NSK Technical Journal

Motion & Control

No. 8

May 2000

NSK

ISSN1342-3630

MOTION & CONTROL No. 8
NSK Technical Journal
Printed and Published: May 2000
ISSN1342-3630
Publisher: NSK Ltd., Ohsaki, Shinagawa, Tokyo, JAPAN
Public Relations Department
TEL +81-3-3779-7051
FAX +81-3-3779-7431
Editor: Kyozaburo FURUMURA
Managing Editor: Yasuhiko MORITA
Design, Typesetting & Printing: Fuji Ad. Systems Corp.

Cover photos: RANE NASTECH LTD. (India)
NSK CORPORATION (U.S.A.)
NSK-RHP EUROPE LTD. and NSK-RHP
EUROPEAN TECHNOLOGY CO., LTD. (U.K.)

NSK Technical Journal

Motion & Control

No. 8
May 2000

NSK

Contents

Development of NSK Extra-Capacity Sealed-Clean™ Roll Neck Bearings for Rolling Mills

Tomoyuki Aizawa and Kazuo Akagami
Research and Development Center
Sadayuki Tanaka
Bearing Technology Center

ABSTRACT

Four-row sealed tapered roller bearings used on roll necks of rolling mills are required to achieve longer life amid severe environmental conditions such as high operating load, extreme shock loads and the penetration of water and scale into the bearing. In response, NSK developed Extra-Capacity Sealed-Clean™ Roll Neck Bearings. Realizing longer life and higher reliability, the new bearing has higher load capacity, is made of Super-TF material that lengthens life under severe lubricating conditions and utilizes a new bore seal that controls the build-up of negative pressure in the bearing interior.

1. Introduction

Four-row tapered roller bearings are primarily used to support rolls in rolling mills of steelworks. Fig. 1 shows a typical sealed-clean roll neck bearing incorporated into the work roll chock of a cold rolling mill. As shown, the mill's design restricts three critical bearing dimensions: the outside diameter, which obviously must be less than the total roll diameter and allow space for the chock; the bore diameter, which must be large to ensure the strength of the roll neck; and the bearing assembly width. So, while being designed to minimize inner and outer ring thickness as well as the gap between rollers, roll neck bearings must achieve long life and high load capacity. Additionally, roll neck bearings are exposed to severe environmental conditions such as high load, extreme shock loads and the entry of water and scale into the bearing. The most severe of these environmental conditions, the one capable of reducing bearing life the most, has been the entry of water and scale into the bearing and its extremely harmful effect on lubricating conditions.

Twenty years ago, to mitigate the effects of water and scale and to reduce maintenance, NSK was the first in the world to develop Sealed-Clean™ Roll Neck Bearings.[1] Today sealed roll neck bearings are becoming more popular at steel mills all over the world. In sealed roll neck bearings, the seals are usually installed without changing the bearing width. As a result, the rollers are shorter and the load capacity is lower than bearings without seals. For this reason, raising the load capacity of sealed roll neck bearings became an important development objective.

Achieving longer service life, NSK has recently developed Extra-Capacity Sealed-Clean™ Roll Neck Bearings (hereafter referred to as Extra-Capacity Bearings; Photo 1) with increased load capacity and sealing effectiveness. This paper describes the features of the new bearing and discusses the development of the new sealing arrangement.

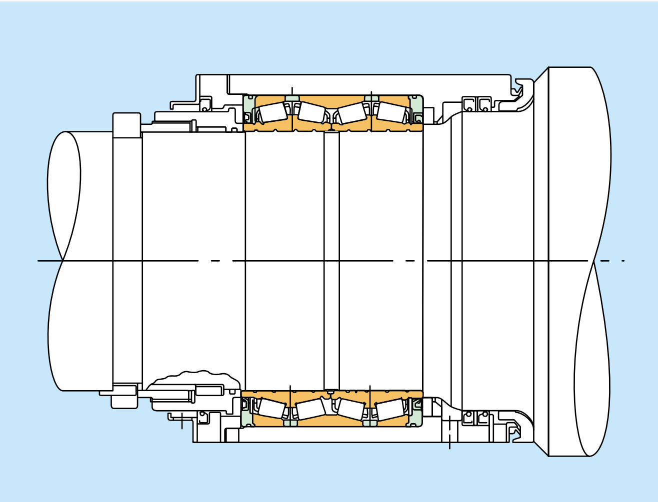


Fig. 1 Work roll chock of a cold rolling mill

Photo 1 NSK Extra-Capacity Sealed-Clean™ Roll Neck Bearings

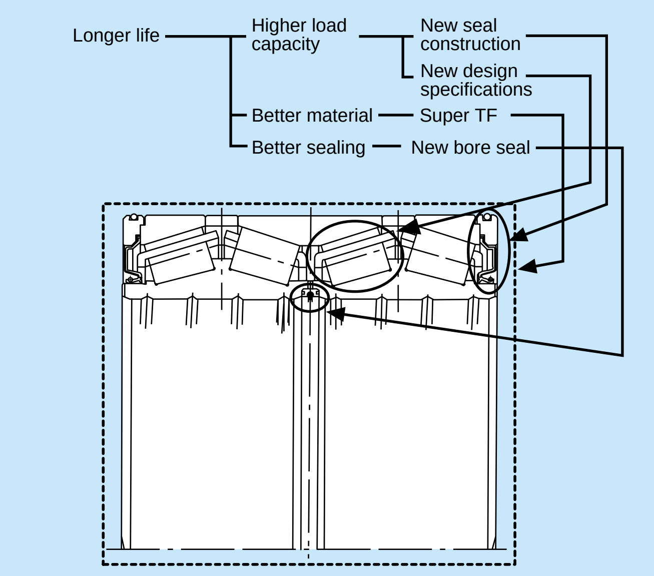


Fig. 2 Features of Extra-Capacity Bearing

Photo 2 Construction around main seal of Extra-Capacity Bearings

2. Features of Extra-Capacity Bearings

Extra-Capacity Bearings were developed targeting longer service life through higher load capacity and better sealing. The features of Extra-Capacity Bearings are summarized in Fig. 2 and discussed in further detail in sections 2.1–2.3.

2.1 Higher load capacity

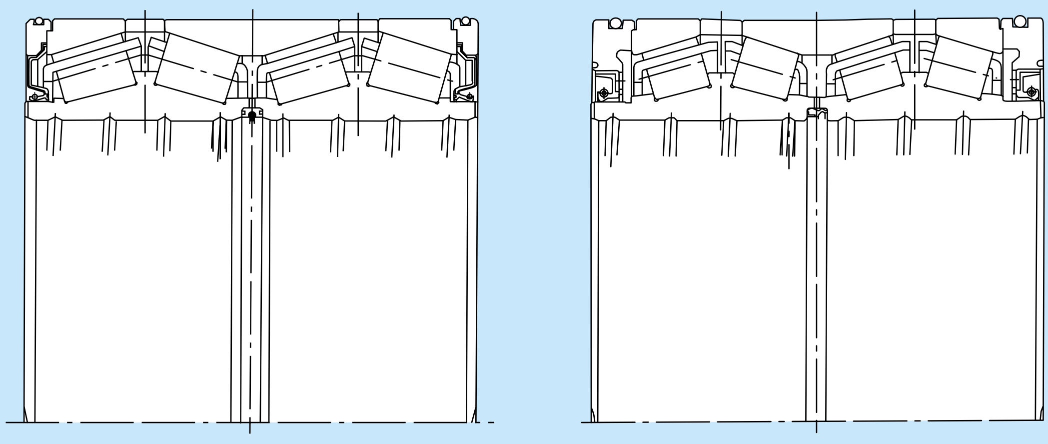
Load capacity (basic dynamic load rating) is the most important factor influencing bearing life.

The rolling contact surfaces of bearings are subjected to fatigue in the form of cyclic stress that over time leads to flaking. Considering bearing life from a statistical perspective, the total number of rotations that 90% of bearings achieve without flaking from rolling fatigue is called the basic rating life or L_{10} life. Additionally, the load at which the basic rating life is one million rotations is called the basic dynamic load rating (load capacity). The relationship between basic dynamic load rating (C), bearing load (P), and L_{10} life (L_{10}) is described for roller bearings by this equation:

$$L_{10}\ (\text{rev.}) = (C/P)^{10/3} \times 10^6$$

Achieving longer service life, Extra-Capacity Bearings have higher load capacity than conventional sealed roll neck bearings. Table 1 compares the load capacity of selected sealed roll neck bearings for work rolls. As shown in the table, Extra-Capacity Bearings have 15 to 34% higher load capacity than conventional bearings. This equates to 1.6 to 2.7-times longer life.

Cross-sections of a conventional sealed roll neck bearing (no. 343KVE4557E) and Extra-Capacity Bearing (no. 343KVS4551E) are compared in Fig. 3. Clearly, the rollers in the Extra-Capacity Bearing are larger. In the conventional bearing, the width of the main seal restricts the length of the rollers and therefore limits the load capacity of the bearing. In contrast, the cage flange is included within the seal space of the Extra-Capacity Bearing, allowing for longer rollers (Photo 2). The cage



Extra-Capacity Bearing

Conventional bearing

Fig. 3 Comparison of conventional and Extra-Capacity Bearing designs

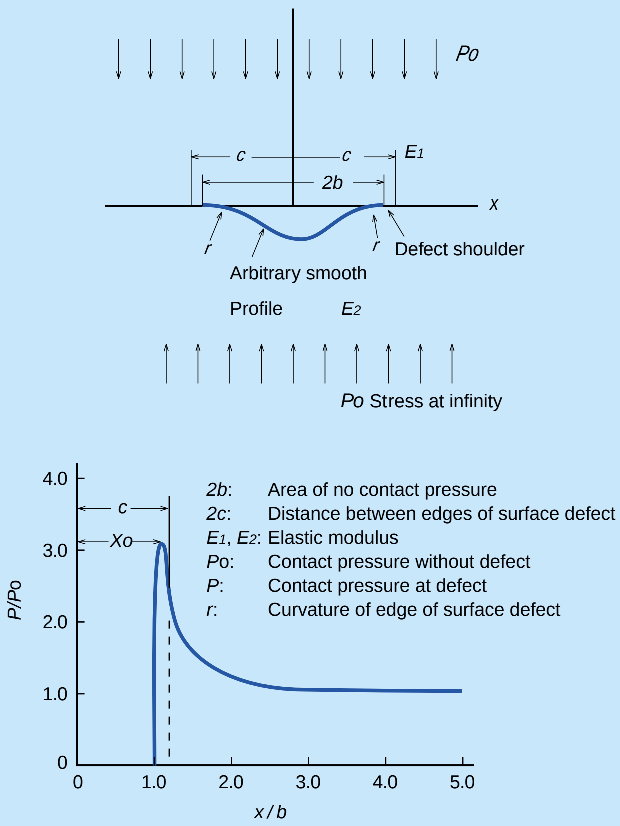


Fig. 4 Profile of surface defect and contact pressure around edge of surface defect

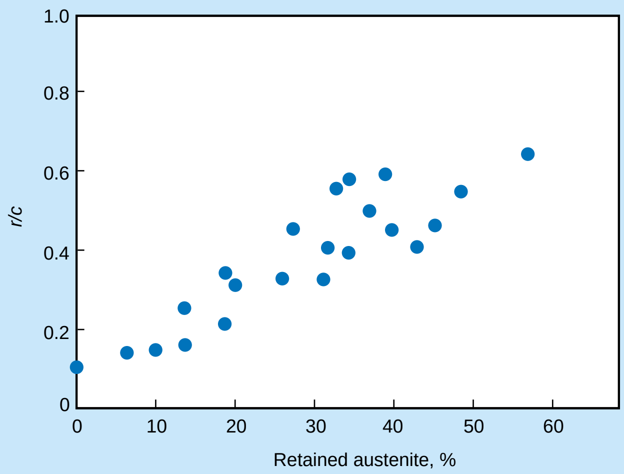


Fig. 5 Relationship between r/c and retained austenite

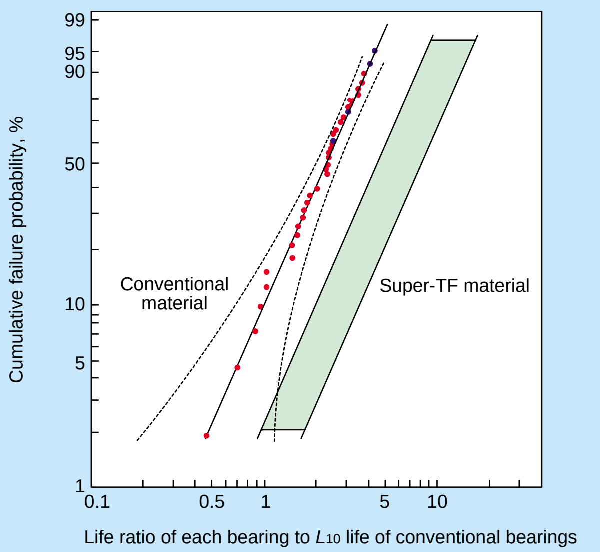


Fig. 6 Field data on the life of Super-TF material when used in roll neck bearings for cold rolling mills

diameter is also increased to facilitate more and larger rollers without reducing cage strength. Along with changes in the cage design, better performance is realized through improved cage accuracy.

2.2 New material, Super-TF

NSK's specially developed Super-TF material[2] is used for Extra-Capacity Bearings.

When foreign debris enters a bearing, flaking originating from dents caused by this debris can occur. As shown in Fig. 4, the stress concentration around the edge of such a dent is responsible for flaking.[3] The degree of the stress concentration is a function of the distance between the edges of the dent (2*c*) and the curvature of the edge of the dent (*r*). Specifically, with increasing *r*/*c* value, the stress concentration is smaller and service life is therefore longer. In an industry first, NSK realized the role retained austenite plays in minimizing the stress concentrations around debris dents (Fig. 5) and developed a material based on this discovery. With optimum retained austenite content, the material, TF steel, extends service life in environments contaminated with foreign debris. Since its development, NSK has made further improvements to create the Super-TF steel used in Extra-Capacity Bearings. Fig. 6 shows field data on the life of Super-TF material when used in roll neck bearings for cold rolling mills. It is evident that this material is effective in mill operating conditions. With Super-TF, Extra-Capacity

Table 1 Increased load capacity of Extra-Capacity Bearings

Bearing no.	Bearing size, mm	Basic dynamic load rating, kN	
		Extra-Capacity Bearings	Conventional bearings
STF254KVS3551E	ϕ254 × ϕ358.775 × 269.875	2510 (+15%)	2180
STF276KVS3951E	ϕ276.225 × ϕ393.7 × 269.875	2750 (+20%)	2290
STF343KVS4551E	ϕ343.052 × ϕ457.098 × 254	2830 (+29%)	2200
STF482KVS6151E	ϕ482.6 × ϕ615.95 × 330.2	4900 (+34%)	3650

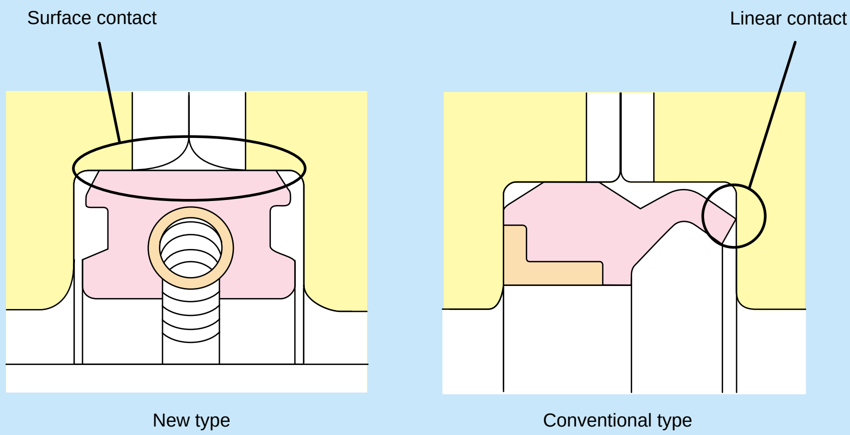


Fig. 7 Bore seal

Bearings have achieved longer life amid scale-contaminated conditions.

2.3 Better sealing

Even when calculated life is long, the entry of water and contaminants into a bearing wreaks havoc on lubricating conditions and reduces bearing life.

In the course of developing Extra-Capacity Bearings, the relationship between the negative pressure that develops inside sealed roll neck bearings and the entry of water was established. Reducing the entry of water and thus enhancing bearing reliability, a bore seal (Fig. 7) was employed that suppresses the build-up of negative pressure by allowing the bearing to breathe.

3. Seal Development Process

The purpose of bearing seals is to prevent the entry of water and scale and ensure longer service life. In practice, however, water sometimes enters bearings and compromises their performance. To clarify the process of water entry into sealed roll neck bearings, NSK conducted tests in which actual operating conditions were simulated. The test results are described in the following sections.

3.1 Simulation tests

Tests simulating field conditions were conducted with sealed roll neck bearings commonly used in cold rolling mills (I.D. ϕ343.052 mm × O.D. ϕ457.098 mm × width 254 mm). Photo 3 and Fig. 8 show the test apparatus and its structure while Fig. 9 shows the construction around the test chock. Bearing load was a radial constant load of 294 kN and, replicating actual conditions, the speed pattern shown in Fig. 10 was followed. Water was splashed onto the chock at a rate of about 100 L/min. In actual applications, water enters chocks through the chock seal. In order to simulate this phenomenon, water was injected into the chock at a rate of 50 cm^3/min. Similar to actual rolling mills, water was discharged from the chock through a drain hole provided in the bottom. Tests were conducted for 50 hours, and the water content of the grease was measured after the tests. To facilitate evaluation of the water content of the grease, an Na grease

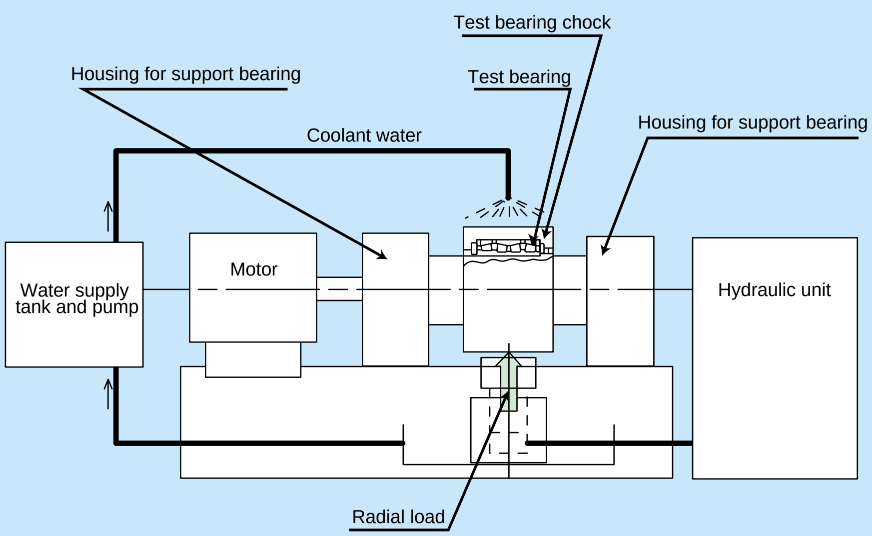


Fig. 8 Structure of roll neck bearing test apparatus

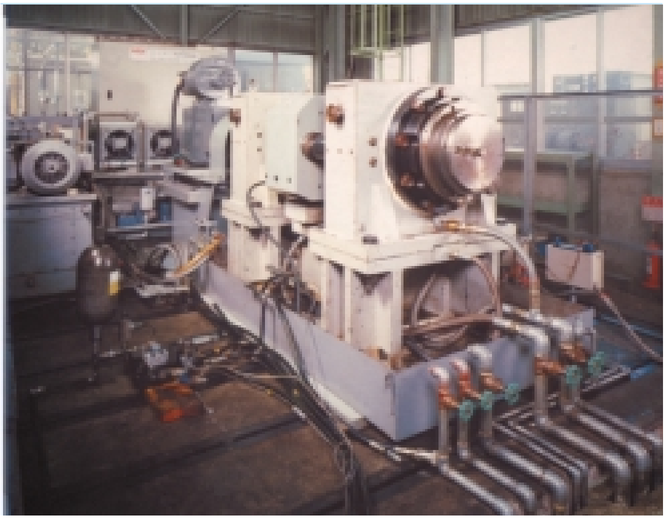


Photo 3 Roll neck bearing test apparatus

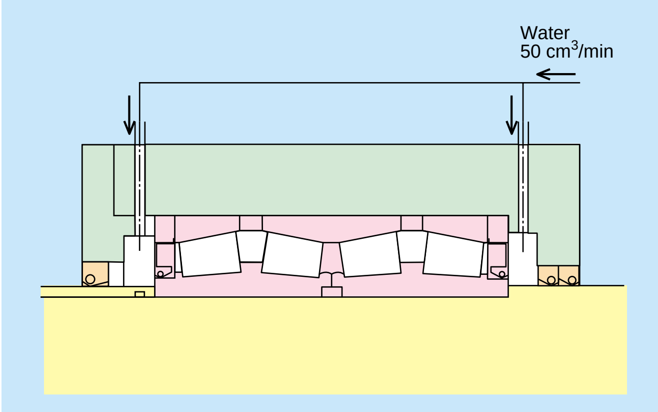


Fig. 9 Area around chock of the roll neck bearing test apparatus

that readily absorbs water was used instead of NSK's standard grease. Combinations of several types of main seals and bore seals were tested. The water content of the grease after the tests varied widely depending on the main seal and bore seal combination. During the tests, some seal combinations resulted in negative bearing internal pressure. Fig. 11 illustrates how negative pressure changed in relation to changes in speed and temperature during a test. With negative bearing internal pressure, the temperature of the main seal lip rises because of the higher contact pressure between the seal lip and the inner ring.

