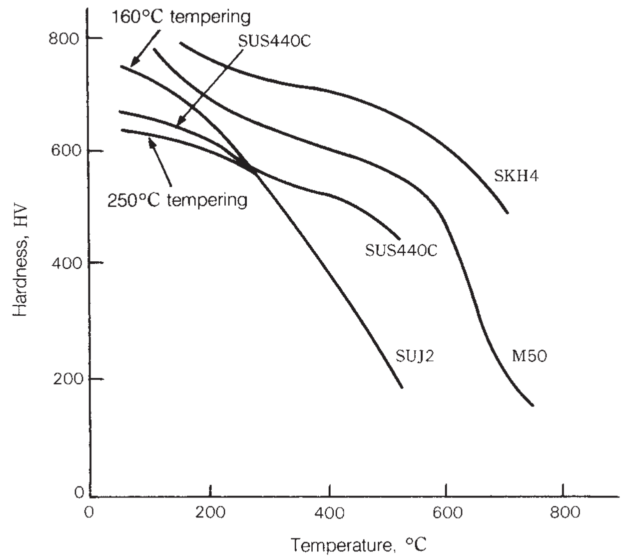


Fig. 1 Hardness of high-temperature materials

Table 1 High-temperature bearing materials

Steel type	Chemical composition %									Remarks
	C	Si	Mn	Ni	Cr	Mo	W	V	Co	
SUJ2	1.02	0.25	≦0.5	—	1.45	—	—	—	—	General use
SKH4	0.78	≦0.4	≦0.4	—	4.15	—	18.0	1.25	10.0	High-temperature use
M50	0.81	≦0.25	≦0.35	≦0.10	4.0	4.25	≦0.25	1.0	≦0.25	High-temperature use
SUS 440C	1.08	≦1.0	≦1.0	≦0.60	17.0	≦0.75	—	—	—	Corrosion resistance/ high temperature

Remarks Figures without≦mark indicate median of tolerance.

10.4 Dimensional stability of bearing steel

Sectional changes or changes in the dimensions of rolling bearings as time passes during operation is called aging deformation. When the inner ring develops expansion due to such deformation, the result is a decrease in the interference between the shaft and inner ring. This becomes one of the causes of inner ring creep. Creep phenomenon, by which the shaft and inner ring slip mutually, causes the bearing to proceed from heat generation to seizure, resulting in critical damage to the entire machine. Consequently, appropriate measures must be taken against aging deformation of the bearing depending on the application.

Aging deformation of bearings may be attributed to secular thermal decomposition of retained austenite in steel after heat treatment. The bearing develops gradual expansion along with phase transformation.

The dimensional stability of the bearings, therefore, varies in accordance with the relative relationship between the tempering during heat treatment and the bearing's operating temperature. The bearing dimensional stability increases with rising tempering temperature while the retained austenite decomposition gradually expands as the bearing's operating temperature rises.

Fig. 1 shows how temperature influences the bearing's dimensional stability. In the right-hand portion of the figure, the interference between the inner ring and shaft in various shaft tolerance classes is shown as percentages for the shaft diameter. As is evident from Fig. 1, the bearing dimensional stability becomes more unfavorable as the bearing's temperature rises. Under these conditions, the interference between the shaft and inner ring of a general bearing is expected to decrease gradually. In this view, loosening of the fit surface needs to be prevented by using a bearing which has received dimension stabilization treatment.

When the bearing temperature is high, there is a possibility of inner ring creep. Since due attention is necessary for selection of an appropriate bearing, it is essential to consult NSK beforehand.

