Development of High-speed Angular Contact Ball Bearings for Machine Tool Spindles "High Ability Bearings"

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Recently machine-tool spindles have been radically improved in speed and efficiency for improving productivity and reducing processing cost including such challenges as energy saving and environmental friendliness.

To meet such demands, Koyo has developed a new series of high-speed angular contact ball bearing series called "High Ability Bearings" which has much advantage in high-speed, prompt start/stop and low temperature-rise performance. The maximum rotational speed limit of the bearings showed 1.3 times higher and the temperature rise 20 to 30% lower in oil-air or grease lubrication compared with conventional Koyo high-speed bearings (ACH).

This paper describes the design outlines of High Ability Bearing series and its excellent performance.

Key Words: *angular contact ball bearing, machine-tool spindle, high-speed rotation, low temperature rise, oil-air*

1. Introduction

Recently, machine tool spindles have been radically improved in speed and efficiency, reflecting growing demands from various industries on improvement of productivity and reduction of processing cost[1) 2)]. Specifically, increasing number of current high-speed machining centers have both advantages of reduced actual cutting time enabled by high-speed rotation as well as quickness in tooling change and startup (i.e., reduced idle time). Such a high-speed and high efficient spindle requires a bearing that can provide not only high-speed rotation but also reliability in prompt start/stop performance.

Machine tool spindles now have another challenge: energy saving and environmental friendliness, which are now vital requirements for every manufacturer in every field which is urged to perform production activities in an ecologically satisfactory manner. Due to this reason, it is desired that bearings used for machine tool spindles consume less air and generate less noise when being used in oil-air lubrication, and are lubricated with more environmentally friendly greases[3)].

In order to satisfy such conditions, it is important to improve machine tool spindle bearings in high-speed, prompt start & stop, and low temperature performance with a lubrication method that consumes relatively small electric power.

Now, Koyo has developed a new series of bearings called "High Ability Bearings" as one of the lineup of high-speed angular contact ball bearings for machine tool spindles. The name "High Ability Bearings" comes from the newly designed bearings' high ability in high-speed, prompt start/stop, and low temperature-rise performance. This paper describes the design outline of High Ability Bearings series and its excellent performance.

2. Design Outline of High Ability Bearings

In order to achieve high-speed, prompt start/stop, and low-temperature-rise performance of an angular ball bearing, it is necessary to take the following factors into consideration.

① an increase in internal load due to a centrifugal force that acts on rolling elements (i.e., an increase in pressure at raceway contact);

② slight slip[4) 5)] occurring between a rolling element and raceway (e.g., spin slip) and macroscopic slip;

③ decrease of internal clearance caused by changes such as centrifugal expansion of an inner ring raceway or temperature difference between an inner ring and outer ring (e.g., an increase in preload, reduced clearance); and

④ in case of oil air or oil mist lubrication, insufficient lubricant supply due to wind pressure on the side surfaces of a bearing (hereinafter referred to as air curtain).

In order to minimize the above factors, Koyo provided High Ability Bearings with the following design improvements.

(1) Optimized internal specifications

Bearings' internal specifications that have great influence on bearing performance include ball diameter, curvature, and contact angle. Using the design analysis program[6) 7)] developed by Koyo, such decisive specifications were optimized in high-speed and low-temperature-rise performance[8)].

Figure 1 shows an example of comparing conventional bearings with High Ability Bearings (hereinafter referred to as test bearings) by calculating simulation values of their friction loss values (PV value), a value that is generated by slight slide between a rolling element and a raceway and greatly affects temperature rise characteristic. As seen from **Fig. 1**, test bearings show smaller friction loss (PV value) than that of conventional bearings, showing their superiority in high-speed and low-temperature-rise performance.

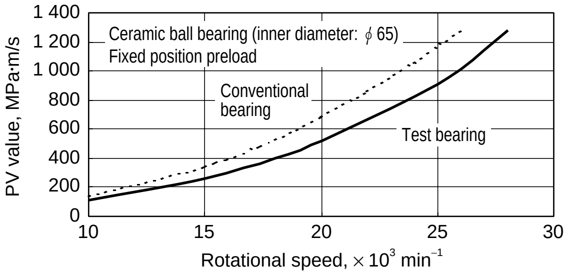


Fig. 1 Calculated PV values of test bearing and conventional product (ACH)

(2) Design for effective lubrication

Oil-supply holes for oil air or oil mist lubrication are provided in a raceway to ensure direct oil supply into a bearing. This design avoids insufficient supply of oil air or oil mist due to air curtain generated along a side face of a high-speed rotating bearing. This design also improves lubrication reliability of a bearing when rotating at high-speed with oil air or oil mist lubrication and intends to reduce environmental burdens such as air consumption and noise.