The correlation between maximum negative pressure during the test and water content of the grease after the test is illustrated in Fig. 12. Water enters bearings more readily with increasing negative pressure. In the tests, the negative pressure condition varied with the type of bore seal. Specifically, negative pressure was higher and water entry greater with the bore seal designed to ensure a high degree of sealing. To understand better how the bore seal related to water entry, a bearing without a bore seal was tested. Negative pressure was not generated and water entry was negligible.

To summarize, while water does not enter bearings through the bore seal, the bore seal greatly affects the degree of water entry. Tighter bore seals cause more negative pressure, resulting in more water entry through the main seals.

3.2 Main seal test

To evaluate the effect of bearing internal negative pressure on main seal performance, tests were conducted with only main seals. Fig. 13 shows the structure of the test apparatus. Test seals were installed in the housing and a pump was used to control the pressure within the space between the seals, housing and shaft. The rotational speed was 1 000 rpm, and water was splashed onto the seals at a rate of 15 L/min. Some seals were tested under atmospheric pressure and some under the negative pressure pattern described in Fig. 14. The degree of water entry through the seals was measured after the test. Table 2 presents the results. Under atmospheric pressure conditions, water did not penetrate the seals even after 200 hours. On the other hand, under the alternating negative pressure conditions, water penetrated the seals after only 50 hours. These results indicate that negative pressure compromises the performance of main seals.

3.3 New bore seal that prevents negative pressure and water entry

As described above, suppressing the build-up of negative pressure inside the bearing is essential for preventing the

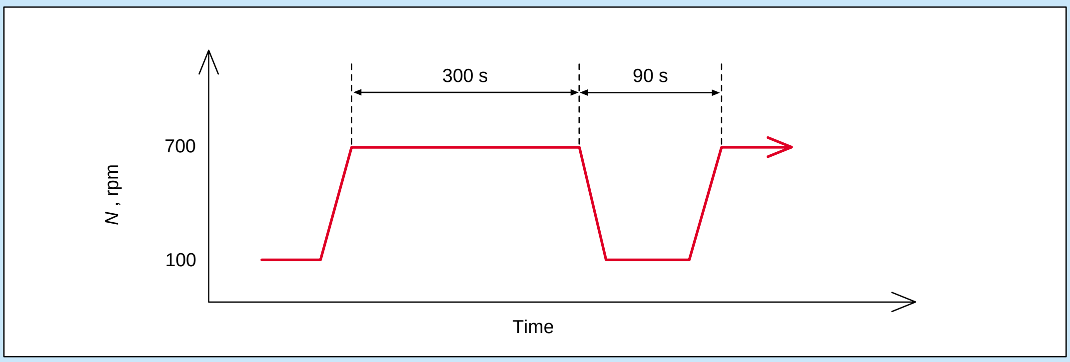


Fig. 10 Speed pattern of simulation tests

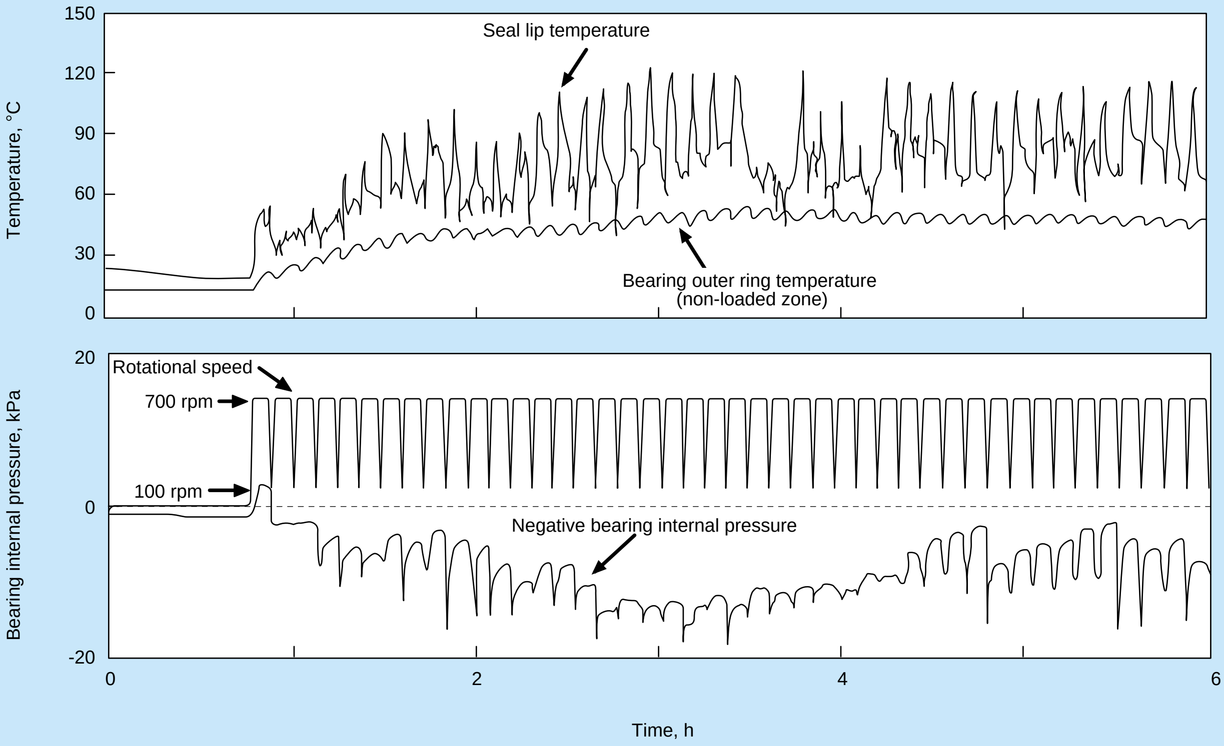


Fig. 11 Temperature, speed and negative internal pressure of a simulation test

entry of water. The most effective method for achieving this was to allow the bore seal (which is not directly exposed to water) to breathe along with the fluctuating pressure caused by rising and falling bearing temperature and changes in rotational speed. At the same time, the bore seal's original functions—preventing the entry of water and contaminants from the neck side—had to be maintained. Consequently, the new bore seal for Extra-Capacity Bearings was developed to achieve a balance between breathing and sealing.

The bore seal for Extra-Capacity Bearings employs surface contact instead of linear contact (Fig. 7). Fig. 15 shows the structure of the bore seal test apparatus. The test bore seal is inserted into the area between the two housings, which are essentially equivalent to the inner rings of an actual bearing. This area is connected by grooves to an internal space that replicates the bearing interior. The test bore seal separates this inner space from

Table 2 Main seal test results

Pressure conditions	Normal atmospheric pressure conditions	Alternating normal and atmospheric pressure conditions
Test hours	200	50
Amount of water entry, cm^3	None	50

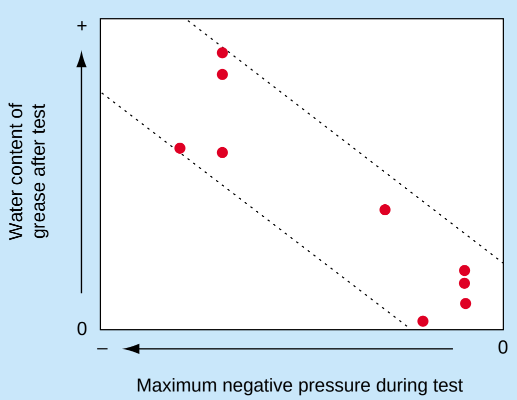


Fig. 12 Maximum negative pressure and water entry

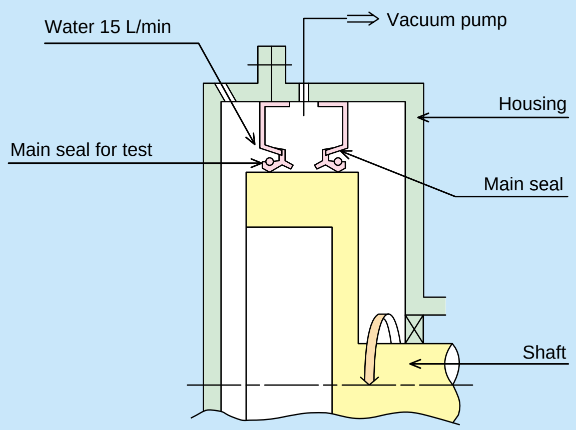


Fig. 13 Main seal test apparatus

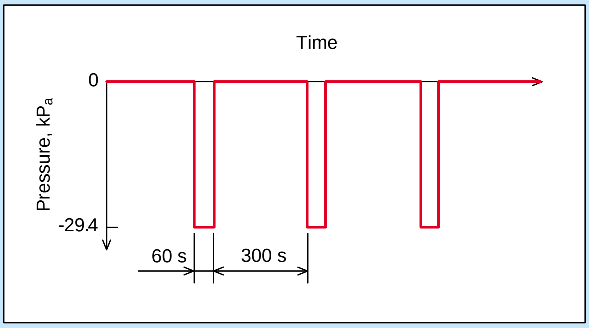


Fig. 14 Negative pressure pattern

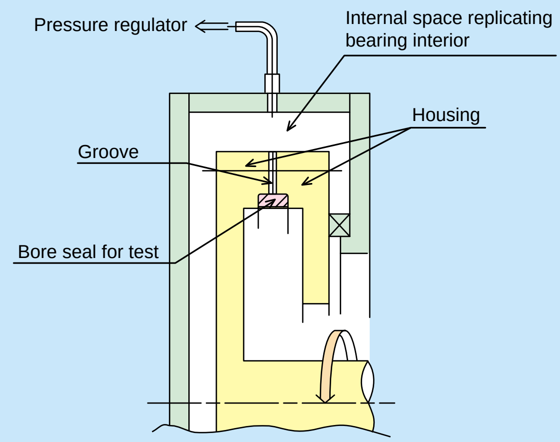


Fig. 15 Bore seal test apparatus

the exterior of the test apparatus. In the tests, the pressure in the internal space was initially made negative and then this pressure was measured both during rotation and while stopped. Tests were conducted with the conventional linear contact seal and with the newly developed surface contact seal. Fig. 16 presents the test results. The linear contact bore seal demonstrated high seal tightness both during rotation and while stopped. On the other hand, the surface contact bore seal demonstrated high seal tightness similar to that of the linear contact seal while stopped, but showed adequate breathing capability during rotation.

To confirm the effectiveness of the new bore seal in actual bearings, a simulation test under the conditions described in section 3.1 (Figs. 8, 9 and 10) was conducted. Fig. 17 compares the negative pressure conditions of the conventional and new bore seals during the tests. The conventional bore seal showed increasing negative pressure over time while the new bore seal for Extra-Capacity Bearings suppressed negative pressure throughout the tests. Fig. 18 compares data on maximum negative pressure and water content of grease after the tests. Maximum negative pressure and the water content of grease after the tests were substantially reduced with the new bore seal. These results clearly indicate that Extra-Capacity Bearings offer greater reliability than conventional sealed roll neck bearings.

4. Conclusion

With higher load capacity and improved reliability through better sealing, new Extra-Capacity Sealed-Clean™ Roll Neck Bearings for rolling mills are sure to satisfy the expectations of users for longer service life. At NSK we will continue our development efforts to create products that meet user needs for longer life and reduced maintenance in increasingly severe operating conditions.

Acknowledgment

We wish to express our appreciation to NOK Corporation for their cooperation during testing of the main seal.

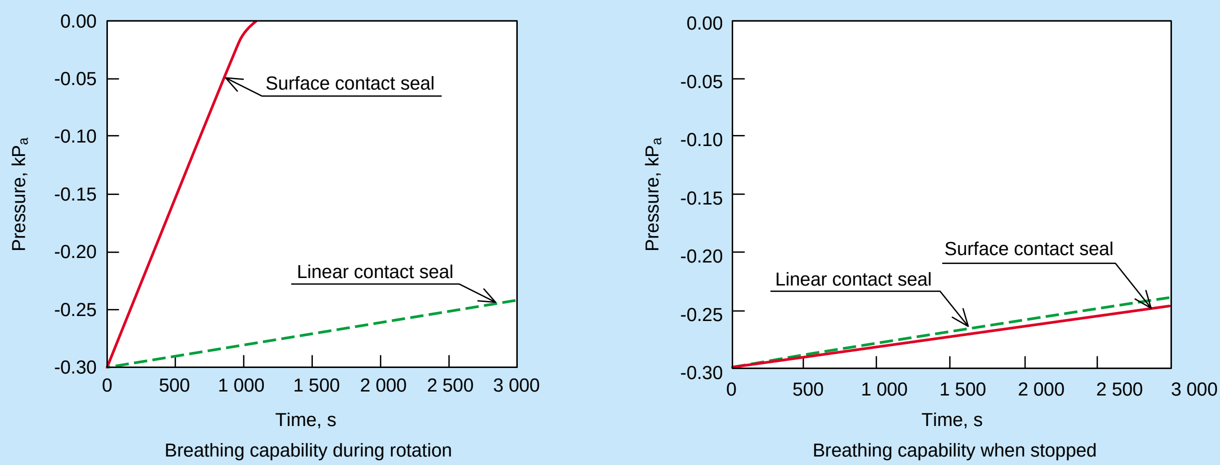


Fig. 16 Bore seal breathing capability test results

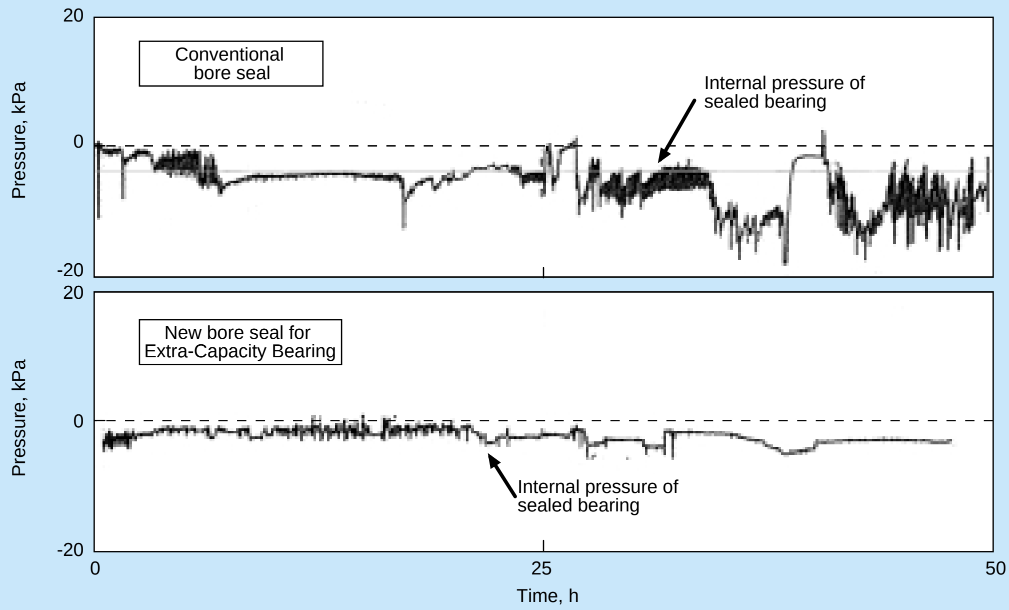


Fig. 17 Comparison of negative pressure conditions during tests

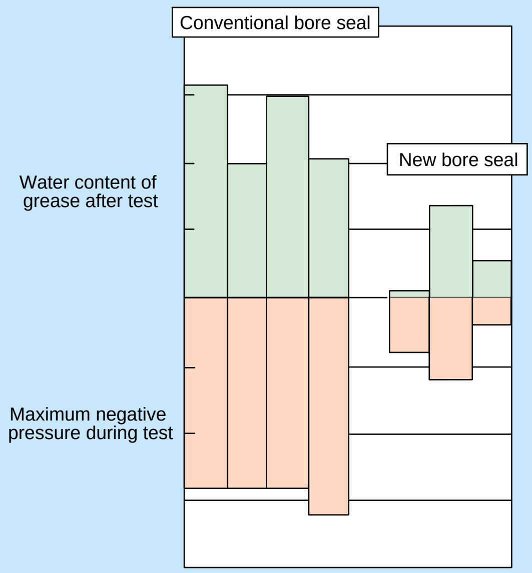


Fig. 18 Comparison of maximum negative pressure and water content of grease

Tomoyuki Aizawa

Kazuo Akagami

Sadayuki Tanaka

References:

1) K. Uchida, “Sealing of Four-row Tapered Roller Bearings for Work Roll Necks in Four-high Rolling Mills,” NSK Bearing Journal No.639 (1980) 19-25. [in Japanese]

2) K. Furumura, “Recent Trends in Research and Development of Rolling Bearings at NSK,” NSK Motion & Control No.1 (1996) 5-12.

3) Y. P. Chiu and J. Y. Liu, “An Analytical Study of the Stress Concentration around a Furrow Shaped Surface Defect in Rolling Contact,” Trans ASME, JOLT, Vol. 92 (1970) 258-263.