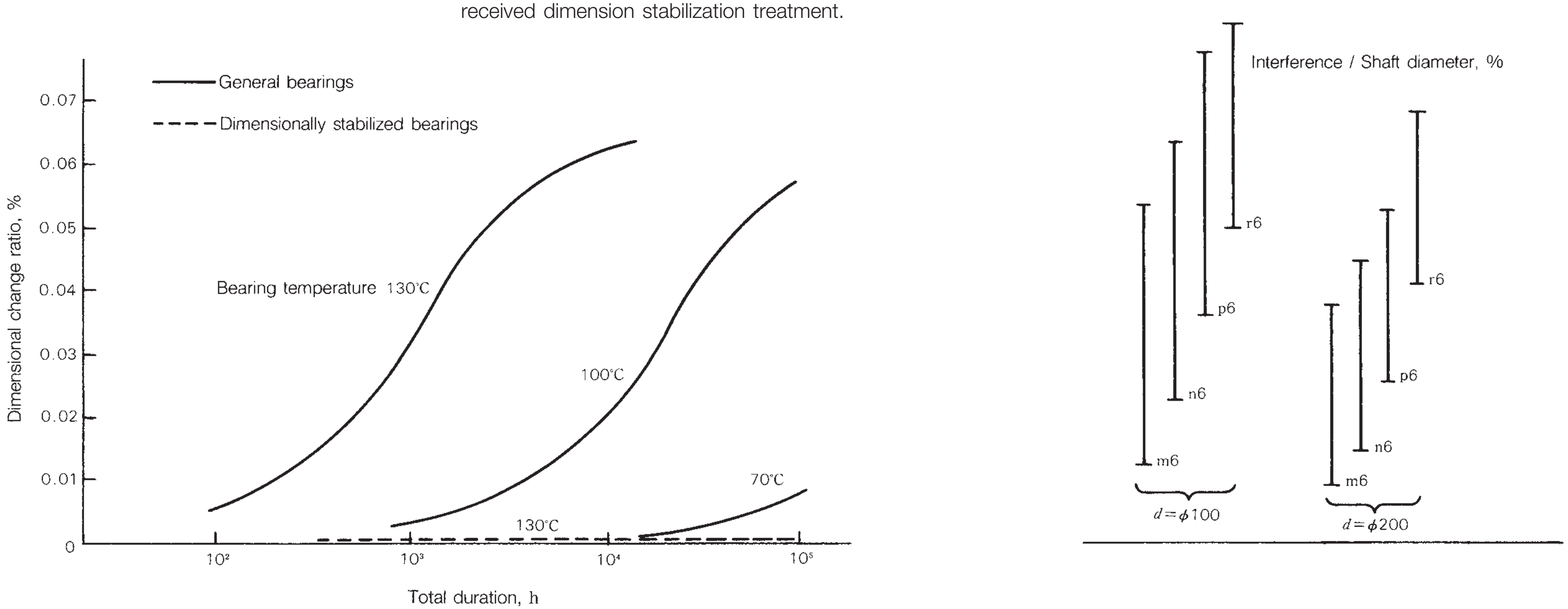


Fig. 1 Bearing temperature and dimensional change ratio

10.5 Characteristics of bearing and shaft/housing materials

Rolling bearings must be able to resist high load, run at high speed, and endure long-time operation. It is also important to know the characteristics of the shaft and housing materials if the bearing performance is to be fully exploited. Physical and mechanical properties or typical materials of a bearing and shaft/housing are shown for reference in Table 1.

Table 1 Physical and mechanical properties of bearing and shaft/housing materials