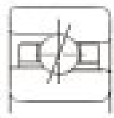
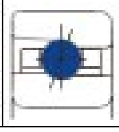
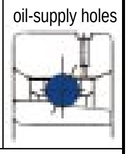
(3) Adoption of high-performance material

The bearings comprise ceramic balls[1] which have been used in high-speed rotation and carburized steel for inner ring which is superior for anti-centrifugal stress occurring during ultra high-speed rotation.

What is noteworthy is that a bearing with ceramic balls can be used up to a speed 1.3 times higher than that of a bearing with steel balls due to ceramics' superior characteristics[9] such as small density, heat-resistance, and small thermal expansion[10].

Table 1 shows the outline of type Ⅰ to type Ⅳ test bearings that have the above-described design improvements.

Table 1 Test bearings

	Type Ⅰ	Type Ⅱ	Type Ⅲ[11]	Type Ⅳ
Configuration				
Lubrication	Grease/Oil-air lubrication		Oil-air lubrication only	
Rolling element material	Bearing steel	Ceramics		
Raceway material	Bearing steel		Inner ring: Carburized steel Outer ring: Bearing steel	

3. High-speed and Temperature Rise Test

3. 1 Test Method

In order to clarify the basic performance, type Ⅰ to type Ⅲ test bearings were evaluated for their high-speed rotational limit and outer ring's temperature rise (i.e., difference between outer ring temperature and room temperature). Performance of type Ⅳ is described later. **Table 2** shows the test conditions and **Fig. 2** the structure of the test apparatus. **Figures 3** and **4** show lubrication methods.

The test bearings were assembled in back-to-back arrangement in two rows (DB) and subjected to preload at a fixed position. After that, the test bearings were rotated with oil-air lubrication at room temperature in the natural cooling condition.

Table 2 High-speed and temperature rise test conditions

Test		Type Ⅰ test		Type Ⅱ test		Type Ⅲ test	
Test bearing (contact angle: 20°)	Type	Conventional bearing (ACH)	Type Ⅰ (internal specifications changed)	Conventional bearing (3NCACH)	Type Ⅱ (internal specifications changed)	Conventional bearing, conventional lubrication method	Type Ⅲ, Type Ⅲ lubrication method
	Size	ϕ 65×ϕ 100×18		ϕ 65×ϕ 100×18		ϕ 35×ϕ 62×14	
	Ball material	Bearing steel		Ceramics		Ceramics	
	Raceway material	Bearing steel		Bearing steel		Bearing steel	
Preload, N		150, fixed position		150, fixed position		39, fixed position	
Lubrication conditions	Oil viscosity	Equivalent to ISO VG32		Equivalent to ISO VG32		Equivalent to ISO VG32	
	Oil rate, ml/8 min	0.03		0.03		0.03	
	Air rate, Nl/min	46		46		27	
	Oil supply method	**Fig. 3**		**Fig. 3**		**Fig. 3**	**Fig. 4**
Cooling condition		Natural cooling		Natural cooling		Natural cooling	