Ball Screw with Rotating Nut and Vibration Damper

Hideyuki Sato
Precision Machinery and Parts Technology Center

ABSTRACT

In recent years, feed rates of tables using ball screws have increased remarkably. For high-speed ball screws, two key restrictions are critical speed and stroke length. The maximum rotational speed of a ball screw has been governed by the critical speed and this is why it has been said that high-speed rotation is impossible for a long-stroke ball screw. In response, NSK developed a rotating-nut ball screw that has a vibration damper and is capable of exceeding the critical speed. In testing, a standard ball screw with no damper vibrated considerably while running and when stopped, while the new ball screw demonstrated nearly flawless performance. Though it was said to have been impossible, the new ball screw can exceed the critical speed in a relatively easy manner.

1. Introduction

Remarkable increases in feeding speed have been achieved for tables driven by ball screws. For example, traverse speeds have exceeded 60 m/min (1 m/s) in machining centers, and speeds of 90 m/min (1.5 m/s) are common with punching presses and laser cutting machines. In addition, robots and automatic insertion machines are required to have maximum speeds of 2 m/s.

Various problems arise when the rotational speed of a ball screw is increased.[1)] Two of the most serious of these are critical speed and limitations on stroke length. An increase in stroke length causes a decrease in critical speed, which governs the maximum speed of a linear motion mechanism driven by a ball screw. To cope with the problem, we have developed a ball screw with a rotating nut and vibration damper (patents pending) that can be operated beyond the critical speed in an easy manner.

2. Critical Speed of Ball Screws

2.1 General description

In JIS B 0153, the critical speed is defined as the rotational speed at which a rotating system is resonating. This standard also adds that there is a critical speed corresponding to each unique mode of a whole system that comprises multiple rotating systems. To represent the critical speed simply, a balance of forces is assumed for an elastic rotor with a single disk (Fig. 1). Because the elastic resilience of the shaft and centrifugal force F shall be balanced, the following equation is obtained:

$$k\rho = F = (\rho + \varepsilon)\, m\omega^2 \qquad (1)$$

m: Mass of disk
k: Shaft rigidity against bending
ρ: Elastic deflection of the shaft
ε: Eccentricity (distance from rotating shaft to the center of gravity G)
ω: Angular speed of the shaft

From this equation, deflection of the shaft can be determined:

$$\rho = \varepsilon \frac{(\omega / \omega_n)^2}{1- (\omega / \omega_n)^2} \qquad (2)$$

In this equation, $\sqrt{k/m}$ is assumed to be ω_n. This value agrees with the natural angular frequency of the vibration system, which is determined by the mass of the disk, m, and the spring constant of the shaft, k. A graph of Equation (2) is shown in Fig. 2. The critical speed is where $\omega = \omega_n$. Deflection of the shaft in this case can be calculated to be infinitely large. The critical speed can be safely passed if acceleration is high enough that the time permitted for the shaft to be deflected is minimized.[2)]

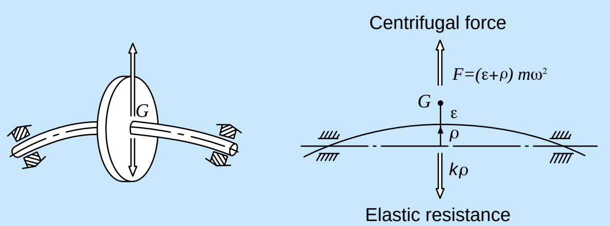


Fig. 1 Force balance during shaft vibration

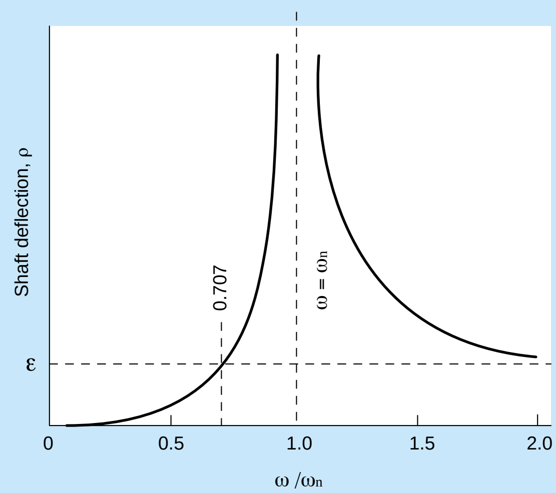


Fig. 2 Deflection of elastic rotor

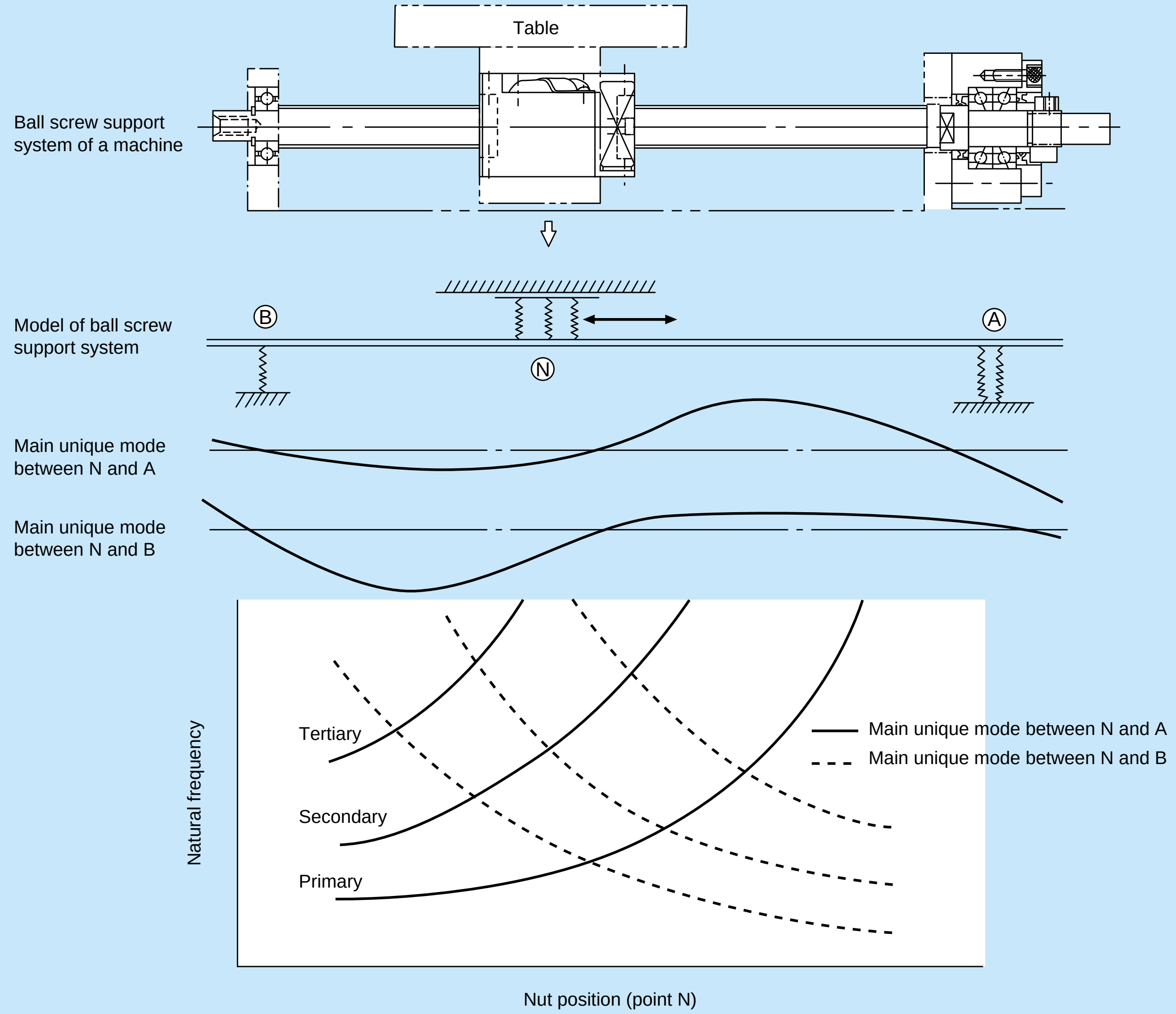


Fig. 3 Model of radial vibration system of a ball screw

2.2 Radial natural frequency of ball screw shaft

Fig. 3 is a model of the radial vibration system of a ball screw. The screw shaft is supported at three points: the support bearings (A and B) and a nut (N). The point N moves as the screw rotates.

In Fig. 3, the screw shaft has two modes: one is a unique mode mainly of (N – A) beam structure and the other is the mode between N and B. Needless to say, each of these modes has secondary or higher order modes.

As point N approaches point A and the distance between the two points decreases, the natural frequency of the mode between N and A increases while, conversely, the natural frequency of the mode between N and B decreases. Therefore, as shown in Fig. 3, the natural frequency of the screw shaft depends on the position of the nut and changes instantly in response to the nut's movement during operation.[1] There exists no simple critical speed like the one described in section 2.1 because the natural frequency of the screw shaft is not constant.

2.3 Critical speed of ball screws

Fig. 4 shows the relationship between the natural frequency of a ball screw and its critical and rotational speeds. Fig. 5 shows the vibration of this same ball screw when rotated. Critical speeds are at points where the ball screw's rotational speed meets the screw's natural frequency. Because ball screws pass critical speeds very quickly, they can be operated safely beyond critical speeds if vibration does not persist for a long period.

Realistically, however, a screw shaft vibrates

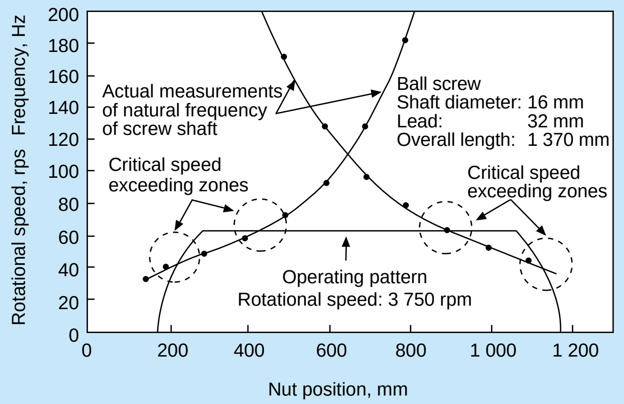


Fig. 4 Natural frequency and critical speeds of a screw shaft

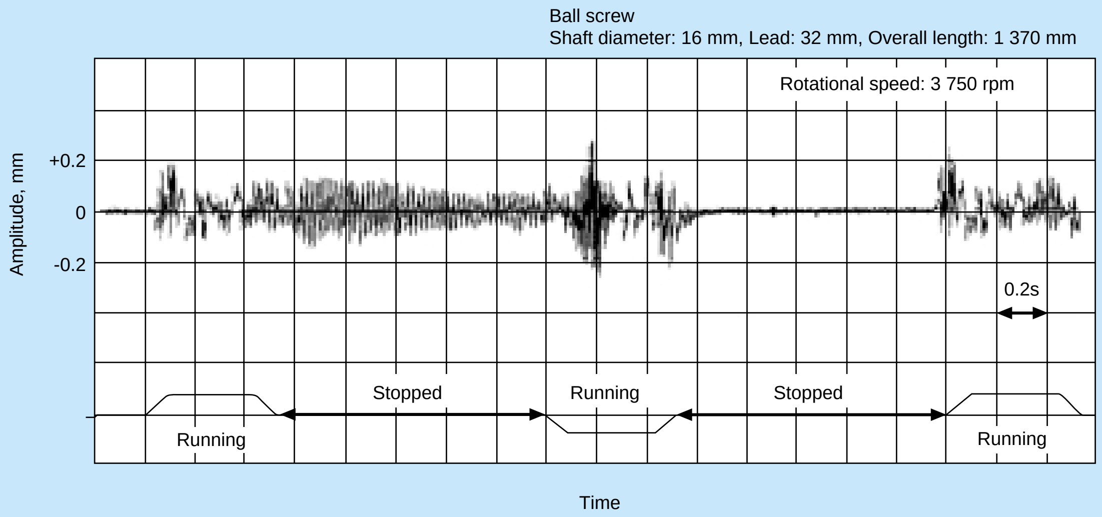


Fig. 5 Vibration of rotating ball screw

substantially when rotated at speeds above the critical speed and continues to do so due to its slow damping characteristics (Fig. 5). This is because the screw shaft is a slender rod with low dynamic rigidity in the radial direction, which makes vibration hard to dampen once the screw shaft is excited. As a result, the screw shaft may vibrate with a visible magnitude of several millimeters or more. The shaft's vibration, in turn, causes other components of the machine to vibrate, generating noise and in some cases, causing damage to the support bearings or nut and instability of the servo system. This is the reason why it has been said that ball screws cannot be used at speeds above the critical speed. Such problems exist not only with shaft rotation, but also with nut rotation while the shaft is fixed. During nut rotation, the rotating vibration force of the nut may agitate the screw shaft, which has low dynamic rigidity.

Different from ordinary critical speeds, the critical speed of a ball screw is one at which the screw shaft is excited by the rotating vibration of the shaft or nut and begins to resonate with the natural radial frequency. This phenomenon is a series of transitional forced and free vibration.

3. Measures for Overcoming Limitations of Critical Speed

Generally, when the maximum rotating speed allowed by the critical speed does not meet operating requirements, the following measures can be taken:

(1) Increasing the size of the screw shaft

Increasing the shaft's flexural rigidity raises its natural frequency, thus raising the maximum rotational speed. The major drawback of this method, however, is that the load inertia on the motor increases substantially. This is not favorable in terms of the following error of the servomechanism during high acceleration/deceleration. To illustrate, when the shaft diameter is changed from 40 to 50 mm, the maximum rotating speed increases by 25% while the load inertia on the motor rises 250%.

(2) Providing intermediate support to the shaft

Providing support to the shaft between the support bearings and the ball nut on either side raises the natural frequency of the shaft, increasing the allowable rotating speed. As ball screws have a long screw shaft that is low in dynamic rigidity in the radial direction, even simple intermediate support substantially increases the critical speed. Note, however, that this method requires careful attention to the structure of the system because the number of parts increases and it becomes more complicated.

An example of using intermediate support is the single-axis high-speed table shown in Fig. 6 (patent pending).[3] Ball nuts of two intermediate supports are put on the drive ball screw and are positioned at the approximate middle point between the support bearings on either end and the ball nut of the drive ball screw. They are allowed to freely rotate on the drive ball screw. An intermediate support is driven by its own ball screw whose speed is reduced to one half of that of the drive ball screw. As a rod connects the two intermediate supports, they move together with the single-axis table. In this high-speed table, a ball screw with a shaft diameter of 16 mm achieves a feed rate of 2 m/s and an average acceleration/deceleration rate of 2 G at a stroke of 1 m. When used in this manner, intermediate support can be an effective means of increasing speed capability.

(3) Increasing damping capacity

Because the moment that the ball screw shaft is in complete resonance is only instantaneous, enhancing the damping capability and increasing the dynamic rigidity of the screw shaft allow the ball screw to exceed the critical speed safely. This concept became the basis for developing our ball screw with a rotating nut and vibration damper.

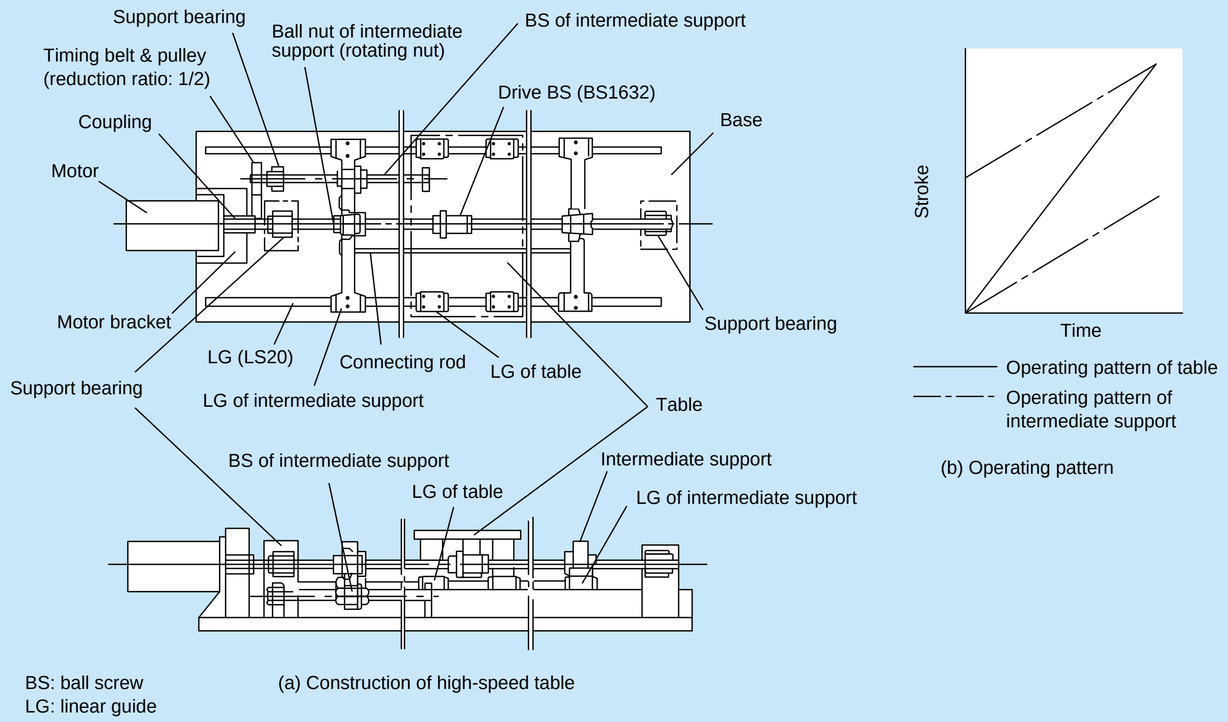


Fig. 6 Structure of single-axis high-speed table

This ball screw has a damper in the screw shaft that makes exceeding the critical speed easy. However, from the dynamic viewpoint of a rotating body, a screw shaft that incorporates a damper cannot be rotated,[2] so the nut is therefore rotated instead. In contrast to the two methods described above, in which the natural frequency of the screw shaft is increased, this method is an entirely different way of approaching the problem, leaving the natural frequency of the screw shaft unchanged.

4. Features of Ball Screw with Rotating Nut and Vibration Damper

Ball screws are generally operated with rotation of the screw shaft. However, as the screw shaft becomes longer and motor load inertia increases, it is more favorable to rotate the nut than the shaft. When multiple tables are driven with one screw shaft, the shaft is fixed and the nut is rotated.

Because the nut is rotated while the shaft is fixed, the situation differs from the ordinary critical speed described above. Exceeding the critical speed causes shaft resonance because of the rotating vibration force of the nut. The solution is to incorporate a damper in the fixed screw shaft to increase the damping capability. This allows the critical speed to be safely exceeded. This concept has been employed to create our ball screw with a rotating nut and vibration damper.