	Material	Heat treatment	Density g/cm³	Specific heat kJ/(kg·K)	Thermal conductivity W/(m·K)	Electric resistance μΩ·cm	Linear expansion coeff. (0 to 100°C) ×10⁻⁶/°C	Young's modulus MPa {kgf/mm²}	Yield point MPa {kgf/mm²}	Tensile strength MPa {kgf/mm²}	Elongation %	Hardness HB	Remarks
Bearing	SUJ2	Quenching, tempering	7.83	0.47	46	22	12.5	208 000 {21 200}	1 370 {140}	1 570 to 1 960 {160 to 200}	0.5 Max.	650 to 740	High carbon chrome bearing steel No. 2
	SUJ2	Spheroidizing annealing	7.86				11.9		420 {43}	647 {66}	27	180	
	SCr420	Quenching, low temp tempering	7.83		48	21	12.8		882 {90}	1 225 {125}	15	370	Chrome steel
	SAE4320 (SNCM420)	Quenching, low temp tempering			44	20	11.7		902 {92}	1 009 {103}	16	**293 to 375	Nickel chrome molybdenum steel
	SNCM815	Quenching, low temp tempering	7.89		40	35	—		—	*1 080 {110} Min.	*12 Min.	*311 to 375	
	SUS440C	Quenching, low temp tempering	7.68	0.46	24	60	10.1	200 000 {20 400}	1 860 {190}	1 960 {200}	—	**580	Martensitic stainless steel
	SPCC	Annealing	7.86	0.47	59	15	11.6	206 000 {21 000}	—	*275 {28} Min.	*32 Min.	—	Cold rolled steel plate
	S25C	Annealing		0.48	50	17	11.8		323 {33}	431 {44}	33	120	Carbon steel for machine structure
	CAC301 (HBsC1)	—	8.5	0.38	123	6.2	19.1	103 000 {10 500}	—	*431 {44} Min.	*20 Min.	—	High-tension brass
Shaft	S45C	Quenching, 650°C tempering	7.83	0.48	47	18	12.8	207 000 {21 100}	440 {45}	735 {75}	25	217	Carbon steel for machine structure
	SCr430	Quenching, 520 to 620°C fast cooling				22	12.5	208 000 {21 100}	*637 {65} Min.	*784 {80} Min.	*18 Min.	*229 to 293	Chrome steel
	SCr440	Quenching, 520 to 620°C fast cooling			45	23			*784 {80} Min.	*930 {95} Min.	*13 Min.	*269 to 331	
	SCM420	Quenching, 150 to 200°C air cooling		0.47	48	21	12.8		—	*930 {95} Min.	*14 Min.	*262 to 352	Chrome molybdenum steel
	SNCM439	Quenching, 650°C tempering			38	30	11.3	207 000 {21 100}	920 {94}	1 030 {105}	18	320	Nickel chrome molybdenum steel
	SC46	Normalizing	—	—	—	—	—	206 000 {21 000}	294 {30}	520 {53}	27	143	Low carbon cast steel
	SUS420J2	1 038°C oil cooling, 400°C air cooling	7.75	0.46	22	55	10.4	200 000 {20 400}	1 440 {147}	1 650 {168}	10	400	Martensitic stainless steel
Housing	FC200	Casting	7.3	0.50	43	—		98 000 {10 000}	—	*200 {20} Min.	—	*217 Max.	Gray cast iron
	FCD400	Casting	7.0	0.48	20	—	11.7		*250 {26} Min.	*400 {41} Min.	*12 Min.	*201 00Max.	Spheroidal graphite cast iron
	A1100	Annealing	2.69	0.90	222	3.0	23.7	70 600 {7 200}	34 {3.5}	78 {8}	35	—	Pure aluminum
	AC4C	Casting	2.68	0.88	151	4.2	21.5	72 000 {7 350}	88 {9}	167 {17}	7	—	Aluminum alloy for sand casting
	ADC10	Casting	2.74	0.96	96	7.5	22.0	71 000 {7 240}	167 {17}	323 {33}	4	—	Aluminum alloy for die casting
	SUS304	Annealing	8.03	0.50	15	72	15.7 to 16.8	193 000 {19 700}	245 {25}	588 {60}	60	150	Austenitic stainless steel

Note * JIS standard or reference value.
** Though Rockwell C scale is generally used, Brinel hardness is shown for comparison.

Remarks Proportional limits of SUJ2 and SCr420 are 833 MPa {85 kgf/mm²} and 440 MPa {45 kgf/mm²} respectively as reference.

10.6 Engineering ceramics as bearing material

Ceramics are superior to metal materials in corrosion, heat, and wear resistance, but limited in application because they are generally fragile. But engineering ceramics that have overcome this problem of fragility are highlighted as materials to replace metals in various fields. Engineering ceramics have already been used widely for cutting tools, valves, nozzles, heat insulation materials, and structural members.

More specifically, ceramic material is highlighted as a bearing material. In practice, the angular contact ball bearing with silicon nitride balls is applied to the head spindle of machine tools. The heat generation characteristics and machine rigidity allow this material to offer functions which have not been available up to now with other materials.

Characteristics of engineering ceramics and bearing steel are shown in Table 1. Engineering ceramics have the following advantages as a bearing material over metals:

- ○ Low density for weight reduction and high-speed rotation
- ○ High hardness and small frictional coefficient, and superiority in wear resistance
- ○ Small coefficient of thermal expansion and satisfactory dimensional stability
- ○ Superior heat resistance and less strength degradation at high temperature
- ○ Excellent corrosion resistance
- ○ Superior electric insulation
- ○ Non-magnetic

Development of applications that take advantage of these characteristics are actively underway. For example, bearings for rotary units to handle molten metals, and non-lubricated bearings in clean environments (clean rooms, semiconductor manufacture systems, etc.).

Engineering ceramics include many kinds such as silicon nitride, silicon carbonate, alumina, partially-stabilized zirconia. Each of these materials has its own distinctive properties.

To successfully use ceramics as bearing material, it is essential to know various properties of ceramic materials and to select the material to match the operating conditions. Though suffering from problems of workability and cost, improvement in material design and manufacturing technology will further accelerate application of ceramic bearings in high temperature environments, corrosive environments, and in vacuum environments.