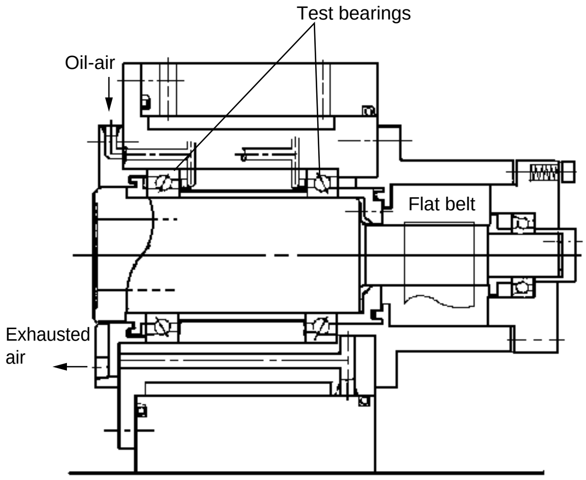


Fig. 2 Test equipment A

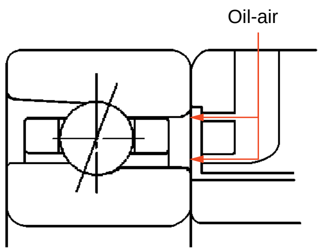


Fig. 3 Lubrication method for conventional products, Type Ⅰ and Type Ⅱ

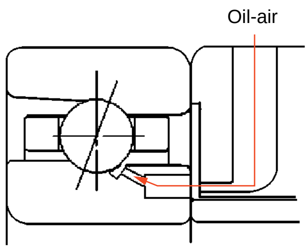


Fig. 4 Lubrication method for Type Ⅲ

3. 2 Test Result of Type Ⅰ

Type Ⅰ test bearing, in which both materials of raceways and rolling elements are bearing steel and only internal design is changed, was tested compared with a conventional high-speed bearing (Koyo ACH series). **Figure 5** shows the relation between rotational speed and temperature rise.

It was confirmed that type Ⅰ was 1.3 times higher than the conventional bearing in rotational speed limit and 20-30% lower than the conventional one in temperature rise, proving that type Ⅰ has superior high-speed and lower temperature-rise performance. These effects are probably attributed to the above-mentioned design improvement by which friction loss caused by slight slip at a raceway contact is reduced. Type Ⅰ showed the high-speed rotational limit of $d_m n$ value*) of 1.65 million, which is equal to that of conventional hybrid ceramic bearings (see **Fig. 6**).

*) $d_m n$ value = bearing PCD(mm) × rotational speed n (min^{-1})

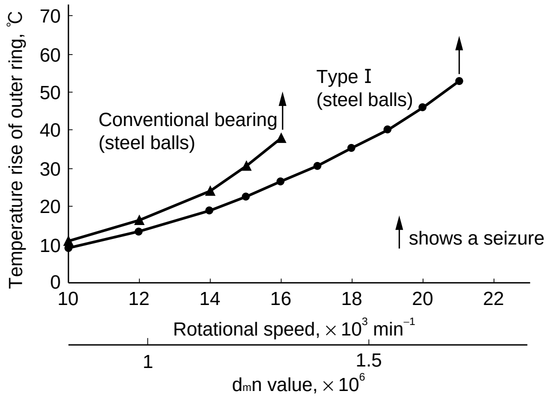


Fig. 5 Test results of Type Ⅰ

3. 3 Test Result of Type Ⅱ

A test was conducted with type Ⅱ test bearing having optimized internal design and ceramic balls and the result was compared with a conventional ceramic ball bearing (3NACACH). **Figure 6** shows the result of this test.

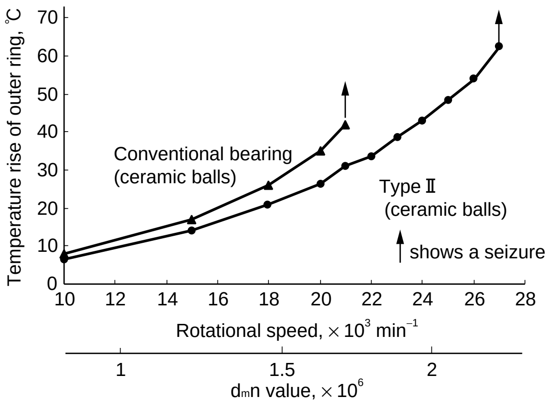


Fig. 6 Test results of Type Ⅱ

It was confirmed that type Ⅱ was 1.3 times higher than the conventional bearing in high-speed rotational limit and 20-30% lower than the conventional one in temperature rise, proving that the above-described internal design optimization is very effective. Comparison between **Fig. 5** and **Fig. 6** provides the fact that type Ⅱ ceramic ball bearing has 1.3 times higher high-speed limit and about 30% to 60% lower temperature rise compared with those of type Ⅰ with bearing steel balls, thereby showing that the use of ceramics in place of bearing steel provides great improvement in performance. Type Ⅱ showed the high-speed rotational limit of $d_m n$ value of 2.145 million.

3. 4 Test Result of Type Ⅲ

Type Ⅲ test bearing, in which oil-supply holes were provided in the inner ring to ensure direct oil supply into a bearing, and a conventional bearing was tested for comparison of its high-speed performance, and the result is shown in **Fig. 7**.