The ball screw has a hollow shaft into which a thin rod is inserted. When the shaft is about to vibrate, the inserted rod knocks against the inside wall of the shaft to dampen the vibration. Note, however, that when the stroke gets longer, the natural frequency of the shaft decreases, making the inserted rod vibrate together with the vibrating shaft and thus reducing damping capability to nearly nothing. In response, a means has been devised to bring the critical speed of the shaft and the natural frequency of the rod closer to each other, which in turn causes the vibration of the inserted rod and the shaft to readily cancel each other out. Features of the new ball screw include:

(1) Interchangeability is ensured because there is no difference between the outside dimensions of this ball screw and existing ball screws.
(2) Enabling as much downsizing of the table as possible, the shaft diameter and other dimensions are not increased. Consequently, the nut inertia is reduced, which is not only conducive to high acceleration/deceleration operation but also reducing motor size.
(3) It is not necessary to take the critical speed into account when determining the maximum rotating speed of the ball screw. Only the allowable rotational speed with the d_mN value need be taken into account.
(4) The design is simple with only a small increase in cost.

5. Advantages of Ball Screw with Rotating Nut and Vibration Damper

5.1 Dynamic characteristics at excitation of screw shaft

Fig. 7 shows the response waveforms of two screw shafts when struck with a hammer. The diameter of the shafts was 40 mm and the length 4 100 mm; the nut was positioned 3 630 mm from the fixed end. As indicated in the figure, the standard ball screw with no damper provided poor damping capability, while the ball screw with the damper achieved extremely high damping capability. Fig. 8 is a bode diagram of the compliance to a sinusoidal excitation. The compliance at the natural frequency of the ball screw with the damper was more than 10 dB lower, indicating that dynamic rigidity is more than tripled. As the natural frequency of a ball screw changes in relation to the nut position, it is necessary to check the natural frequency when the nut is positioned at various points along the shaft. Fig. 9 shows the relationship between the natural frequency and compliance for various nut positions when a sinusoidal excitation is applied to the screw shaft at a point between the nut and the fixed end. It is evident from the figure that, with the damper, compliance is more than 10 dB lower in all frequency bands and dynamic rigidity is more than tripled.

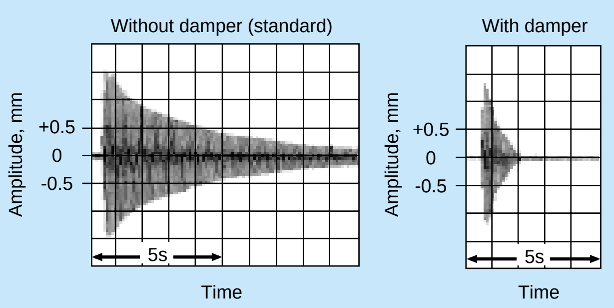


Fig. 7 Vibration response of screw shafts when hammered

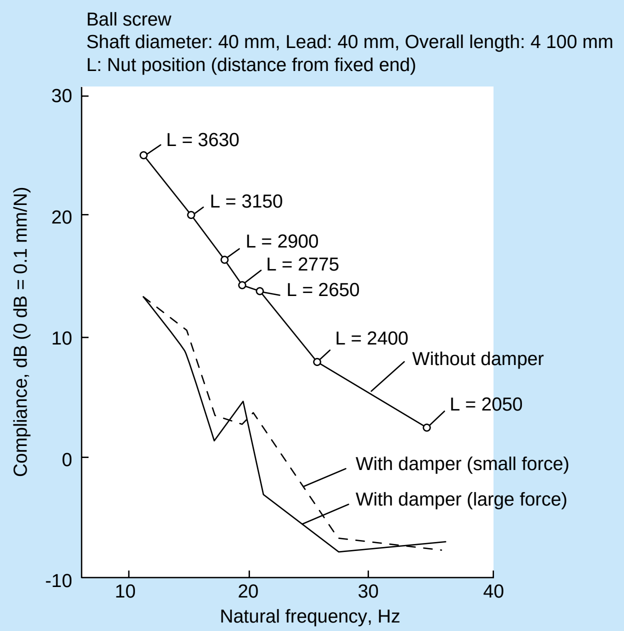


Fig. 9 Natural frequency and compliance

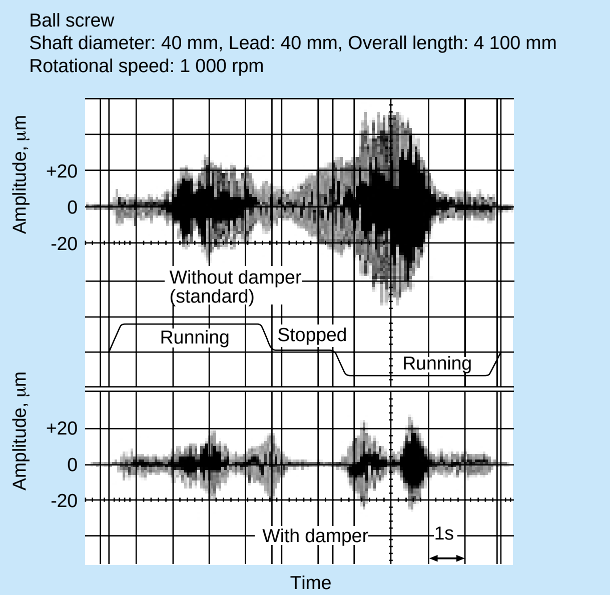


Fig. 10 Vibration during nut rotation

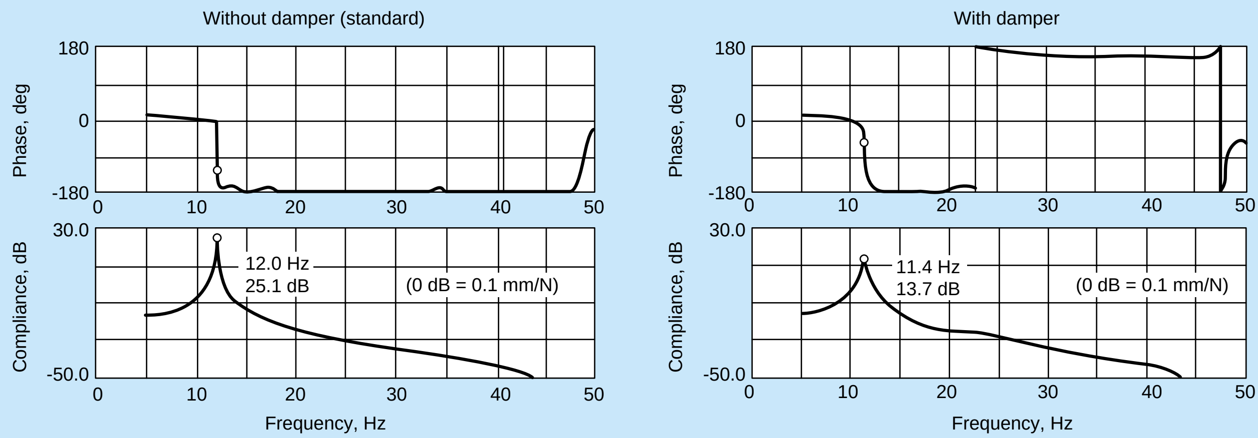


Fig. 8 Bode diagram of forced vibration on screw shaft

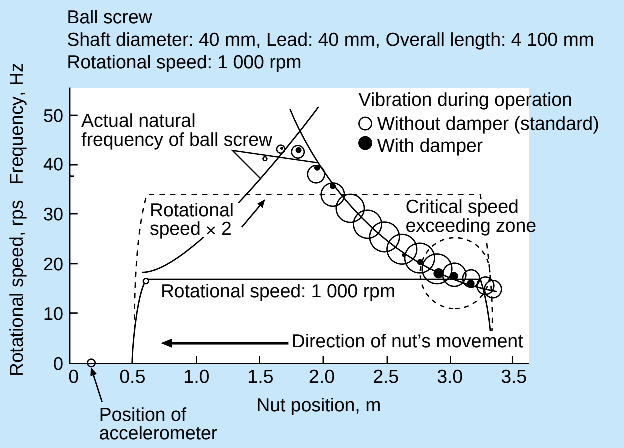


Fig. 11 Resonance suppression during nut rotation

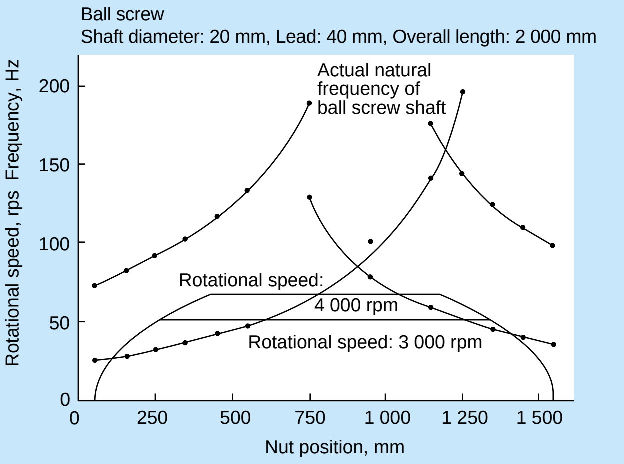


Fig. 12 Natural frequency and critical speed of screw shaft

5.2 Characteristics of ball screw during operation

Figs. 10 and 11 show vibration measurements taken on new and conventional ball screws operating in an actual machine. Fig. 10 shows the relation between time and vibration of the screw shaft. The damper effect can be observed as the amplitude is reduced both while the ball screw is running and when it is stopped. Fig. 11 shows the nut's position on the x-axis and the frequency of the screw shaft on the y-axis. The magnitude of vibration amplitude at each point is represented by the size of the circle. It is observed that the frequency changes along the natural frequency on the side where an accelerometer is attached. The amplitude of the standard ball screw without the damper does not damp when it is exceeding the critical speed. Instead, the amplitude of the vibration increases. On the other hand, the ball screw with the damper shows slight resonance at the time when the critical speed is reached, but this resonance is small and the vibration is quickly damped after passing the critical speed. For ease of measurement, these results were obtained near the end of the shaft, where vibration is lower. The actual amplitude of vibration near the center of the shaft of the standard ball screw with no damper was estimated visually to be about 3 mm. With the damper, the vibration was damped rapidly and could not be perceived visually.

Fig. 12 shows the natural frequency and critical speed of the screw shaft of a ball screw operating in a single-axis table. The diameter of the shaft was 20 mm and its length 2 000 mm. In this case, the critical speed is exceeded at 1 500 rpm. Fig. 13 shows vibration measurements taken at 3 000 rpm. While considerable vibration was observed in the ball screw with no damper both while it was running

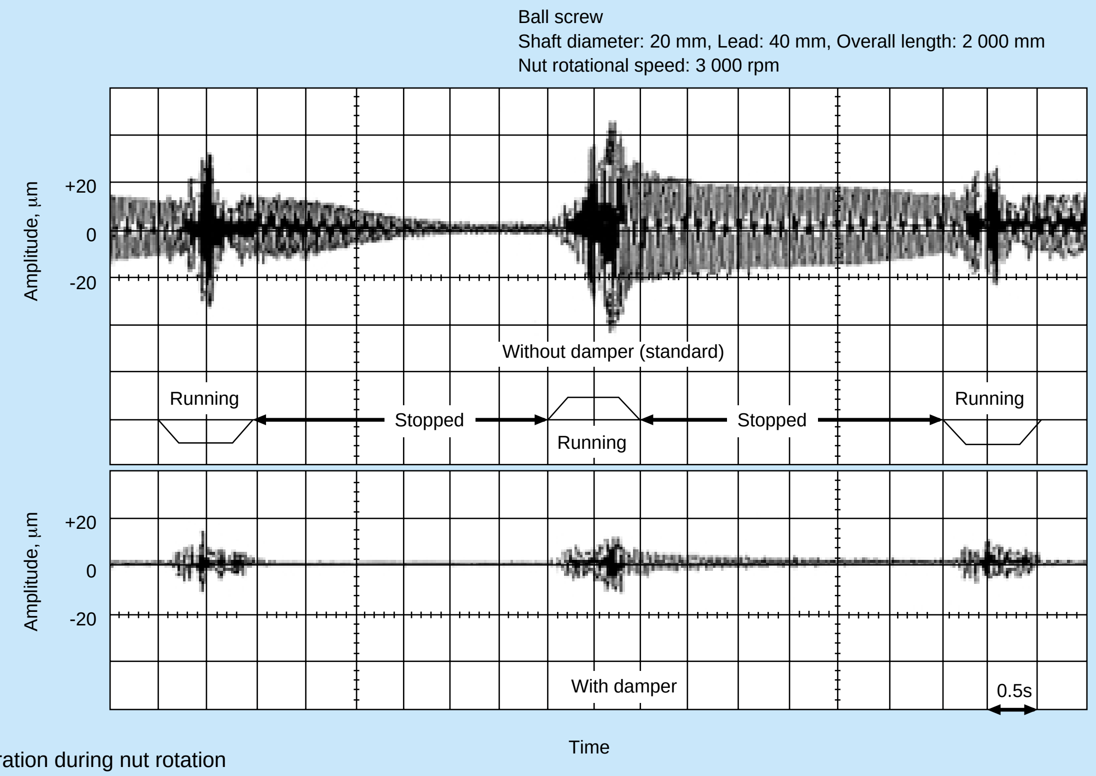


Fig. 13 Vibration during nut rotation

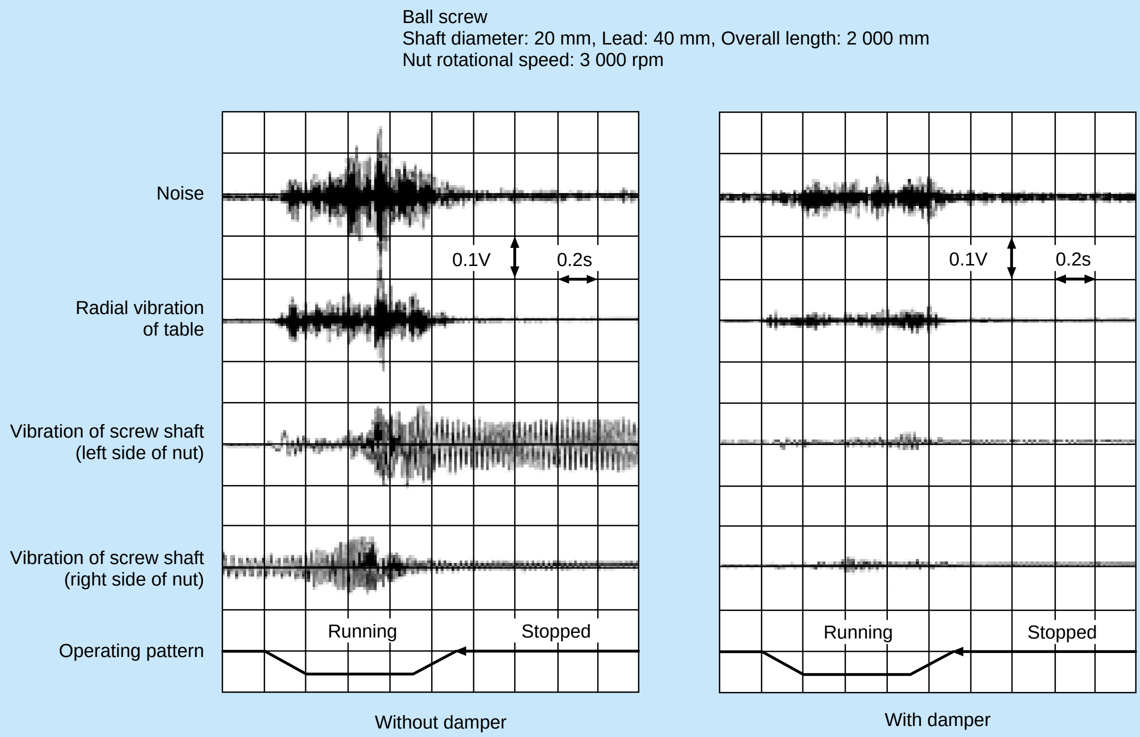


Fig. 14 Noise and vibration during nut rotation

and when it was stopped, the vibration level of the ball screw with the damper was very low and posed no problems. Even at 4 000 rpm, which equates to an extremely high traverse speed of 2.67 m/s, vibration was controlled and presented no performance problems. [4)]

When ball screws are used above the critical speed, the vibration of the screw shaft generates noise and is also transferred to other components of the machine. Measurements of this sound and vibration were taken on the ball screw in the two previous tests. Fig. 14 shows the noise level of the unit, the radial vibration of the table and the vibration of the screw shaft. In the standard ball screw with no damper, the noise of the unit and the vibration of the table grew dramatically when the vibration of the screw shaft increased. The noise generated was quite harsh. Note that these results were obtained with a single-axis table. Noise and vibration can be even greater depending on the specific characteristics of a given machine. In contrast, the ball screw with the damper demonstrated no such problems.

5.3 Residual vibration of ball screw when stopped

Fig. 15 shows the results of measurements of residual vibration in the axial direction after stopping the table. A non-contact speedometer was used to measure the residual vibration. In the standard ball screw with no damper, the screw shaft continues to vibrate even after the table stops. The effect of the vibrating shaft is apparent in the axial vibration of the table, which continues after the table is stopped. With the damper, the vibration of the screw shaft ceases immediately and with it, the table vibration. This indicates that the damper enhances axial positioning accuracy.

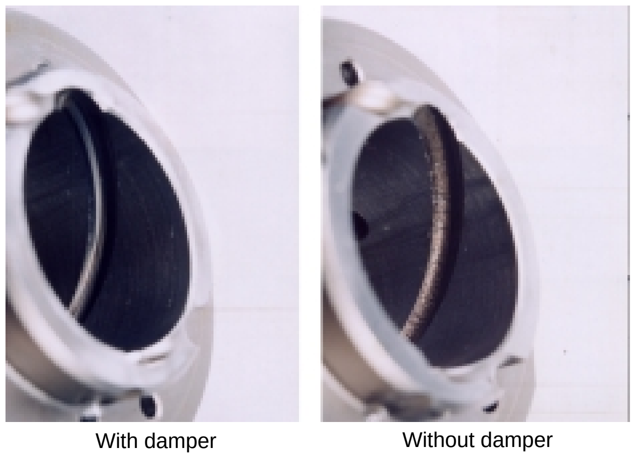


Photo 1 Effect of damper on ball nut groove endurance

5.4 Results of endurance test

Photo 1 shows the ball nut grooves of the ball screws in the tests of Figs. 12 - 15 after a high-speed endurance test during which the critical speed was exceeded. With no damper, flaking is observed over a wide area in the nut groove after running for only 2 000 km. On the other hand, with the damper, almost no deterioration was observed even after running for 10 000 km.