What is required most of the engineering ceramics as bearing materials is greater reliability in terms of rolling fatigue life. In particular, ceramic bearings are used at high temperatures or high speeds. Thus, any damage will exert an adverse effect on performance of peripheral devices of the machine. Numerous measures have been taken such as processing the raw material powder to sintering and machining in order to enhance the reliability of the rolling life.

Table 1 Properties of engineering ceramics and metal material (bearing steel)

Material	Density g/cm^3	Hardness HV	Young's modulus GPa {$\times 10^4 kgf/mm^2$}	Flexural strength MPa {kgf/mm^2}	Fracture toughness $MPa \cdot m^{1/2}$	Linear thermal expansion coeff. $\times 10^{-6}/°C$	Thermal shock resistance °C	Thermal conductivity W/(m·K) {cal/cm·s°C}	Electric resistance $\Omega \cdot cm$
Silicon nitride (Si_3N_4)	3.1 to 3.3	1 500 to 2 000	250 to 330 {2.5 to 3.3}	700 to 1 000 {70 to 100}	5.2 to 7.0	2.5 to 3.3	800 to 1 000	12 to 50 {0.03 to 0.12}	10^{13} to 10^{14}
Silicon carbonate (SiC)	3.1 to 3.2	1 800 to 2 500	310 to 450 {3.1 to 4.5}	500 to 900 {50 to 90}	3.0 to 5.0	3.8 to 5.0	400 to 700	46 to 75 {0.11 to 0.18}	100 to 200
Alumina (Al_2O_3)	3.6 to 3.9	1 900 to 2 700	300 to 390 {3.0 to 3.9}	300 to 500 {30 to 50}	3.8 to 4.5	6.8 to 8.1	190 to 210	17 to 33 {0.04 to 0.08}	10^{14} to 10^{16}
Partly-stabilized zirconia (ZrO_2)	5.8 to 6.1	1 300 to 1 500	150 to 210 {1.5 to 2.1}	900 to 1 200 {90 to 120}	8.5 to 10.0	9.2 to 10.5	230 to 350	2 to 3 {0.005 to 0.008}	10^{10} to 10^{12}
Bearing steel	7.8	700	208 {2.1}	—	14 to 18	12.5	—	50 {0.12}	10^{-5}

Fig. 1 shows a Weibull plot of the results of a test with radial ball bearings using ceramic balls of silicon nitride of six kinds of HIP (sintered under atmospheric pressure) differing in raw material, structure, and components. The test was conducted, with 3/8" diameter ceramic balls incorporated into inner and outer rings of bearing steel, under conditions of Table 2.

X and Y in Fig. 1 are bearings with NSK-made ceramic balls developed under strict control of the material manufacturing process. A theoretical calculation life (L_{10}) of bearing with steel balls under the same test conditions is 263 hours. It can, therefore, be stated that NSK-made ceramic balls have a life of more than eight times as long as L_{10} of bearings with steel balls. Other ceramic balls develop flaking while suffering wider variance within a shorter period of time.

The flaking pattern shows a unique fatigue appearance (Photo 1), mostly indicating a type of flaking which is generated by foreign metallic material, segregation of the sintering auxiliary agent, or the occurrence of pores.

The commonly highlighted strength characteristics of engineering ceramics are flexural strength, hardness, and K_{IC} (fracture toughness). Apart from these characteristics, the material needs to be free from defects such as pores or segregation of the auxiliary agent. This can be accomplished through cleaning of the material base and optimum sintering.

Accordingly, due and careful consideration of the material maker is necessary during processing stages from raw material powder to sintering in order to transform ceramics into a an extremely reliable engineering bearing material.

Table 2 Test conditions

Test bearing	6206 with 8 ceramic balls and nylon cage
Support bearing	6304
Radial load	3 800 N {390 kgf}
Max. contact surface pressure	2 800 MPa {290 kgf/mm^2}
Speed	3 000 min^{-1}
Lubrication	FBK oil RO-68