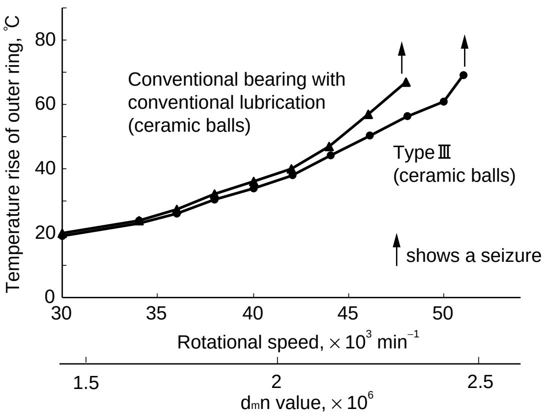


Fig. 7 Test result of Type Ⅲ

As seen from **Fig. 7**, it was confirmed that type Ⅲ was 1.1 times higher than the conventional bearing in high-speed rotational limit, and 5-10% lower than the conventional one in temperature rise. These effects are probably attributed to the above-mentioned design improvement in which oil-air is directly supplied to a bearing, resulting in improvement of lubrication reliability for high-speed rotation. Type Ⅲ showed the high-speed rotational limit of $d_m n$ value of 2.425 million.

4. Energy Saving and Environmental Friendliness Tests

Recently, machine tool spindles are required to have not only high-speed and high efficient performance but also be energy saving and environmentally friendly. The same can apply to bearings for machine tool spindles and it is required to develop such a bearing that is superior in energy-saving and environmental-friendliness. Hereinafter, the results of the following tests are described for evaluating these performance of the test bearing: high-speed test under grease lubrication, air supply parameter test, and noise characteristic test under oil-air lubrication.

4. 1 High-Speed Test under Grease Lubrication

If high-speed rotation which has been enabled by oil-air lubrication can be provided by grease lubrication, it can eliminate a high pressure air and lubricating apparatus as well as related problems such as mist occurrence and hissing noise, thereby increasing bearings' energy-saving and environmental-friendliness performance.

Type Ⅱ bearing with ceramic balls and the conventional bearing (3NCACH) with ceramic balls were rotated at high-speed with grease lubrication. For comparison, another conventional bearing with steel balls was also rotated at high-speed with oil-air lubrication.

Table 3 shows the test bearing and test conditions. The test apparatus is the same as shown in **Fig. 2**.

Figure 8 shows the relation between rotational speed and temperature rise.

Table 3 Conditions for high-speed rotation test with grease lubrication

Test bearing		Type Ⅱ (ceramic balls)	Conventional bearing (ceramic balls)	Conventional bearing (steel balls)
	Type			
	Size	$\phi 65 \times \phi 100 \times 18$		
Preload, N		150 N at fixed position		
Lubrication conditions		ISOFLEX NBU15 grease lubrication, Amount: 10% of bearing inside space		Oil-air lubrication with ISO VG32 oil at 0.03 ml/8 min, Air: 46 Nl/min, Nozzle (see **Fig. 3**)
Cooling condition		Jacket oil cooling (room temperature control)		

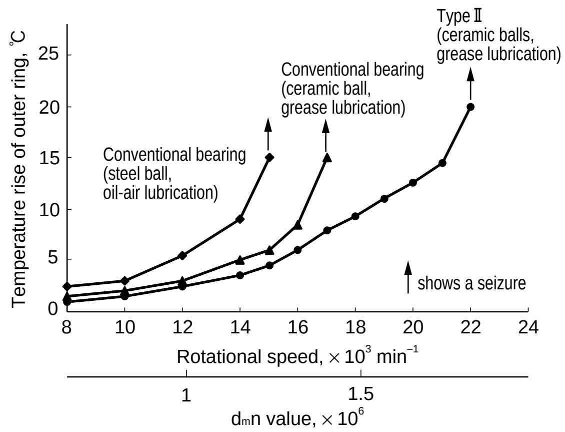


Fig. 8 Results of high-speed rotation test with grease lubrication

It was confirmed that type Ⅱ was about 1.3 times higher than the conventional bearing in high-speed rotational limit with grease lubrication, showing the $d_m n$ value of 1.73 million. It was also confirmed that type Ⅱ was 20% - 30% lower than the conventional one in temperature rise, showing superior high-speed performance. Comparison between this result and the high rotation test result of the conventional bearing with steel balls with oil-air lubrication showed that type Ⅱ had 1.5 times higher high-speed rotational limit and 50 to 60% lower temperature rise than those of the conventional steel ball bearing. From these results, it can be said that type Ⅱ bearing with grease lubrication can be used in place of a conventional steel ball bearing with oil-air lubrication for machine tool spindle application.