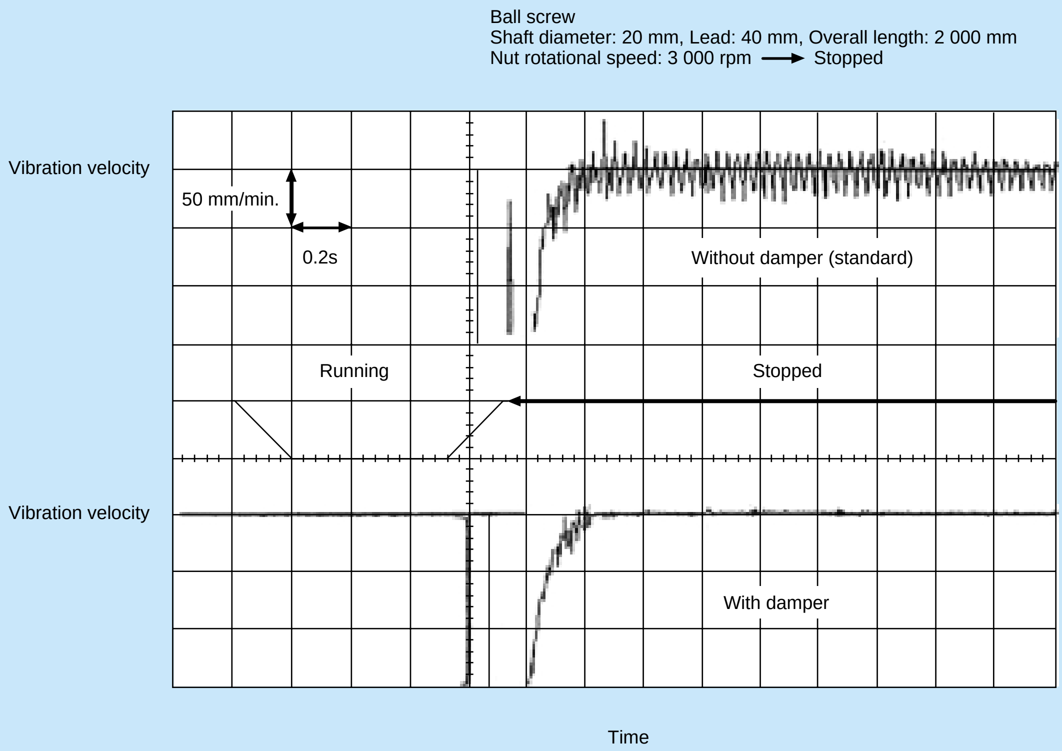


Fig. 15 Residual vibration in axial direction

6. Conclusion

Hideyuki Sato

The various tests presented in this report demonstrate the effectiveness of NSK's ball screw with rotating nut and vibration damper. The new ball screw refutes the conventionally held idea that high-speed drive with long stroke was impossible. In the future, still higher traverse speed, coupled with associated increases in stroke, will be required. At the same time, machines are expected to become more compact and lightweight. At NSK we will continue the development of products that meet the needs of the market.

References:

1) Yamaguchi, T. "High Speed Feed of Ball Screw," Motion Engineering Japan '94. Symposium papers. (1994) D3.3.1-10 [in Japanese].
2) Gasch, R. & Pfützner, H. "Rotordynamik - eine Einführung," Translated by Miwa, S. (1978) 5-45, Morihoku Shuppan [in Japanese].
3) Tamaki, A. "High Speed Low Noise Table and Applications," Mechanical Automation, 25-3 (1993), 41 – 48 [in Japanese].
4) Yamaguchi, T "Technology in Improving Ball Screw Function," J.JSPE. 61-3 (1995) 333 – 335 [in Japanese].

Ceramic Bearings for Special Environments

Shin Niizeki
Bearing Technology Center

ABSTRACT

Compared to steel, ceramic materials offer superior corrosion and heat resistance, higher dimensional stability, and lower density, which facilitates high speed. NSK's silicon nitride bearings have been used with successful results in machine tool spindles for more than 10 years. Recently, NSK has developed ceramic bearings for special operating conditions including corrosive, vaccum, high-temperature, clean, non-lubricated and seizure-prone environments.

NSK's ceramic bearings are made of silicon nitride, silicon carbide or partially stabilized zirconia, depending on the application. The superiority of these bearings was demonstrated in endurance tests in water, acid solutions, high-temperature vaccum conditions and an oil shut-off test, as well as on a hot-dip galvanizing line.

1. Introduction

Research on ceramic rolling bearings has been ongoing for more than 30 years.[1, 2] As shown in Table 1, ceramics are superior to steel in heat and corrosion resistance, and are lightweight and extremely hard as well. Consequently, ceramic rolling bearings can be used in environments where conventional steel bearings cannot. Accordingly, NSK has long been engaged in research and development of ceramics for rolling bearings. This paper describes the latest advances in ceramic materials for rolling bearings and evaluates the performance of ceramic bearings in various conditions and environments.

2. NSK Ceramics and Bearing Composition

2.1 NSK Ceramics

NSK has developed three types of ceramics: silicon nitride, silicon carbide and partially stabilized zirconia.

2.1.1 Silicon nitride

Silicon nitride bearings are used in high-speed applications like machine tools and aircraft engines, and in oil- and liquid-lubricated machinery operated under heavy load. As shown in Table 1, silicon nitride is superior to bearing steel (AISI 52100) in physical and mechanical properties such as density, strength and heat resistance. It is also satisfactory in terms of rolling fatigue life, making it an outstanding material for rolling bearings. Silicon nitride bearings have been used with successful results in machine tool spindles for more than 10 years.

2.1.2 Silicon carbide

In especially harsh conditions, such as environments where highly corrosive agents are present, even silicon nitride can be corroded. For these environments, NSK's silicon carbide is the most suitable. NSK's silicon carbide bearings have self-lubricating cages and are used in film and semiconductor cleaning systems.

2.1.3 Partially stabilized zirconia

Compared with the other two types of ceramic bearings,

Table 1 Ceramics vs. bearing steel

Characteristics \ Material	Silicon nitride	Silicon carbide	Alumina	Partially stabilized zirconia	Bearing steel AISI 52100
Density, g/cm^3	3.2	3.1	3.7	5.9	7.8
Hardness, Hv	1 600	2 200	2 000	1 400	700
Elastic modulus, GPa	310	420	350	210	210
Thermal expansion coefficient, 10^{-6}/°C	2.8	4.3	7.5	10.5	12.5
Flexural strength, MPa	900	600	400	1 100	—
Thermal shock resistance ΔT, °C	800	500	200	300	—

Table 2 Corrosion resistance and cost of ceramic materials

Items		Ceramics			Stainless steel AISI 440C
		Silicon carbide	Partially stabilized zirconia	Silicon nitride	
Corrosion resistance	Sulfuric acid, 1N (room temperature)	◎	○	△	×
	Sulfuric acid, 1N (150°C)	◎	△	△	×
	Fluoric acid, 1N (room temperature)	◎	△	△	×
Cost		△	○	△	◎

◎: Excellent, ○: Good, △: Fair, ×: Poor

NSK's partially stabilized zirconia bearings have the longest rolling fatigue life in water and can be manufactured at the lowest cost. They are widely applied in the silicon wafer polishing process.

The corrosion resistance and cost of NSK's three types of ceramics are compared in Table 2.

2.2 Composition of ceramic bearings

Ceramic bearings are either all-ceramic or hybrid (Fig. 1). Cages are made from either polyamide resin or self-lubricating material and lubrication is oil, grease or solid lubricant depending on the operating environment.

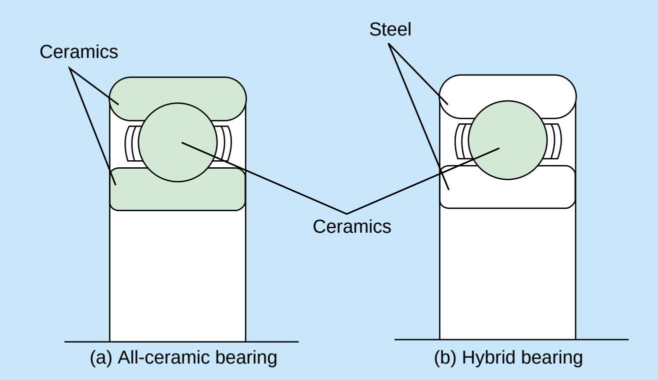


Fig. 1 Types of ceramic bearings

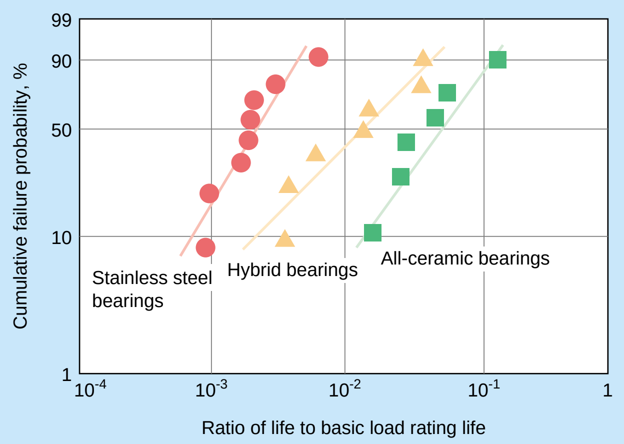


Fig. 2 Endurance life of ceramic bearings in water

3. Rolling Performance of Ceramic Bearings

3.1 Corrosive environments

3.1.1 Endurance life in water

Fig. 2 is a Weibull plot of the results of life tests in water of silicon nitride and stainless steel 6206 deep groove ball bearings.[3] The test load is 980N and rotating speed is 1 000 rpm. Compared to stainless steel bearings, hybrid and all-ceramic bearings lasted three and 20 times longer, respectively. It is presumed that water readily adheres to silicon nitride and forms a better lubrication film, leading to extended bearing life.

Fig. 3 presents results of endurance life tests in water of all-stainless steel bearings and hybrid bearings made from various ceramics including aluminum oxide (AO), partially stabilized zirconia (PSZ) and silicon nitride (SN).[4] The hybrid bearings with stainless steel rings and SN balls and stainless steel rings and PSZ balls demonstrated longer life than the all-stainless steel bearings and are therefore suitable for water environments. The hybrid bearings with stainless steel rings and AO balls had shorter life than the all-stainless steel bearings and are therefore not a feasible alternative.

Fig. 4 compares the life in water of all-ceramic bearings made from silicon nitride, silicon carbide and partially

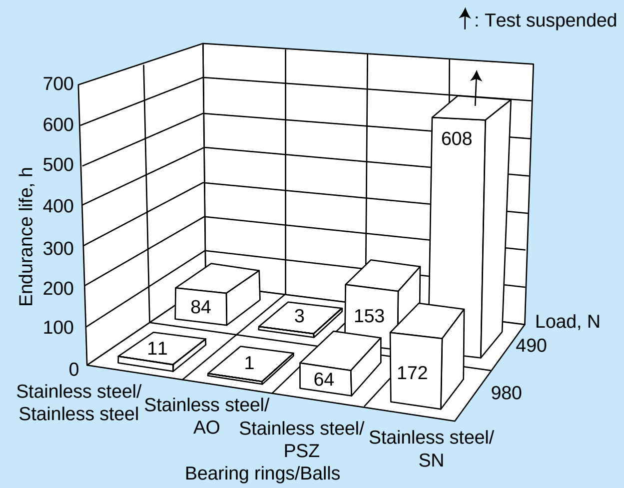


Fig. 3 Endurance life of various hybrid bearings in water

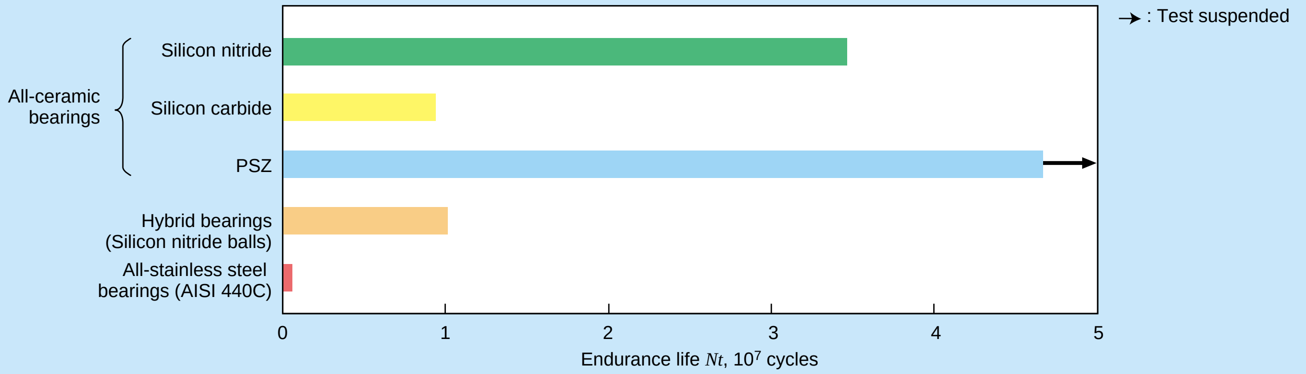
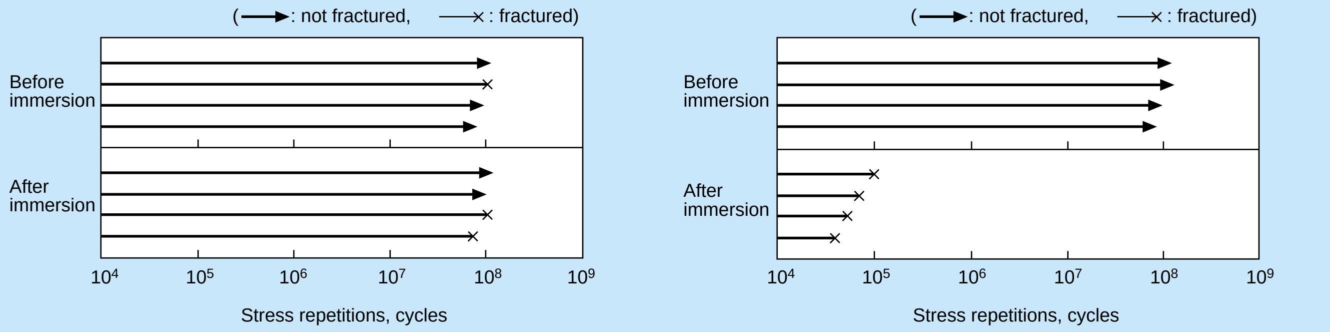


Fig. 4 Endurance life of various all-ceramic bearings in water



(a) New silicon nitride with C_eO_2-MgO as sintering additive

(b) Conventional silicon nitride with Y_2O_3-Al_2O_3 as sintering additive

Fig. 5 Effect of sintering additives on endurance life of ceramic bearings after immersion in acid

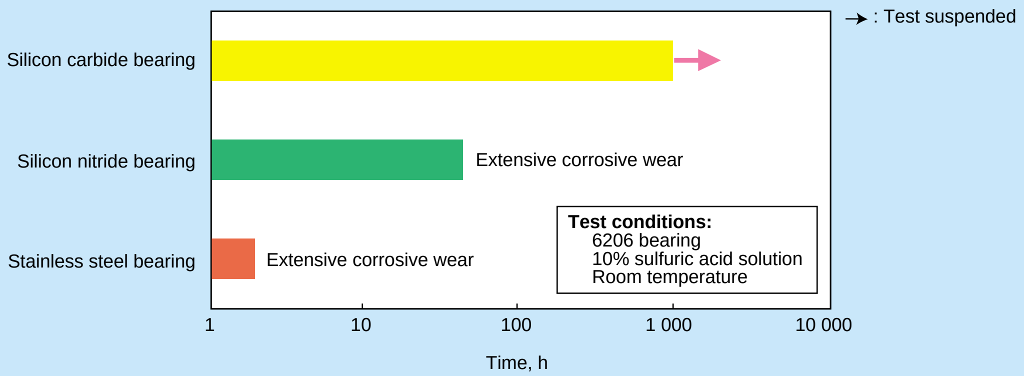


Fig. 6 Endurance life in sulfuric acid solution

stabilized zirconia with a hybrid bearing with silicon nitride balls and an all-stainless steel bearing. [5] The partially stabilized zirconia bearing demonstrated the longest life of all the bearings, including the silicon nitride and silicon carbide ones. It can therefore be concluded that all-ceramic bearings made from partially stabilized zirconia are most suitable for water environments.

3.1.2 Performance in corrosive agents

Generally silicon nitride has excellent corrosion resistance. However, corrosion resistance varies depending on the type and quantity of sintering additives, [6] and certain corrosive agents decrease in hardness and flexural strength.

Fig. 5 shows the results of flat washer endurance life tests of silicon nitride under oil lubrication both before and after 100 hours of immersion in a 3 mol/dm^3 hydrochloric acid solution at 90°C. [6] Silicon nitride with CeO_2-MgO as the sintering additive demonstrated equal endurance life before and after immersion in the acid solution (Fig. 5a). On the other hand, the same type of ceramic with Y_2O_3-Al_2O_3 as the sintering additive demonstrated a significant decrease in endurance life as a result of immersion in the acid solution (Fig. 5b). The sintering additive, Y_2O_3-Al_2O_3, in the silicon nitride grain boundary was eroded by the acid, resulting in deterioration of the binding strength of the sintering additive.

Fig. 6 presents the results of an endurance life test under exposure to a 10% sulfuric acid aqueous solution. In this solution, the carbide-based ceramic bearing proved the most effective.

3.1.3 Performance on a galvanizing line

All-silicon nitride ball bearings with tantalum cages were tested in the steel plate transfer rolls on an actual galvanizing line. [7] Establishing a new high for service life in this application, the bearings operated continuously for about a month while suppressing bearing vibration substantially and improving plating accuracy.

Table 3 summarizes the corrosion resistance of stainless steel bearings and NSK's three types of ceramic bearings. NSK's silicon carbide bearings are the most appropriate for corrosive environments with strong acid solutions while the partially stabilized zirconia bearings are most suitable for water and weak acid solutions.

Table 3 Comparison of ceramic and steel bearings

Corrosive environment / Bearing type	Water	Seawater/ Weak acids	Strong acids (hydrochloric acid, sulfuric acid, etc.)
Stainless steel	△	×	×
Silicon nitride	◎	◎	△
Partially stabilized zirconia	◎	◎	○
Silicon carbide	○	○	◎

◎: Excellent, ○: Good, △: Fair, ×: Poor

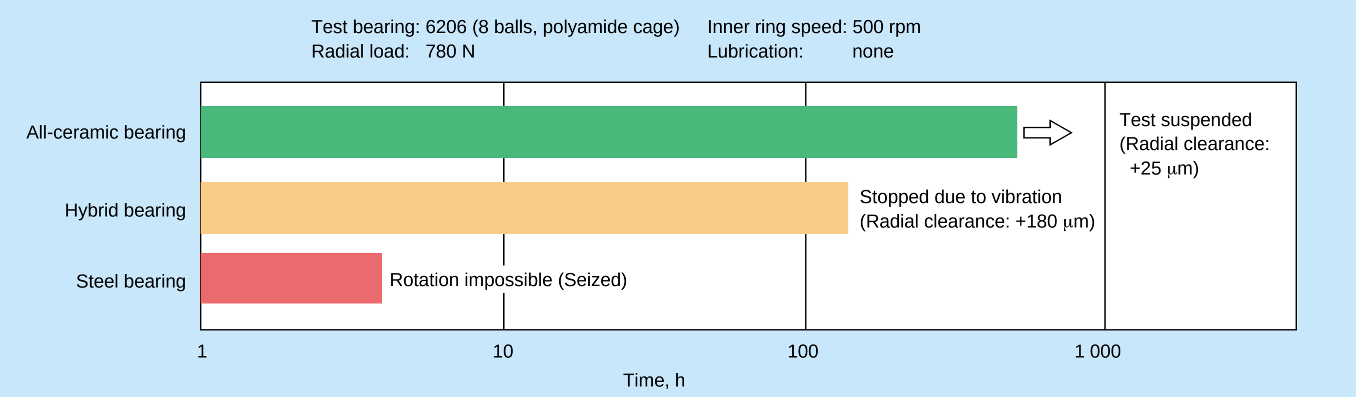


Fig. 7 Endurance life of bearings without lubrication in normal atmosphere

3.2 Performance with poor lubrication

3.2.1 Endurance life without oil or grease lubrication

As ceramics are extremely hard and have outstanding wear resistance, they outperform other materials in bearing life without lubrication. Results of an endurance life test of steel, hybrid and all-silicon nitride bearings operating without lubrication are presented in Fig. 7.[8] The steel bearing seized within a short period while the hybrid and all-ceramic bearings, though sustaining wear, did not. As shown in the figure, the all-ceramic bearing sustained considerably less wear than the hybrid bearing, indicating that its endurance life is much longer.