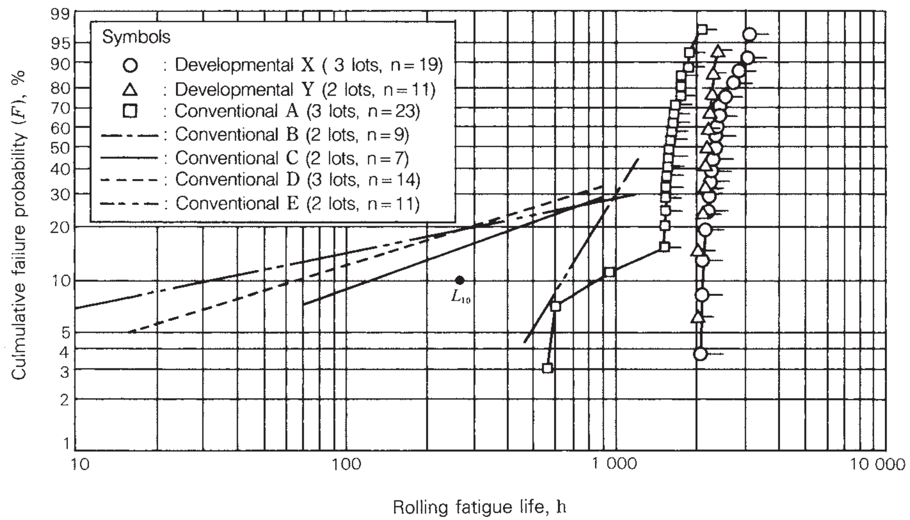


Fig. 1 Weibull plot of life test results

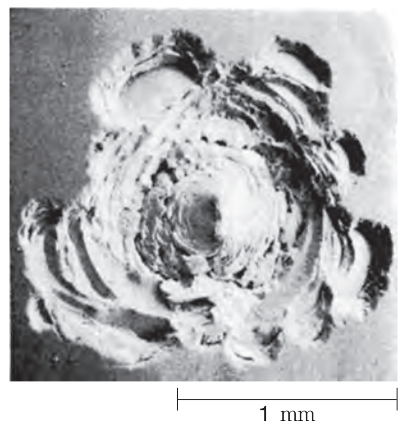


Photo 1 Appearance of flaking

10.7 Physical properties of representative polymers used as bearing material

Because of lightweight, easy formability, and high corrosion resistance, polymer materials are used widely as a material for cages. Polymers may be used independently, but they are usually combined with functional fillers to form a composite material. Composites can be customized to have specific properties. In this way composites can be designed to be bearing materials. For example, fillers can be used to improve such properties as low friction, low wear, non-stick slip characteristic, high limit PV value, non-scrubbing of counterpart material, mechanical properties, and heat resistance, etc.

Table 1 shows characteristics of representative polymer materials used for bearings.

Table 1 Characteristics of representative polymers

Plastics	Elastic modulus (GPa) (1)	Strength GPa (1)	Density g/cm^3	Specific elastic modulus $\times 10^4$mm	Specific strength $\times 10^4$mm	Melting point °C	Glass transition temp °C	Thermal deformation temperature °C (2)	Continuous operating temperature °C	Remarks
Polyethylene HDPE	0.11	0.03	0.96	12.6	3.3	132	−20	75/50	—	High creep and toughness, softening
UHMWPE	50.5	0.025	0.94	53.2	2.7	136	−20	75/50	—	
Polyamide Nylon 6	2.5	0.07	1.13	221.2	6.2	215	50	150/57	80 to 120	High water absorption and toughness
Nylon 66	3.0	0.08	1.14	263.2	7.0	264	60	180/60	80 to 120	
Nylon 11	1.25	0.04	1.04	120.2	3.8	180	—	150/55	Lower than nylon 6 or 66	Low water absorption
Polytetra fluoroethylene PTFE	0.40	0.028	2.16	18.5	1.3	327	115	120/—	260	High creep, sintering,low friction and adhesion, inert. Stable at 290°C
Poly buthylene terephthalate PBT	2.7	0.06	1.31	206.1	4.6	225	30	230/215	155	
Polyacetal POM Homo-polymer	3.2	0.07	1.42	225.3	4.9	175	−13	170/120	—	High hardness and toughness, low water absorption
Co-polymer	2.9	0.06	1.41	205.7	4.3	165	—	155/110	104	
Polyether sulfon PES	2.46	0.086	1.37	179.6	6.3	—	225	210/203	180	Usable up to 200°C Chemically stable
Polysulfon PSf	2.5	0.07	1.24	201.6	5.6	—	190	181/175	150	
Polyallylate (Aromatic polyester)	1.3	0.07	1.35	96.3	5.2	350	—	293	300	Inert, high hardness, Used as filler for PTFE Stable up to 320°C
	3.0	0.075	1.40	214.3	5.4	350	—	293	260 to 300	
Polyphenylene sulfide PPS (GF 40%)	4.2	0.14	1.64	256.1	8.5	275	94	>260	220	Hot cured at 360°C
Polyether ether keton PEEK	1.7	0.093	1.30	130.8	7.2	335	144	152	240	
Poly-meta-phenylene isophthalic amide	10 (fiber)	0.7	1.38	724.6	50.7	375	>230	280	220	Fire retardant, heat resistance fiber
	7.7 (mold)	0.18	1.33	579	13.5	415 (decomposition)	>230	280	220	
Polypromellitic imide (Aromatic polyimide) PI	3 (film)	0.17	1.43	203	7.0	Heat de-composition	417 decomposition	360/250	300 (3)	No change in inert gas up to 350°C
	2.5 to 3.2 (mold)	0.1	1.43	203	7.0	Heat de-composition	417 decomposition	360/250	260	Usable up to 300°C for bearing. Sintering, no fusion (molded products)
Polyamide imide PAI	4.7	0.2	1.41	333.3	14.2	—	280	260	210	Usable up to 290°C as adhesive or enamel Improved polyimide of melting forming
Polyether imide (Aromatic polyimide) PI	3.6	0.107	1.27	240.9	—	—	215	210/200	170	Improved polyimide of melting forming
Polyamino bis-maleimide	—	0.35	1.6	—	21.9	—	—	330 (3)	260	