4. 2 Air Supply Parameter Test under Oil-air Lubrication

In order to confirm whether it is possible to reduce air amount during oil-air lubrication, type Ⅲ bearing in which oil-air is supplied from the inner ring side and conventional bearings with oil-air lubrication were tested for their temperature rise performance under various air supply rates. **Table 4** shows test bearing and test conditions. **Figure 9** shows the structure of test apparatus.

Table 4 Conditions for energy-saving and environmental-friendliness test with oil-air lubrication

Test bearing	Type	Conventional bearing (ACH) with conventional lubrication method	Type Ⅲ
	Size	$\phi 80 \times \phi 140 \times 22$	
	Ball material	Ceramics	
	Raceway material	SUJ2	
Preload, N		196, fixed position	
Lubrication conditions	Oil viscosity	Equivalent to ISO V32	
	Oil rate	0.03 ml/8 min	
	Oil supply method	**Fig. 3**	**Fig. 4**
Cooling condition		Natural cooling	

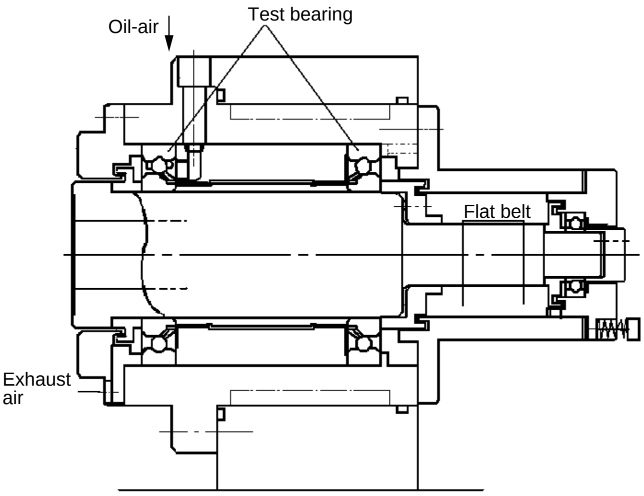


Fig. 9 Test equipment B

Figure 10 shows the temperature change of exhausted air of the bearings rotating at a constant speed of 18 000 min^{-1} ($d_m n$ value 1.98 million) with various air supply rates. As seen in **Fig. 10**, it was confirmed that type Ⅲ showed lower temperature rise and type Ⅲ could reduce about 10 to 20% air supply as compared with that of the conventional lubrication method when compared at the same temperature rise point. It must be noted, however, that since reduction in air supply tends to cause higher temperature rise of a bearing, air supply rate must be appropriately determined in accordance with the spindle specification by considering whether either of temperature rise factor or air-saving factor should be prioritized.

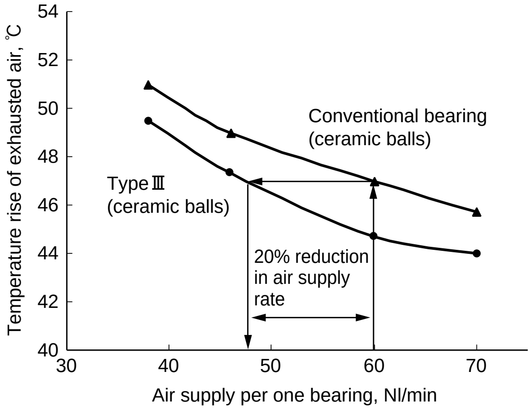


Fig. 10 Relationship between air supply rate and temperature rise

4. 3 Noise Test under Oil-air Lubrication

From an environmental point, oil-air hissing noise generated by revolution of bearing balls under the oil-air lubrication is another problem. Hereinafter, type Ⅲ bearing in which oil-air is supplied from inner ring side and a conventional one with conventional oil-air supply method was tested for their noise. Test bearings and test apparatus are the same as those used in **Table 4** and **Fig. 9**, respectively. Test conditions for this test is the same as those shown in **Table 4**, except for the point that air supply rate is fixed at 46 Nl/min. Noise was measured by a precision sound level meter at a position 150mm apart from the end of test apparatus spindle. **Figure 11** shows the relation between the rotational speed and the noise of these bearings.