3.2.2 Performance in high-temperature vacuum

An all-silicon nitride ball bearing with a self-lubricating laminated cage (mainly composed of MoS_2) and with MoS_2-coated rings and balls proved superior in durability in a high-temperature vacuum environment. Fig. 8 shows the change over time in the dynamic frictional torque of various bearings in 10^{-4} – 10^{-6} Pa at 300°C.[9] The all-ceramic bearing rotated continuously for 3 810 hours. Compared with the hybrid bearings, the all-ceramic bearing was superior in both dynamic frictional torque and life.

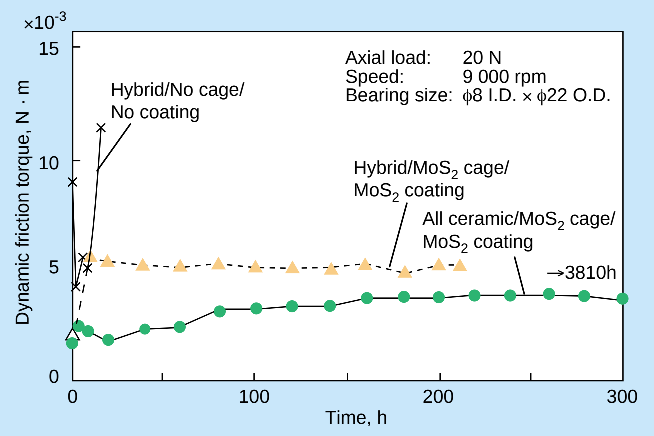


Fig. 8 Endurance life of ceramic bearings in vacuum and high temperature

3.2.3 Particle generation

Among ceramics, partially stabilized zirconia used in combination with steel is known to generate the fewest particles. As shown in the test results presented in Fig. 9, hybrid bearings with partially stabilized zirconia balls generated fewer particles than stainless steel bearings with fluoride grease or stainless steel bearings with a gold coating.[10] The combination of dissimilar materials is an effective means to reduce particle generation.

3.3 Performance under oil lubrication

3.3.1 Rolling fatigue life

The rolling fatigue life (ISO 281) of silicon nitride bearings under oil lubrication is at least longer than the basic rating life of steel bearings. Fig. 10 shows the results of life tests of all-silicon nitride and silicon nitride hybrid bearings relative to the basic rating life of steel bearings.[11] All-silicon nitride bearings demonstrated rolling fatigue

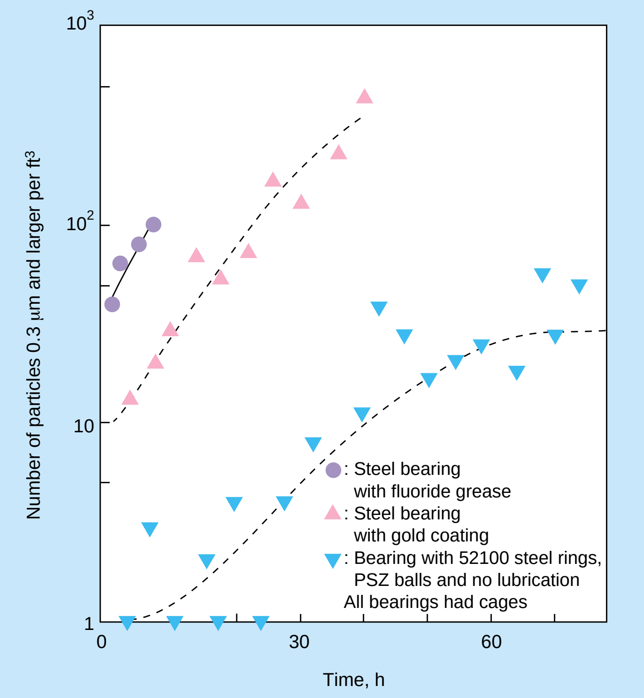


Fig. 9 Particle generation of bearings

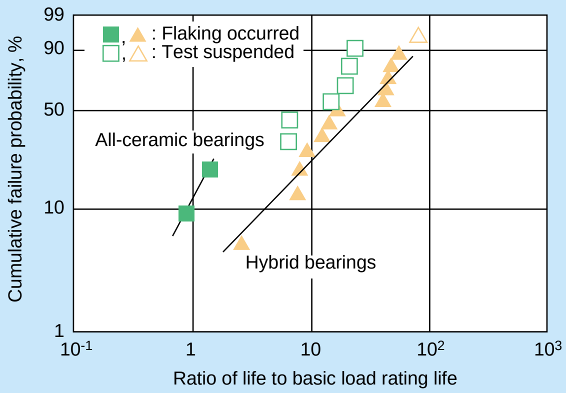


Fig. 10 Rolling fatigue life of bearings under oil lubrication

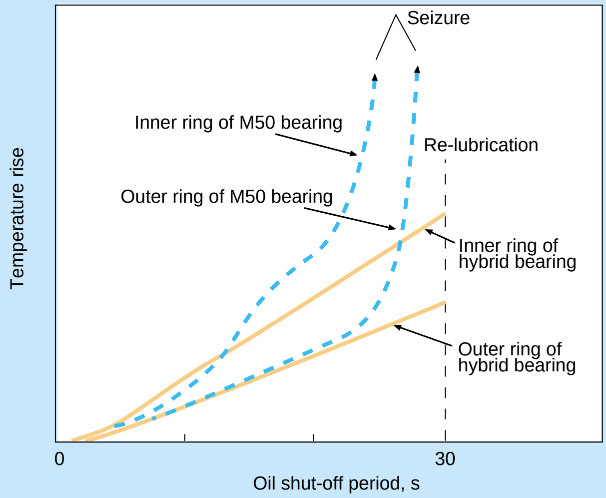


Fig. 11 Temperature rise of hybrid bearing and M50 bearing after oil shut-off

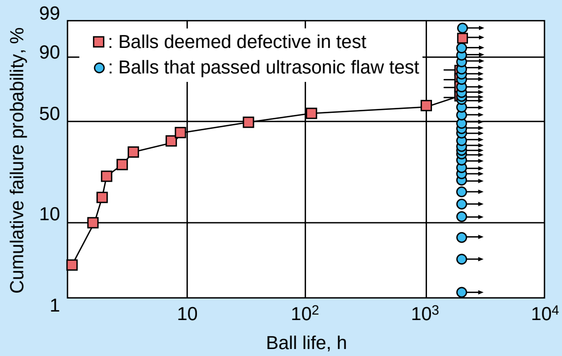


Fig. 12 Rolling fatigue life of ceramic balls tested by ultrasonic flaw detection method

life equal to or a little longer than the basic rating life of steel bearings while the hybrid bearings eclipsed the basic rating life of steel bearings by a factor of four. The failure mode for all of the bearings in the test was flaking.

As the rolling fatigue life of steel bearings is more than ten times their basic rating life in good lubrication, silicon nitride bearings are inferior to steel bearings. The principal reason is that silicon nitride bearings sustain higher contact pressure because they are less elastic than steel. Still, because the rolling fatigue life of silicon nitride bearings is at least longer than the basic rating life of steel bearings, silicon nitride bearings are feasible for some applications. Note that the most important feature of all-silicon nitride bearings is their superior performance in applications where lubrication is poor due to extreme temperatures, water-ingress or vacuum conditions.

3.3.2 High-speed performance

NSK produces high-speed bearings specifically designed for machine tool spindles. Because the density of silicon nitride is only 40% that of steel, substituting steel balls with ceramic ones greatly facilitates high-speed rotation. In a machine tool spindle under position preload, the centrifugal force acting on ceramic rolling elements is substantially lower, resulting in suppression of heat generation between the balls and outer ring. [12] The result is superior high-speed performance. Hybrid bearings have demonstrated excellent high-speed performance not only with grease lubrication, but also with oil-air lubrication. [13] NSK's recently developed ROBUST Series for machine tool spindles includes hybrid bearings. [14]

3.3.3 Seizure resistance

High-speed performance is also required for aircraft engines. At the same time, seizure resistance is extremely important for safety reasons. [15] This critical performance attribute was assessed in an oil shut-off test in which aircraft engine conditions were closely replicated. Fig. 11 shows the temperature rise of M50 heat-resistant steel and hybrid bearings (M50 rings and silicon nitride balls) after the supply of lubricating oil was shut off. [16] The *PV* value, which is an index that reflects the risk of seizure, was kept constant for both bearings. In the test, the hybrid bearing demonstrated excellent high-speed performance, reaching a $d_m n$ value (ball pitch diameter, mm × speed, rpm) of 3.1 million. After the oil supply was shut off, the steel bearing seized before reaching the 30-second re-lubrication point while the hybrid bearing returned to stable operation after being re-lubricated and did not sustain any damage. The superior seizure resistance demonstrated by the hybrid bearing can be attributed to two factors: the disinclination of two different materials to adhere to each other and the smaller increase in preload that results from the low linear expansion coefficient of the ceramic balls. [16]

For applications in aircraft engines, bearings must not only meet requirements for high performance, but also strict safety standards. NSK has developed a unique non-destructive ultrasonic flaw detection method for hybrid ceramic bearings for aircraft engines. [17] This method can detect surface and subsurface defects that shorten rolling fatigue life. Fig. 12 presents the results of rolling fatigue life tests of silicon nitride balls that were tested with the new method. The balls that were deemed defective through this method demonstrated shorter rolling fatigue life, while every one of the balls that passed the inspection lasted until the test was suspended after 2 000 hours, nearly eight times the basic rating life of steel bearings. [17)] NSK's ultrasonic flaw detection method was thus shown to be an effective non-destructive means of inspecting ceramic balls.

4. Life Equation for Ceramic Bearings

NSK has performed life tests under various environments as described in Section 3. Estimating the life of ceramic bearings can be carried out as follows:

$$L = a_{CL} \cdot a_{CM} (C_r/P)^3$$

where,

L: Basic rating life (90% reliability life), 10^6 rev

C_r: Basic dynamic load rating of steel bearings of the same size, N

P: Dynamic equivalent load, N

a_{CL}: Lubrication coefficient

a_{CM}: Material coefficient

Table 4 lists the lubrication and material coefficients.

Table 4 a_{CL} and a_{CM} in life equation of ceramic bearings

Lubrication	a_{CL}	Bearing type	a_{CM}
Oil or Grease	1	Hybrid	4
		All-ceramic	1
Water	0.02	Hybrid	0.1
		All-ceramic	1

5. Conclusion

The characteristics of NSK's ceramic materials for rolling bearings and the results of recent performance tests of ceramic bearings in a variety of environments have been described. Ceramic bearings are believed to have additional superior performance attributes. NSK will conduct further research and development to meet the needs of the market.

References:

1) E. V. Zaretsky & W. J. Anderson, "Rolling-Contact Fatigue Studies with Four Tool Steels and a Crystallized Glass Ceramics," J. Basic Eng., Trans. ASME, December (1961) 603.
2) R. J. Parker, S. J. Grisaffe & E. V. Zaretsky, "Rolling-Contact Studies with Four Refractory Materials to 2000 F," ASLE Trans., 8, (1965) 208.
3) S. Niizeki, K. Nonaka, H. Tanaka & S. Matsunaga, "Rolling Life of Ceramic Bearings Under Oil Lubrication and Water Lubrication," Proc. Inter. Tribology Conf., Yokohama (1995) 1399.
4) S. Niizeki, H. Tanaka & S. Matsunaga, "Rolling Performance in Water of Hybrid Bearings with Normal Sintered Ceramic Balls," Proc. JAST Trib. Conf., Kitakyushu, 1996-10, 425.*
5) T. Yamamoto, S. Niizeki, H. Ito & S. Matsunaga, "Rolling Performance of Ceramic Bearings under Water Lubrication," Proc. JAST Trib. Conf., Osaka, 1997-11, 306.*
6) S. Niizeki, T. Abe & K. Furumura, "Reliability for Rolling Fatigue Life and Corrosion Resistance of Ceramic Balls made of Si_3N_4," Proc. JAST Trib. Conf., Fukuoka, 1991-10, 67.*
7) A. Yakawa, T. Mori, M. Tada, K. Nojima, T. Tsuda, K. Hashimoto, K. Andou, A. Aoki & S. Matsunaga, "Development of Ceramic Ball-Bearing for Support Rolls in a Hot Dip Plating Bath," Proc. 92nd Meeting Surf. Finish. Soc. Japan, 205.*
8) S. Niizeki, K. Nonaka, H, Tanaka & S. Matsunaga, "Comparative Study between Ceramic Bearings and All Steel Bearings," NSK Techical Journal, 658 (1994) 19.*
9) T. Ogawa, K. Konishi, S. Aihara & T. Sawamoto, "Development of Ball Bearings with Solid Film for High-Vacuum, High-Temperature, High-Speed Application," Lub. Eng., 49-4 (1993) 291.
10) H. Ito, K. Hachiya & M. Naka, "Out-Particle Performance of Ceramic Bearings and Solid-Lubricated Bearings," Proc. JAST Trib. Conf., Tokyo, 1992-5, 339.*
11) S. Niizeki, K. Nonaka, H, Tanaka & S. Matsunaga, "Rolling Fatigue Life of Ceramic Bearings," Proc. JAST Trib. Conf., Kanazawa, 1994-10, 753.*
12) H. Aramaki, Y. Shoda & T. Sawamoto, "High-Speed and Low Temperature-Rising of Ball Bearings with Silicon Nitride Ceramic Balls in High Speed Spindles for Machine Tools," Proc. JAST Trib. Conf., 30 (1986) 269.*
13) H. Aramaki, Y. Shoda, Y. Morishita & T. Sawamoto, "The Performance of Ball Bearings with Silicon Nitride Ceramic Balls in High Speed Spindles for Machine Tools," Trans. ASME, J. Tribology, 88-Trib-8 (1988).
14) Y. Ohura, Y. Katsuno and S. Sugita, "ROBUST Series High-Speed Precision Angular Contact Ball Bearings for Machine Tool Spindles," NSK Technical Journal No. 668 (1999) 20.*
15) A. Matsuura, Y. Masumoto, K. Shika & Y. Ohura, "Application of Ceramic Bearing for Main Shaft on Aircraft Engine," Proc. 34th Conf. Aerospace Propulsion, (1994) 252.*
16) Y. Shoda, "Hybrid Ceramic Rolling Bearings," NSK Technical Journal No. 653 (1992) 33.*
17) J. Sahara, S. Niizeki, S. Wada, T. Abe & K. Furumura, "Development of Ultrasonic Testing Method for Finished Ceramic Balls," Proc. of NDT Soc. Japan, Autumn (1991) 67.*

[* in Japanese]

Shin Niizeki

Excellent Stainless Bearing Steel (ES1)

Susumu Tanaka, Kenji Yamamura and Manabu Oohori
Research and Development Center

ABSTRACT

NSK has developed Excellent Stainless Bearing Steel (ES1), a new steel that is superior to conventional AISI 440C steel in corrosion resistance and rolling contact fatigue life.

AISI 440C has been used in applications where corrosion resistance is of primary concern. However, its performance has not always been satisfactory because it contains coarse eutectic carbides that act as crack initiators under rolling contact stress and reduce Cr content in the martensitic matrix to the carbides. In contrast, ES1 steel has no eutectic carbides but consists of fine carbides, nitrides and strong martensite, resulting in improved resistance to corrosion and fatigue. ES1 has optimum nitrogen content and lower carbon content to suppress the eutectic carbides generated in conventional steelmaking process. In testing, ES1 outperformed other stainless steels in a 5% aqueous sodium chloride immersion test, a salt-water spray test, 5-N sulfuric acid and 5-N hydrochloride solution immersion tests, and life tests in water.

1. Introduction

Rolling bearings are often used under severe conditions such as high contact pressure, high temperature and contaminated lubrication. In response, NSK has undertaken extensive research and made great strides in the field of material and heat treatments, as demonstrated by HTF and STF bearings.[1)–3)] Today, with the use of bearings in various corrosive environments increasing, interest in stainless steel and ceramic bearings is growing.

Stainless steel for rolling bearings must have high hardness. To date, high-hardness, high-carbon martensitic AISI 440C steel has been widely used, but its corrosion resistance and other performance characteristics have not always been adequate. To remedy this, NSK developed Excellent Stainless Bearing Steel (ES1), which is superior to conventional AISI 440C steel in corrosion resistance and other performance attributes. In this report, we review this outstanding new bearing material.

2. Development Concepts

AISI 440C has high carbon and Cr content, and when it solidifies, coarse eutectic carbides in which Cr is concentrated are produced. These carbides remain unchanged even after heat treatment (Photo 1a). High contact pressure between the rolling elements and bearing rings causes stress concentrations in the coarse eutectic carbides, resulting in flaking. In addition, eutectic carbides reduce corrosion resistance due to loss of Cr in the martensitic matrix. The presence of eutectic carbides in steel is therefore extremely undesirable.

Recently, 0.7C – 13Cr martensitic stainless steel (hereafter referred to as “13Cr stainless steel”) was developed by suppressing the formation of eutectic carbides through the reduction of the carbon and Cr content in AISI 440C. However, this steel provides insufficient corrosion resistance because it still contains eutectic carbides (Photo 1).

Recent research has indicated that alloying nitrogen to stainless steel increases corrosion resistance.[4)] Such nitrogen alloying through conventional melting is not easy because blowholes remain in the steel due to the low solubility of nitrogen. Nitrogen alloying of martensitic stainless steel, requires very specialized methods such as pressurized electro-slag remelting (PESR).[5), 6)]

In this context, to develop our highly corrosion-resistant ES1, we lowered the carbon content and increased the nitrogen content of conventional high-carbon martensitic stainless steel (Fig. 1). A sufficient amount of nitrogen is added to molten steel in the conventional steelmaking process. This enhances corrosion resistance and endurance life without considerably increasing production costs.

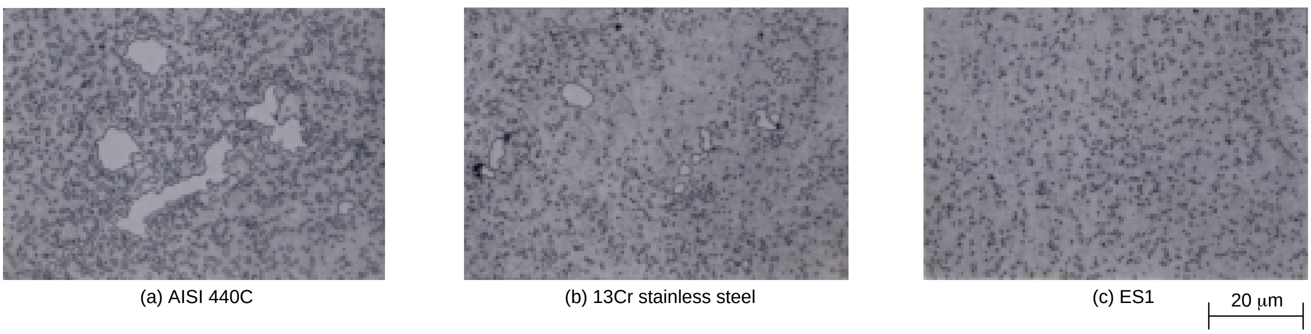


Photo 1 Structure of martensitic stainless bearing steels as viewed with an optical microscope

3. Features of ES1 Steel

3.1 Microscopic structure and hardness

Photo 1c shows the microscopic structure of the new ES1 steel. ES1 has none of the coarse eutectic carbides observed in conventional stainless steel (cf. Photos 1a and 1b). Instead, ES1 has superior microscopic structure with fine carbides distributed evenly. In addition, nitrogen strengthens martensite, thus contributing to higher hardness than conventional stainless steel.