Notes (1) GPa≒10^4 kgf/cm^2=10^2 kgf/mm^2
(2) If there is a slash mark "/" in the thermal deformation temperature column, then the value to the left of the "/" applies to 451 kPa, If there, the value relates to 1.82 MPa.
(3) Reference value

10.8 Characteristics of nylon material for cages

In various bearings these days, plastic cages have come to replace metal cages increasingly. Advantages of using plastic cages may be summarized as follows:

(1) Lightweight and favorable for use with high-speed rotation
(2) Self-lubricating and low wear. Worn powders are usually not produced when plastic cages are used. As a result, a highly clean internal state is maintained.
(3) Low noise appropriate atm silent environments
(4) Highly corrosion resistant, without rusting
(5) Highly shock resistant, proving durable under high moment loading
(6) Easy molding of complicated shapes, ensures high freedom for selection of cage shape. Thus, better cage performance can be obtained.

As to disadvantages when compared with metal cages, plastic cages have low heat resistance and limited operating temperature range (normally 120°C). Due attention is also necessary for use because plastic cages are sensitive to certain chemicals. Polyamide resin is a representative plastic cage material. Among polyamide resins, nylon 66 is used in large quantity because of its high heat resistance and mechanical properties.

Polyamide resin contains the amide coupling (-NHCO-) with hydrogen bonding capability in the molecular chain and is characterized by its regulation of mechanical properties and water absorption according to the concentration and hydrogen bonding state. High water absorption (Fig. 1) of nylon 66 is generally regarded as a shortcoming because it causes dimensional distortion or deterioration of rigidity. On the other hand, however, water absorption helps enhance flexibility and prevents cage damage during bearing assembly when a cage is required to have a substantial holding interference for the rolling elements. This also causes improvement is toughness which is effective for shock absorption during use. In this way, a so-called shortcoming may be considered as an advantage under certain conditions.

Nylon can be improved substantially in strength and heat resistance by adding a small amount of fiber. Therefore, materials reinforced by glass fiber may be used depending on the cage type and application. In view of maintaining deformation of the cage during assembly of bearings, it is common to use a relatively small amount of glass fiber to reinforce the cage. (Table 1)

Nylon 66 demonstrates vastly superior performance under mild operating conditions and has wide application possibilities as a mainstream plastic cage material. However, it often develops sudden deterioration under severe conditions (in high temperature oil, etc.). Therefore, due attention should be paid to this material during practical operation.

As an example, Table 2 shows the time necessary for the endurance performance of various nylon 66 materials to drop to 50% of the initial value under several different cases.

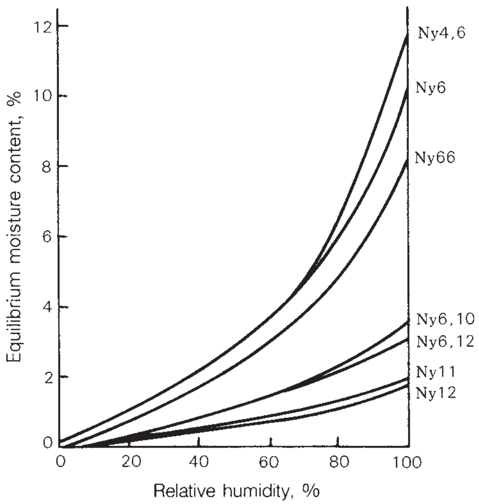


Fig. 1 Equilibrium moisture content and relative humidity of various nylons

Material deterioration in oil varies depending on the kind of oil. Deterioration is excessive if the oil contains an extreme-pressure agent. It is known that sulfurous extreme-pressure agents accelerate deterioration more than phosphorous extreme-pressure agents and such deterioration occurs more rapidly with rising temperatures.