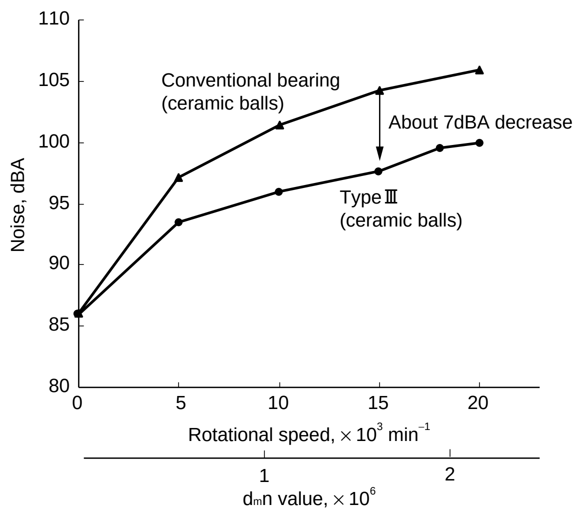


Fig. 11 Result of noise characteristic test

From **Fig. 11**, it was confirmed that type Ⅲ had smaller noise at each rotational speed and showed remarkably reduced noise of about 5 to 7 dBA over 10 000 min^{-1}. These effects are probably attributed to type Ⅲ's oil supply method in which oil is supplied to the contact part between a bearing inner ring and balls by which the air hissing noise generated by ball movement is reduced.

5. Ultra-high-Speed Rotation Test

Type Ⅳ is a bearing in which an outer ring has nozzle holes and is designed for ultra-high-speed rotation application. This was tested at ultra-high-speed rotation under oil-air lubrication. **Table 5** shows a test bearing and test conditions. A built-in-type test apparatus (i.e., motor-built-in-type test apparatus) as shown in **Fig. 12** was used and the test was performed with constant preload. **Figure 14** shows the relation between rotational speed and the temperature rise.

The result of this test showed that type Ⅳ could rotate at ultra-high-speed of $d_m n$ value of 3.3 million (inner diameter ϕ 50 × 54 000 min^{-1}) with oil-air lubrication that consumes very small amount of oil, showing that it has superior high-speed rotational performance. Such a high-speed rotation has been impossible without oil lubrication using large amount of oil such as jet lubrication or under-race lubrication.

After the test, type Ⅳ showed no abnormality and was in a state that ensured continuous operation.

Table 5 Conditions for ultra-high-speed rotation test

Test bearing	Type	Type Ⅳ
	Size	ϕ 50 × ϕ 72 × 12
	Ball material	Ceramics
	Raceway materials	Outer ring: bearing steel Inner ring: carburized steel
Preload, N		500, constant pressure
Lubrication conditions	Oil viscosity	Equivalent to ISO VG10
	Oil supply rate	0.03 ml/2 min × 2
	Air supply rate	86 Nl/min
	Oil supply method	**Fig. 13**
Cooling condition		Jacket oil cooling (room temperature control)