3.2 Corrosion resistance

3.2.1 Aqueous sodium chloride solution immersion test

ϕ18 × 10 mm test pieces of ES1, 13Cr stainless steel and AISI 440C were immersed in a 5% aqueous sodium chloride solution at room temperature for 8 hours. Before immersion in the solution, all surfaces of the test pieces were polished, one end of each test piece was finished with #800 emery paper, and then passivation treatment was applied. Photo 2 shows the test pieces after the test. The conventional AISI 440C and 13Cr stainless steel rusted, while ES1 did not.

3.2.2 Anodic polarization curve measurement test

The results of the 5% aqueous sodium chloride solution immersion test showed that ES1 is superior in corrosion resistance to AISI 440C and 13Cr stainless steel. To prove this electrochemically, anodic polarization curve measurements were taken per JIS G0579. In this test, the potential was changed in 20 mV/min steps. The measurement results are shown in Fig. 2. ES1 has a wide passive state range and the current density to maintain the passive state in this range is smaller by one order of 10. The test results indicate that ES1 has superior corrosion resistance in terms of electrochemistry.

3.2.3 Saltwater spray test

We conducted a saltwater spray test per JIS Z2371 on 13Cr stainless steel and ES1 bearing inner and outer rings after ultrasonically cleaning them with an organic solvent. Photo 3 shows the bearing rings after the test. Conventional 13Cr stainless steel rusted considerably while ES1 did not.

3.2.4 Aqueous sulfuric acid and hydrochloric acid solution immersion test

In HD cleaners and other applications, rolling bearings are exposed to solutions of sulfuric acid and hydrochloric acid. Accordingly, we evaluated the corrosion resistance of ES1, 13Cr stainless steel and AISI 440C in a 5-N aqueous sulfuric acid solution and 5-N hydrochloric acid solution. In the test, ϕ18 × 10 mm test pieces were immersed in the solutions at room temperature for 20 hours, and then the amount of corrosion was measured. The test results confirm that ES1 is superior to the conventional steels in resistance to sulfuric acid and hydrochloric acid (Fig. 3). Note that while martensitic stainless steels are highly resistant to corrosion in oxidizing nitric acid (except

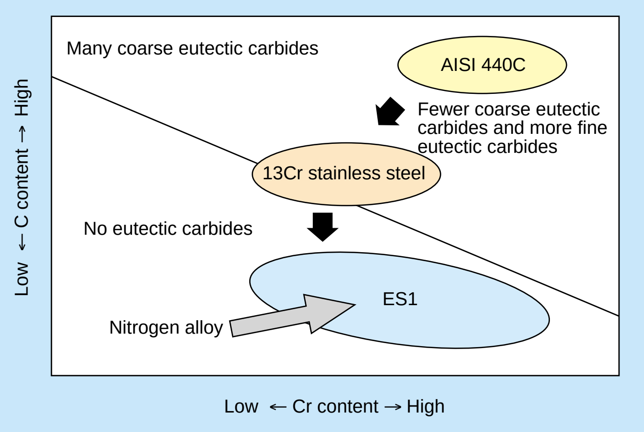


Fig. 1 Development concept

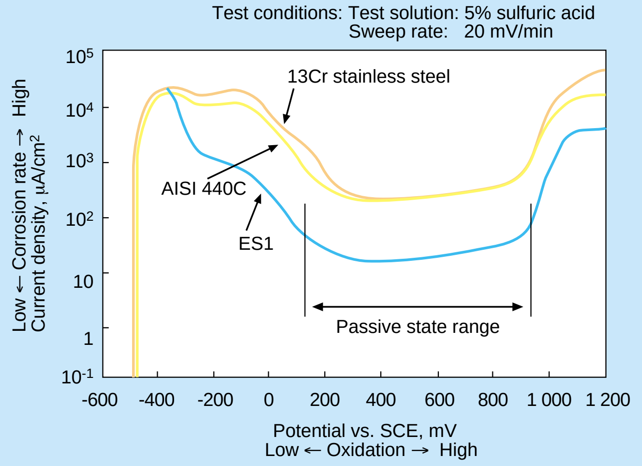
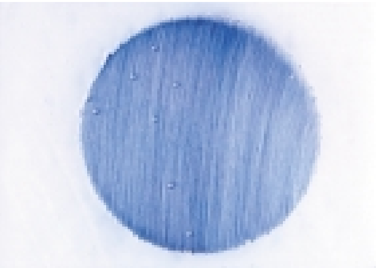
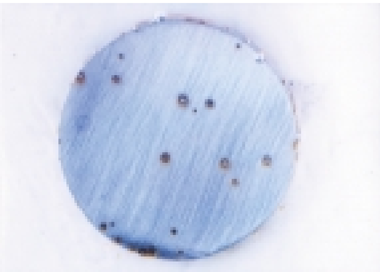


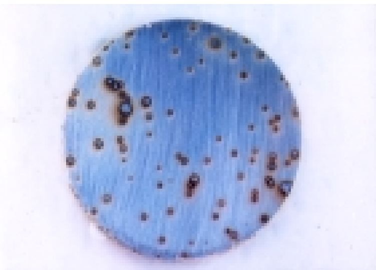
Fig. 2 Anodic polarization curves of stainless bearing steels



(a) ES1



(b) 13Cr stainless steel



(c) AISI 440C

Photo 2 Test pieces after immersion in aqueous sodium chloride solution

Photo 3 Bearing rings after saltwater spray test

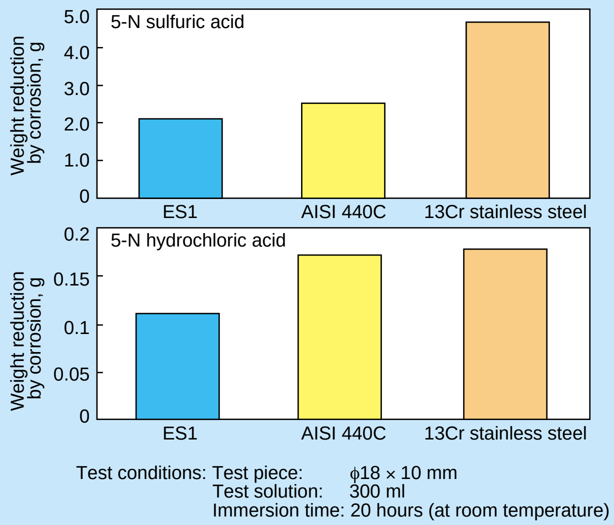


Fig. 3 Weight reduction by corrosion of stainless steels after immersion in 5-N sulfuric acid and 5-N hydrochloric acid

diluted nitric acid), they are not so resistant to sulfuric acid and hydrochloric acid. Because the corrosion resistance of stainless steels varies substantially depending on the concentration and temperature of the corrosive agent, it is vital to have a clear understanding of the operating environment.

3.3 Charpy impact test

Table 1 shows the results of a Charpy impact test using 2 mm V-notched test pieces. ES1 showed greater shock resistance than conventional 13Cr stainless steel.

3.4 Water-submerged life test

Stainless steel rolling bearings are used in precision equipment where even the smallest amount of rust is unacceptable and also in corrosive environments under severe lubrication conditions. We therefore used a special method developed by NSK to evaluate the rolling fatigue life of ES1 and AISI 440C in water.[7] The test bearings were 51305 thrust ball bearings with a fluororesin cage and silicon nitride balls. Bearing life was deemed over when the bearing vibration level reached about five times its initial value. Test conditions included load of 980 N (maximum contact pressure: 1 470 MPa) and rotating speed of 1 000 rpm. Test results indicating that ES1 has about five times longer life than AISI 440C in water are shown in Fig. 4.

Table 1 Results of Charpy impact test (2 mm V-notched test pieces)

Steel type	Hardness (H_RC)	Impact (J/cm^2)
ES1	61.8	4.0
13Cr stainless steel	61.1	3.6

Table 2 Comparison of stainless steels for bearings

Steel type	Hardness	Corrosion resistance	Fatigue life
ES1	○	○	○
13Cr stainless steel	○	△	△
AISI 440C	○	△	×

○: Excellent, △: Fair, ×: Poor

4. Conclusion

NSK has developed Excellent Stainless Bearing Steel (ES1). The new steel is superior to commonly used stainless steels on the market today (Table 2). Nitrogen alloying was applied to achieve both high corrosion resistance and long rolling contact fatigue life without increasing production costs. ES1 has no eutectic carbides but consists of fine carbides and nitrides (mostly carbon nitrides). In testing ES1 outperformed AISI 440C and 13Cr stainless steel in both corrosion resistance and fatigue life. Specifically, ES1 demonstrated its superiority in a 5% aqueous sodium chloride immersion test, a salt-water spray test, 5-N sulfuric acid and 5-N hydrochloric acid solution immersion tests, and life tests in water.

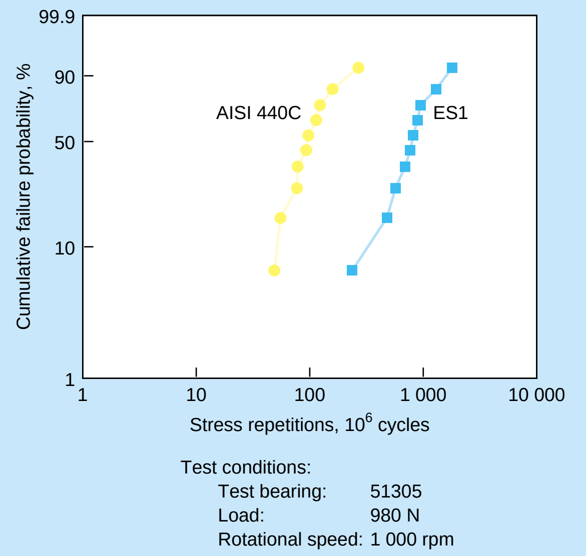


Fig. 4 Life test results in water

References:

1) Y. Murakami, N. Mitamura and K. Furumura, "Long Life Super TF & Hi-TF Bearings under Severe Lubrication Conditions," NSK Technical Journal No. 652 (1992) 9-16.*
2) Y. Murakami, Y. Matsumoto and K. Furumura, "Long Life TF Bearings under Contaminated Lubrication," NSK Technical Journal No. 650 (1989) 1-11.*
3) N. Mitamura, K. Sekino and Y. Murakami, "Development of Bearing under High Temperature Condition," NSK Technical Journal No. 658 (1994) 11-18.*
4) K. Osozawa, "The Effect of Nitrogen on the Corrosion Resistance of Stainless Steels," Heat Treatment Vol. 36 No.4 (1996) 206-212.*
5) H. Berns, "Manufacture and Application of High Nitrogen Steels," Z. Metallkd 86 (1995) 3, 156-163.
6) H. Berns and S. Siebert, "High Nitrogen Austenitic Cases in Stainless Steels," ISIJ International, Vol. 36 (1996) 7, 927-931.
7) H. Sugi, T. Nagato and H. Narai, "Rolling Contact Fatigue Life of Thrust Ball Bearings in Water," NSK Technical Journal No. 657 (1994) 22-27.*

[* in Japanese]


Susumu Tanaka


Kenji Yamamura


Manabu Oohori

Development of NSJ2 Bearing Steel

Nobuaki Mitamura
NSK-RHP European Technology Centre
Yasuo Murakami
Research and Development Center

ABSTRACT

Using special fatigue analysis techniques, NSK has investigated numerous premature bearing failures in a variety of applications. Analysis revealed that in the majority of cases premature bearing failure was from surface-originated fatigue.

NSK therefore developed a new steel, NSJ2, which has better resistance to surface-originated fatigue than conventional bearing steels. As a result, bearings made of NSJ2 steel are less prone to premature failure.

The development of this new bearing steel involved the optimization of alloying additions to give improved resistance to surface-originated fatigue without adversely affecting other important steel properties such as wear resistance and dimensional stability. Consideration was also given to the ease with which bearings could be manufactured in the new steel.

1. Introduction

Many of the rolling bearings produced today are made of AISI 52100 high-carbon chromium bearing steel (equivalent to SUJ2). Over the long, nearly 100-year history of AISI 52100, its main components have scarcely been modified. During this same period, a great deal of research has been conducted on such topics as bearing service life, bearing life evaluation technology, differences between types of premature bearing failures (e.g., failures due to surface- and subsurface-originated fatigue),[1] and material factors that can affect these types of premature bearing failures.[2] Based on the results of this research, improvements were made to steelmaking processes that resulted in higher purity of AISI 52100.[3] The results of studies and the types of premature bearing failures experienced in the field, however, indicate that AISI 52100 is not necessarily the ideal steel for rolling bearings. In response, we analyzed many premature bearing failures with a view to developing a material that would ensure longer bearing service life. In the course of developing this material, we focused not only performance factors like life, but also ease of production. This report gives background on and then describes the characteristics of NSJ2 bearing steel, a new steel with longer life and better performance than AISI 52100.

2. Research on In-Service Bearing Failures

Fatigue failure of rolling bearings in service can be broadly classified into two types: subsurface-originated fatigue and surface-originated fatigue. In subsurface-originated fatigue, a crack initiates below the surface of the bearing raceway at a defect such as a non-metallic inclusion, often in the region of maximum shear stress. This type of fatigue is often associated with good lubrication. In surface-originated fatigue, a crack is initiated at a defect such as a scratch or indentation in the bearing raceway caused by foreign debris. This type of fatigue is associated with poor lubrication. In both surface and subsurface fatigue, the cracks propagate under the influence of cyclic stress until flaking of the bearing raceway occurs.

These types of fatigue can be analyzed using X-ray diffraction (Figs. 1 and 2).[4)–6)] For many years, NSK has used this technology to generate a vast amount of data on

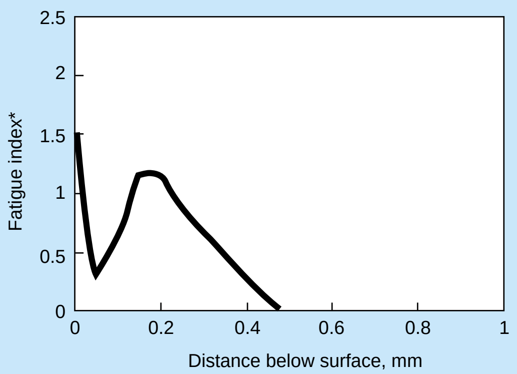


Fig. 1 Fatigue analysis of typical subsurface-originated fatigue

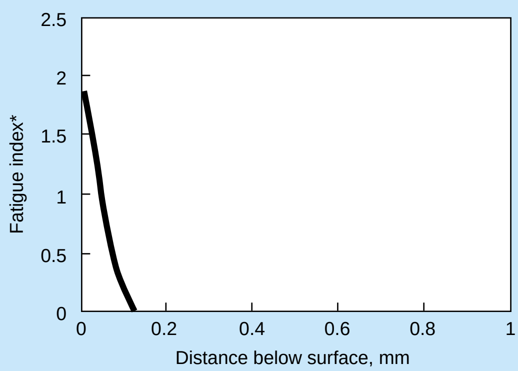


Fig. 2 Fatigue analysis of typical surface-originated fatigue

*The fatigue index is calculated based on changes in the half-value width of martensite and in retained austenite content.

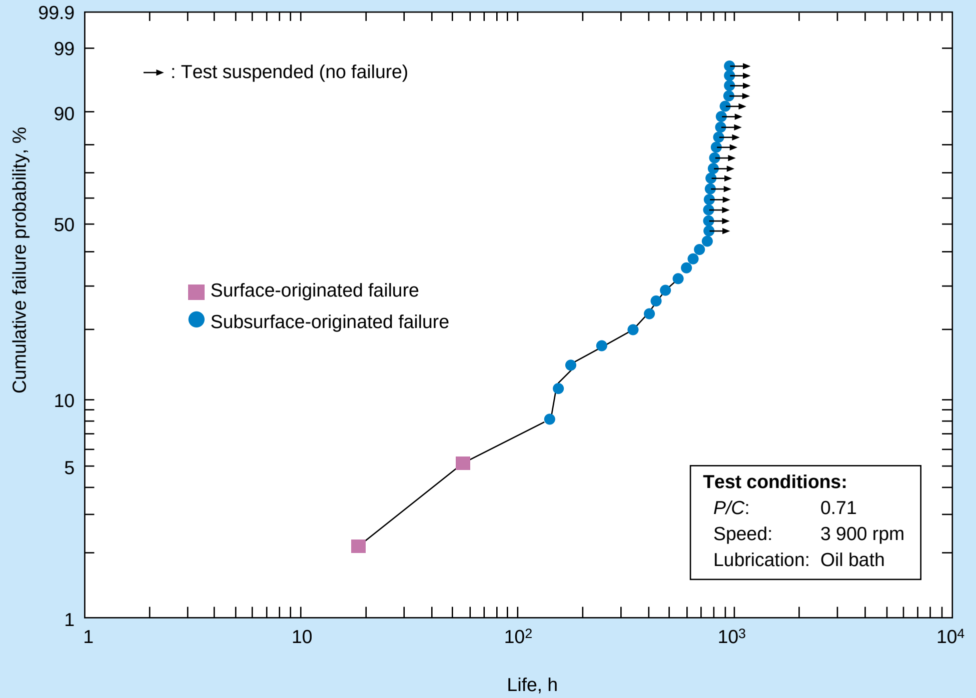


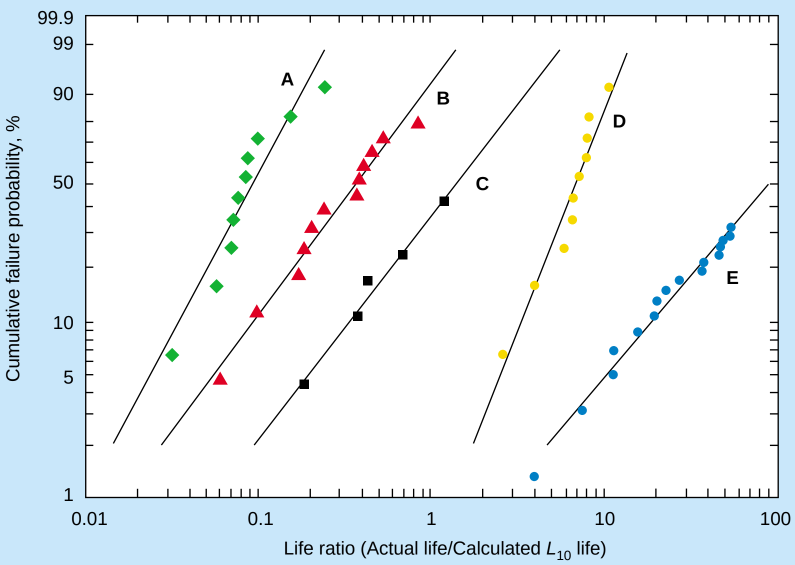
Fig. 3 Surface- and subsurface-originated failures in fatigue life test results of 6206 deep groove ball bearings

the fatigue of bearings in service. From this data, it was found that in applications where fatigue was the main cause of premature bearing failure, the most common type was surface-originated, usually due to poor lubrication conditions.