On the other hand, material deteriorates less in grease or air than in oil. Besides, materials reinforced with glass fiber can suppress deterioration of the strength through material deterioration by means of the reinforcement effect of glass fibers, thereby, helping to extend the durability period.

Table 1 Examples of applications with fiber reinforced nylon cages

	Bearing type	Main aplication	Cage material
Ball bearing	Miniature ball bearings	VCR, IC cooling fans	Nylon 66 (Glass fiber content: 0 to 10%)
	Deep groove ball bearings	Alternators, fan motors for air conditioners	
	Angular contact ball bearings	Magnetic clutches, automotive wheels	
Roller bearing	Needle roller bearings	Automotive transmissions	Nylon 66 (Glass fiber content: 10 to 25%)
	Tapered roller bearings	Automotive wheels	
	ET-type cylindrical roller bearings	General	
	H-type spherical roller bearings	General	

Table 2 Environmental resistance of nylon 66 resin

Environment		Temperature, °C	Glass content	Hours for the physical property value to drop to 50%, h (500 / 1000 / 1500 / 2000)	Remarks
Oil	Gear oil	120	0		Contains an extreme pressure additive
			D		
		140	0		
			A		
			D		
	Synthetic lubricating oil	100	A		Contains an extreme pressure additive
		120	A		
		130	0		
			A		
			C		
		150	0		
			B		
			D		
	Hydraulic oil	80	0		Contains an extreme pressure additive
			D		
		120	0		
			D		
		150	0		
			D		
	ATF oil	120	0		
			D		
		140	0		
			A		
			D		
	Engine oil	120	0		
			D		
Grease		80	0		
			D		
		120	0		
			D		
		130	A		
			D		
Air		160	0		
			A		
			C		
		180	0		
			B		

Class content: A<B<C<D

10.9 Heat-resistant resin materials for cages

Currently, polyamide resin shows superior performance under medium operating environmental conditions. This feature plus its relative inexpensiveness lead to its use in increasing quantities. But, the material suffers from secular material deterioration or aging which creates a practical problem during continuous use at 120°C or more or under constant or intermittent contact with either oils (containing an extreme pressure agent) or acids.

Super-engineering plastics should be used for the cage materials of bearings running in severe environments such as high temperature over 150°C or corrosive chemicals. Though super-engineering plastics have good material properties like heat resistance, chemical resistance, rigidity at high temperature, mechanical strength, they have problems with characteristics required for the cage materials like toughness when molding or bearing assembling, weld strength, fatigue resistance. Also, the material cost is expensive. Table 1 shows the evaluation results of typical super-engineering plastics, which can be injection molded into cage shapes.

Among the materials in Table 1, though the branch type polyphenylene sulfide (PPS) is popularly used, the cage design is restricted since forced-removal from the die is difficult due to poor toughness and brittleness. Moreover, PPS is not always good as a cage material, since the claw, stay, ring, or flange of the cage is easily broken on the bearing assembling line. On the other hand, the heat resistant plastic cage developed by NSK, is made of linear-chain high molecules which have been polymerized from molecular chains. These molecular chains do not contain branch or crosslinking so they have high toughness compared to the former material (branch type PPS). Linear PPS is not only superior in heat resistance, oil resistance, and chemical resistance, but also has good mechanical characteristics such as snap fitting (an important characteristic for cages), and high temperature rigidity.

NSK has reduced the disadvantages associated with linear PPS: difficulty of removing from the die and slow crystallization speed, thereby establishing it as a material suitable for cages. Thus, linear PPS is thought to satisfy the required capabilities for a heat resistant cage material considering the relation between the cost and performance.