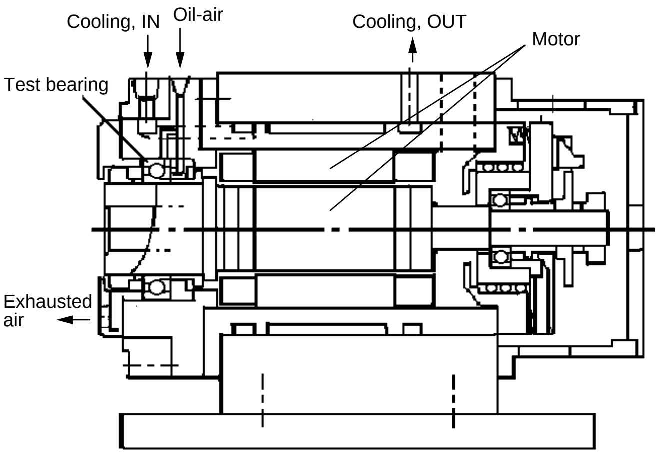


Fig. 12 Test equipment C

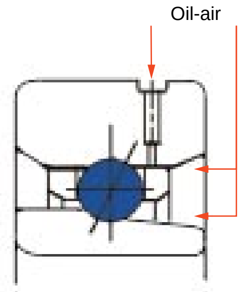


Fig. 13 Lubrication method for Type Ⅳ

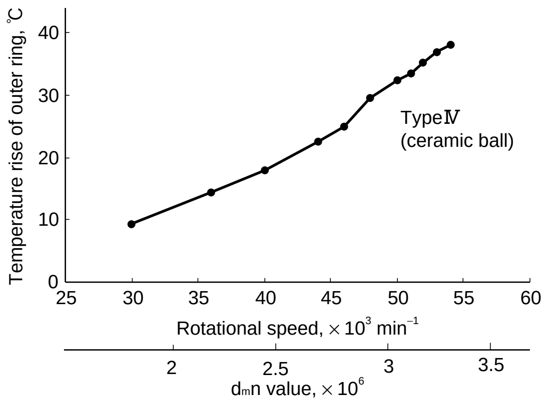


Fig. 14 Results of ultra-high speed rotation test

6. Repeated Prompt Start & Stop Test

It is important that a high-speed and high efficient spindle that is capable of instant start and stop needs therein a bearing that is superior in prompt start & stop performance. In the bearing operating with prompt start and atop repetition, such phenomena as slide between rolling elements and inner ring due to the rolling elements' inertia, an increase in temperature difference between an inner and outer ring, and whirling contact between a retainer and outer ring's guide part. Thus, it can be said that a bearing in prompt start & stop operation is subjected to extremely severe conditions. In this test, type Ⅳ in which nozzle holes were provided in the outer ring was subjected to prompt start & stop test with $d_m n$ value of 2.8 million/3 s × 10^5 cycles under oil-air lubrication. Hereinafter, the result of the test is described.

Table 6 shows a test bearing and test conditions. The test apparatus for this test is the same as that of **Fig. 12**. **Figure 15** shows operation pattern of cycles.

Figure 16 shows the test bearings' peak temperature changes for a bearing outer ring, oil-air exhaust, and a shaft during repeated prompt start & stop test. **Figure 17** shows a measurement chart thereof. Temperatures of a bearing outer ring and oil-air exhaust dramatically changed in one cycle in accordance with prompt start & stop operation. The peak temperature thereof, however, was stable for a long time and this stable condition was maintained until finishing the repeated operation of 10^5 cycles.

After the test of 10^5 cycles, type Ⅳ was inspected for its inside part condition, showing no abnormality in a raceway, retainer guide, and other parts enough to be still operational and proved that type Ⅳ has excellent prompt start & stop performance.

Table 6 Conditions for repeated prompt start/stop test

Test bearing	Type	Type Ⅳ
	Size	ϕ 50 × ϕ 80 × 16
	Ball material	Ceramic
	Raceway material	Outer ring: bearing steel Inner ring: carburized steel
Preload, N		245, constant pressure
Lubrication conditions	Oil viscosity	Equivalent to ISO VG10
	Oil supply rate	0.03 ml/3 min × 2
	Air supply rate	72 Nl/min
	Oil supply method	**Fig. 13**
Cooling condition		Jacket oil cooling (room temperature control)