Table 1 Properties of typical super-engineering plastic materials for cages

Classification	Polyether sulfone (PES)	Polyether imide (PEI)	Polyamide imide (PAI)	Polyether etherketon (PEEK)	Branch type polyphenylene sulfide (PPS)	Linear type polyphenylene sulfide (L-PPS)
Resin	Amorphous resin	Amorphous resin	Amorphous resin	Crystalline resin	Crystalline resin	Crystalline resin
Continuous temp	180°C	170°C	210°C	240°C	220°C	220°C
Physical properties	•Poor toughness (Pay attention to cage shape) •Low weld strength •Small fatigue resistance	•Poor toughness •Small weld strength •Small fatigue resistance	•Very brittle (No forced-removal molding) •Special heat treatment before use •High rigidity, after heat treatment	•Excellent toughness, wear and fatigue resistance •Small weld strength	•Excellent mechanical properties •Slightly low toughness	•Excellent mechanical properties •Good toughness •Good dimensional stability (No water absorption)
Environmental properties	•Water absorption (Poor dimensional stability) •Good aging resistance •Poor stress cracking resistance	•Good aging resistance •Poor stress cracking resistance	•Good environment resistance	•Good environment resistance	•Good environment resistance	•Good environment resistance (Not affected by most chemicals. Doesn't deteriorate in high temperature oil with extreme pressure additives).
Material cost (Superiority)	3	2	5	4	1	1
Cage application	•Many performance problems •High material price	•Many performance problems •High material cost	•Good performance •High material and molding cost (For special applications)	•Excellent performance •High material cost (For special applications)	•Problems with toughness •Cost is high compared to its performance	•Reasonable cost for its performance (For general applications)

10.10 Features and operating temperature range of ball bearing seal material

The sealed ball bearing is a ball bearing with seals as shown in Figs. 1 and 2. There are two seal types: non-contact seal type and contact seal type. For rubber seal material, nitrile rubber is used for general purpose and poly-acrylic rubber, silicon rubber, and fluoric rubber are used depending on temperature conditions.

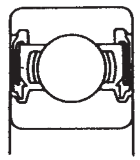
These rubbers have their own unique nature and appropriate rubber must be selected by considering the particular application environment and running conditions.

Table 1 shows principal features of each rubber material and the operating temperature range of the bearing seal. The operating temperature range of Table 1 is a guideline for continuous operation. Thermal aging of rubber is related to the temperature and time. Rubber may be used in a much wider range of operating temperatures depending on the operating time and frequency.

In the non-contact seal, heat generation due to friction on the lip can be ignored. And thermal factors, which cause aging of the rubber, are physical changes due to atmospheric and bearing temperatures. Accordingly, increased hardness or loss of elasticity due to thermal aging exerts only a negligible effect on the seal performance. A rubber non-contact seal can thus be used in an expanded range of operating temperatures greater than that for a contact seal.

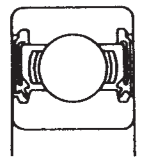
But there are some disadvantages. The contact seal has a problem with wear occurring at the seal lip due to friction, thermal plastic deformation, and hardening. When friction or plastic deformation occurs, the contact pressure between the lip and slide surface decreases, resulting in a clearance. This clearance is minimum and does not cause excessive degradation of sealing performance (for instance, it does not allow dust entry or grease leakage). In most cases, this minor plastic deformation or slightly increased hardness presents no practical problems.

However, in external environments with dust and water in large quantity, the bearing seal is used as an auxiliary seal and a principal seal should be provided separately. As so far described, the operating temperature range of rubber material is only a guideline for selection. Since heat resistant rubber is expensive, it is important to understand the temperature conditions so that an economical selection can be made. Due attention should also be paid not only to heat resistance, but also to the distinctive features of each rubber.



Non-contact rubber seal (VV)

Fig. 1



Contact rubber seal (DDU)

Fig. 2

Table 1 Features and operating temperature range of rubber materials

Material		Nitrile rubber	Polyacrylic rubber	Silicon rubber	Fluorine rubber
Key features		○Most popular seal material ○Superior in oil and wear resistances and mechanical properties ○Readily ages under direct sun-rays ○Less expensive than other rubbers	○Superior in heat and oil resistances ○Large compression causes permanent deformation ○Inferior in cold resistance ○One of the less expensive materials among the high temperature materials ○Attention is necessary because it swells the ester oil based grease	○High heat and cold resistances ○Inferior in mechanical properties other than permanent deformation by compression. Pay attention to tear strength ○Pay attention so as to avoid swell caused by low aniline point mineral oil, silicone grease, and silicone oil	○High heat resistance ○Superior in oil and chemical resistances ○Cold resistance similar to nitrile rubber ○Attention is necessary because it deteriorates the urea grease
Operating temperature range (1) (°C)	Non-contact seal	−50 to +130	−30 to +170	−100 to +250	−50 to +220
	Contact seal	−30 to +110	−15 to +150	−70 to +200	−30 to +200

Note (1) This operating temperature is the temperature of seal rubber materials.