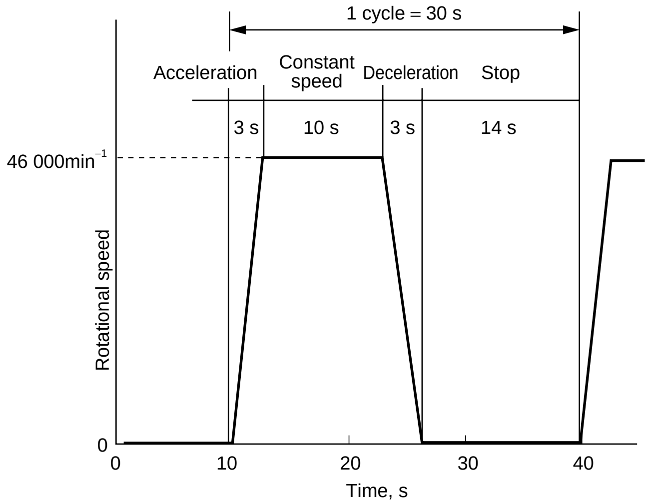


Fig. 15 Operation pattern

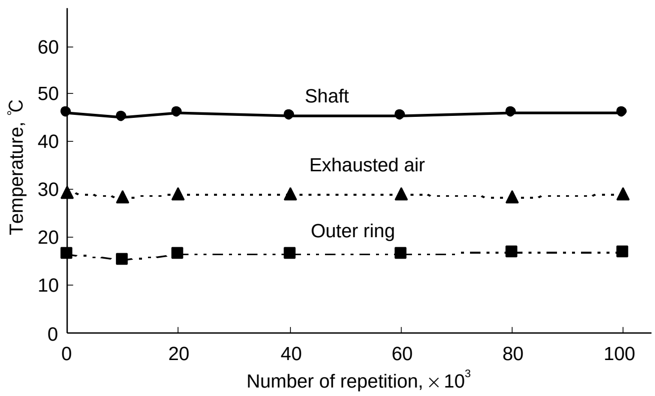


Fig. 16 Change of temperature rise peak

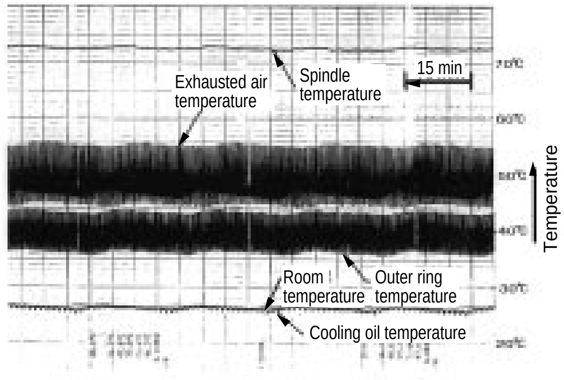


Fig. 17 Temperature measurement chart

7. Conclusions

As described above, various improvements have been made on high-speed angular contact ball bearings for the purpose of further improving their high-speed, high efficiency, energy-saving, and environmental friendliness performance. Shown below is the summary of the performance tests.

1) Optimization of bearing internal design for high-speed and low temperature-rise provided 1.3 times higher rotational speed limit and about 20 to 30% lower temperature rise as compared with a conventional Koyo high-speed bearing (e.g., ACH).
   Specifically, the above optimization allowed:
   · a steel ball bearing to provide $d_m n$ value of 1.65 million with oil-air lubrication under fixed-position preload; and
   · a ceramic ball bearing to provide $d_m n$ value of 2.145 million with oil-air lubrication under fixed-position preload.
2) Provision of oil supply holes in an inner ring for oil-air or oil mist lubrication allowed 1.1 times higher rotational speed limit as compared with conventional oil supply methods.
   Specifically, a bearing with the above improved oil supply method of oil-air lubrication achieved a capability to endure high-speed operation of $d_m n$ value of 2.425 million with fixed-position preload.
3) In order to develop a bearing that is more energy-saving and environmentally friendly, test bearings were tested with grease lubrication at high-speed rotation. As a result, the test bearings showed 1.3 times or more higher rotational speed limit and about 20 to 30% lower temperature rise as compared with conventional ceramic ball bearings.
   When this result is compared with the rotational performance of a conventional steel ball bearing under oil-air lubrication, it means that test bearings have 1.5 times higher high-speed rotational limit and about 50 to 60% lower temperature rise compared with those of the conventional bearing. Thus, it is feasible that the combination of conventional oil-air lubrication and steel ball bearings for spindles can be replaced by the combination of grease lubrication and ceramic ball

bearings as also can be seen from the following result.

· Test bearings having ceramic balls showed $d_m n$ value of 1.73 million with grease lubrication under fixed-position preload.

4) Under oil-air lubrication, a test bearing in which an inner ring has oil supply holes showed about 10 to 20% lower air consumption and smaller noise (i.e., noise reduction of 5-7 dBA) as compared with those of conventional bearings. Thus, the improvement described herein can provide a more energy-saving and environmentally friendly bearing.

5) A bearing having oil supply holes in its outer ring showed superior ultra-high-speed rotation and prompt start & stop performance, thereby proving that it can work with an ultra-high-speed and high efficient spindle. Specifically, it was verified that this bearing could provide $d_m n$ value of 3.3 million of ultra-high-speed rotation and prompt start & stop performance of $d_m n$ value of 2.8 million/ 3 sec.

Based on the result, Koyo has developed "High Ability Bearing" that is excellent in high-speed, prompt start & stop, and low temperature-rise performance as well as in energy efficiency and environmental friendliness.

With High Ability Bearings, Koyo intends to further contribute to high-performance machine tool spindles.

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