Fig. 3 shows the results of a bearing life test that was carried out under good lubrication conditions (filtered elastrohydrodynamic lubrication). Microscopic observation of the bearings after testing showed those with a short life had an arrowhead-like trace of flaking originating from a microscopic dent (Photo 1). This highlights the difficulty of completely preventing surface-originated fatigue from leading to premature bearing failure.

Fig. 4 shows the results of bearing life tests carried out under various lubricating conditions. The bearings tested under good lubricating conditions exhibited flaking from subsurface-originated fatigue and their life was much longer than the theoretical life. This is probably attributable to recent advances in steel mill technology resulting in greatly improved steel cleanliness and the almost total elimination of harmful non-metallic inclusions from which flaking originates. By contrast, the bearings tested under poor lubricating conditions exhibited flaking from surface-originated fatigue. Under these conditions, the life was as short as one twenty-fifth of the theoretical life.

The above results show that in the case of subsurface-originated fatigue, bearings can achieve their theoretical



	Lubrication conditions	*P/C*	*N* (rpm)
A	Contaminated with foreign particles of hardness 870 Hv and average size 100 μm	0.32	3 000
B	Contaminated with foreign particles of hardness 510 Hv and average size 100 μm	0.32	3 000
C	Contaminated with foreign particles of hardness 370 Hv and average size 100 μm	0.32	3 000
D	Contaminated with foreign particles of hardness 1200 Hv and average size 25 μm	0.32	3 000
E	Clean, no foreign particles	0.71	3 900

All bearings were lubricated by the oil bath method

Fig. 4 Fatigue life test results of 6206 bearings under various lubricating conditions

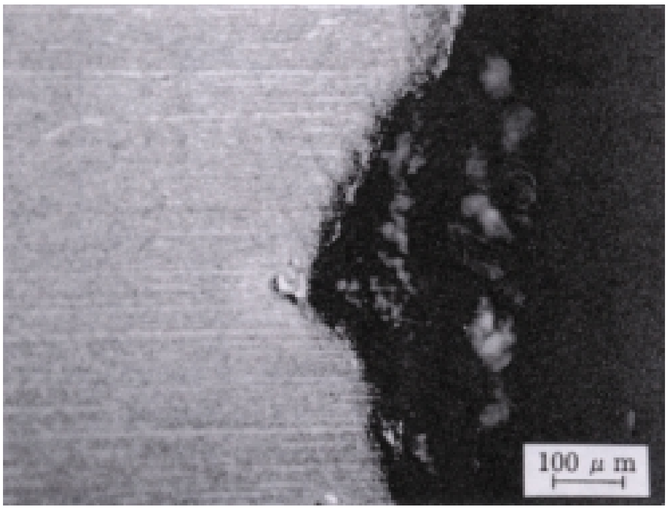


Photo 1 Surface condition of prematurely failed bearing

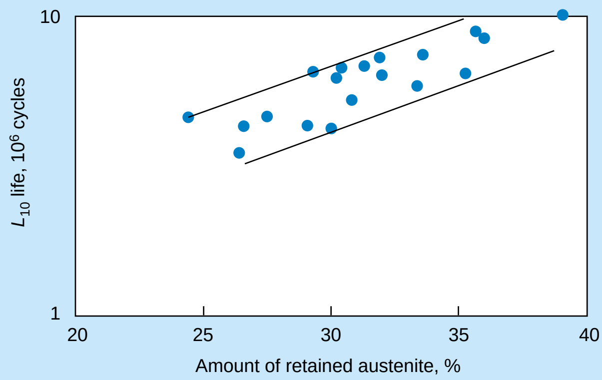


Fig. 5 Relationship between L_{10} life and the amount of retained austenite under contaminated lubrication

life, while in the case of surface-originated fatigue bearing life is often much shorter than the theoretical life. In order to improve bearing reliability in the market, it is necessary to develop a bearing steel with increased resistance to surface-originated fatigue.

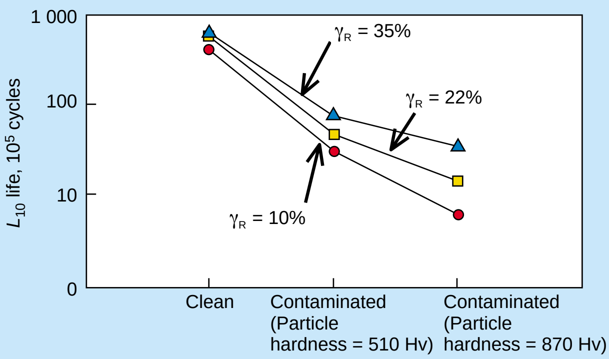


Fig. 6 Relationship between retained austenite content (γ_R), hardness of foreign particles and surface-originated fatigue life

3. Concept of New Bearing Steel

To develop a new steel with improved resistance to surface-originated fatigue and thereby improve the life of bearings operating under poor lubricating conditions, research was conducted on material factors and alloys.[7)]

In relation to material factors it was found that greater retained austenite content in the surface of the material improves resistance to surface-originated fatigue as shown in Fig. 5. Further studies on the relationship between material factors and bearing life under contaminated lubrication conditions revealed that increasing the amount of retained austenite was possibly the most effective way of suppressing premature failure from surface-originated fatigue. Fig. 6 shows the results of life tests carried out on bearings made from steel containing varying percentages of retained austenite. The results of the tests show that as the hardness of the foreign particles increases, bearing life decreases. However, the decrease becomes less pronounced as the amount of retained austenite increases.

Although high retained austenite content improves bearing life under surface-originated fatigue, it reduces the dimensional stability of the bearing. Therefore in the development of a bearing steel resistant to surface-originated fatigue, consideration was given to the dimensional stability of the bearing.

4. Alloy Design

For the purpose of developing a new bearing steel, a number of steels with various compositions were studied to determine the effect of different alloys on performance.

4.1 Improvement in surface-originated fatigue life

Increasing the amount of retained austenite improves resistance to surface-originated fatigue. In alloy design, therefore, steel compositions were formulated that would result in levels of retained austenite above those found in standard heat-treated AISI 52100.

Figs. 7 to 10 show the relation between the main alloying elements and the retained austenite content after hardening and tempering. All these steels were heat-treated in the same way as AISI 52100.

(1) C content

Fig. 7 shows the relation between carbon content and retained austenite. Under normal heat treatment conditions, the amount of retained austenite is closely related to the carbon content: the higher the carbon content, the higher the retained austenite content. However, when the carbon content is in excess of 0.7%, the retained austenite content increases only slightly.

(2) Si content

Fig. 8 shows the relation between Si content and retained austenite. Si has little effect on the level of retained austenite.

(3) Mn and Cr contents

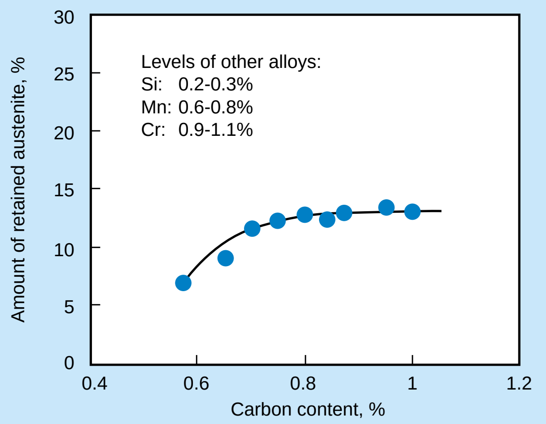


Fig. 7 Relationship between the amount of retained austenite and carbon content

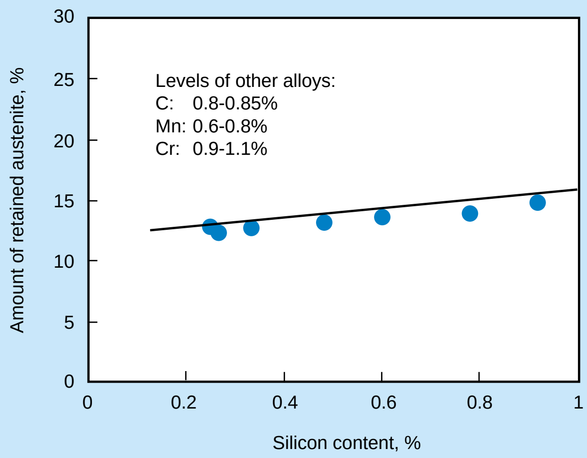


Fig. 8 Relationship between the amount of retained austenite and silicon content

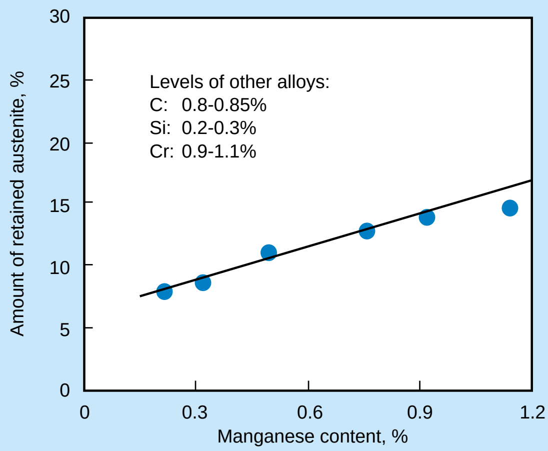


Fig. 9 Relationship between the amount of retained austenite and manganese content

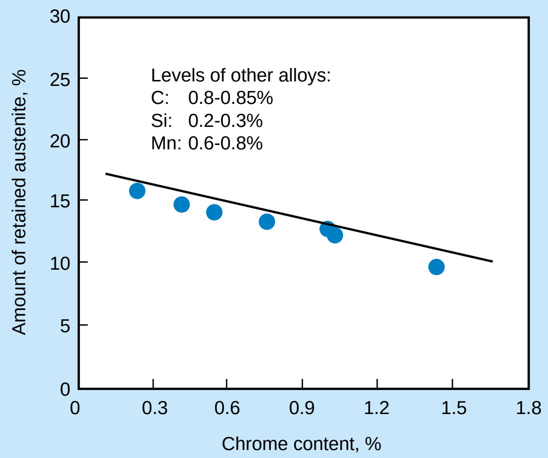


Fig. 10 Relationship between the amount of retained austenite and chrome content

The effects of Mn and Cr content on retained austenite are shown in Figs. 9 and 10, respectively. The higher the Mn content, the higher the retained austenite. Conversely, the higher the Cr content, the lower the retained austenite.

Figs. 11 to 14 show the relation between the alloy elements and bearing life under contaminated lubrication conditions, i.e., surface-originated fatigue. The bearings were tested on a flat-washer type test rig under the following conditions:

Pmax = 4 900 MPa

N = 3 000 cpm

Contaminants:

- Hardness: Hv 540
- Size: 74 - 147 μm
- Quantity: 300 ppm

The retained austenite content was nearly a constant when the carbon content was higher than 0.7%, while bearing life was nearly constant when the carbon content was higher than 0.8%. This indicates that a carbon content of greater than 0.8% is necessary to obtain good bearing life.

Si showed little effect on the retained austenite content, but as the Si content increased so did the bearing life. As to the effect of Mn and Cr on bearing life, the addition of Mn resulted in a higher retained austenite content and improved bearing life, while the addition of Cr led to a lower retained austenite content and a reduction in bearing life.

From these findings it was concluded that increased in C, Mn and Si content lengthens bearing life while, conversely, increased Cr content reduces bearing life.

4.2 Dimensional stability

Generally, the longer a bearing is either used or stored the more likely it is to undergo dimensional change due to the decomposition of its retained austenite. The degree of dimensional change depends on the amount of retained austenite that decomposes; the larger the amount of retained austenite that decomposes, the greater the dimensional change. On the other hand, high levels of retained austenite can be very beneficial to bearing life

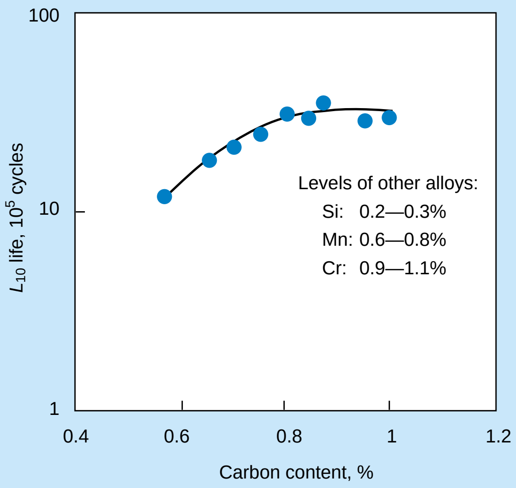


Fig. 11 Relationship between L_{10} life and carbon content under debris-contaminated lubrication

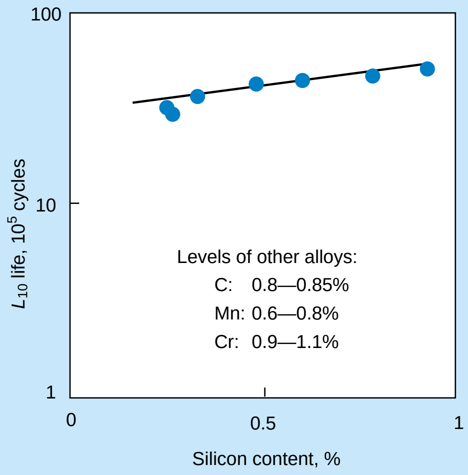


Fig. 12 Relationship between L_{10} life and silicon content under debris-contaminated lubrication

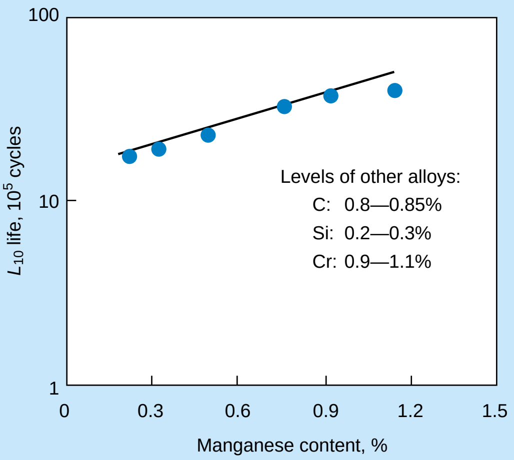


Fig. 13 Relationship between L_{10} life and manganese content under debris-contaminated lubrication

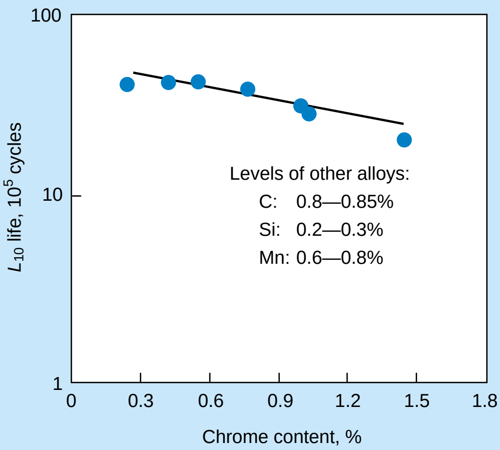


Fig. 14 Relationship between L_{10} life and chrome content under debris-contaminated lubrication

characteristics associated with surface-originated fatigue, as discussed earlier.

Although the amount of dimensional change is proportional to the retained austenite content, what is important is the decomposition rate of the retained austenite. In other words, dimensional change may not occur if the retained austenite does not decompose under the bearing operating conditions including especially the operating temperature. Si significantly affects the retained austenite decomposition rate. Fig. 15 shows the different decomposition rates of retained austenite in two steels with different Si content. As shown in the figure, the decomposition of retained austenite is retarded by increasing the Si content. In addition, an increase in the Si content also increases the resistance to softening during tempering and therefore maintains the hardness of the bearing when operated at high temperatures. Based on these findings, NSK developed NSJ2 steel with higher Si content, a lower rate of retained austenite decomposition and better heat resistance than AISI 52100 (Fig. 16).

4.3 Surface hardness

The analysis results shown in Figs. 7 to 14 indicate that the amount of retained austenite affects bearing life characteristics associated with surface-originated fatigue. On the other hand, bearing surface hardness must also be a consideration from the point of view of wear and indentation resistance.

The precipitation of carbides affects surface hardness. To increase the precipitation of carbides, carbide constituents such as C and Cr must be added to steel. This means that, in spite of the fact that the addition of Cr reduces the retained austenite content and degrades bearing life associated with surface-originated fatigue, a considerable amount of Cr must be added to develop sufficient surface hardness.

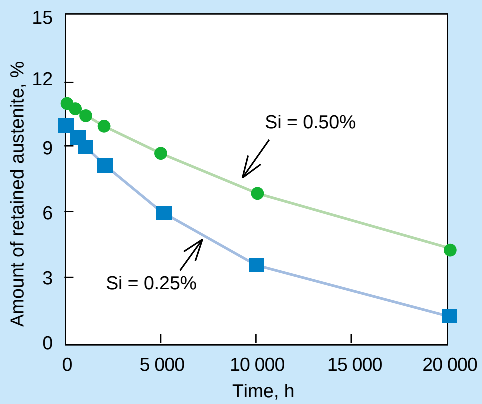


Fig. 15 Influence of silicon content on the retained austenite decomposition rate at 120°C

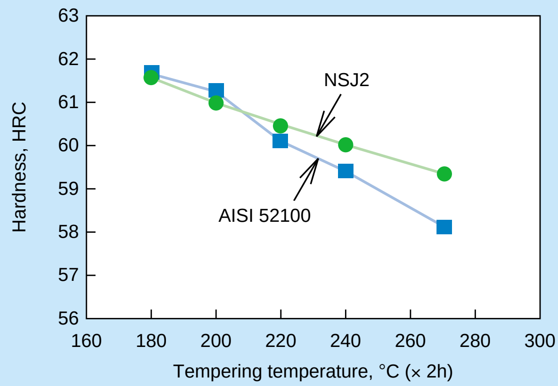


Fig. 16 Tempering resistance of NSJ2 and AISI 52100

4.4 Productivity

As part of developing a new bearing steel, it is not only necessary to consider the functional requirements as described in the previous sections but also the feasibility of manufacturing bearings in the steel. From this viewpoint, manufacturing-related properties like machinability, cold-workability, hardenability and grindability were examined.

5. Performance Evaluation of NSJ2 Bearing Steel

Based on the extensive research summarized in the foregoing, the composition of NSJ2 bearing steel was determined. Test bearings were manufactured and evaluated in a number of tests.

5.1 Life tests

Figs. 17, 18 and 19 show the results of life tests. The results in Fig. 17 show that the life characteristics of the NSJ2 bearings are similar to AISI 52100 bearings under clean lubrication conditions (i.e., subsurface-originated fatigue). However, as shown in Figs. 18 and 19, the NSJ2 bearings performed better than the AISI 52100 bearings under contaminated lubrication conditions (i.e., surface-originated fatigue).

5.2 Dimensional stability test

Fig. 20 shows the change in the dimensions of bearings at 100°C and 120°C. The NSJ2 bearings demonstrated better dimensional stability than the AISI 52100 bearings. This indicates that NSJ2 bearings have better dimensional stability than AISI 52100 bearings over the typical operating temperature range. This is because the retained austenite decomposes more slowly in the NSJ2 steel than in the AISI 52100 steel.

5.3 Wear and seizure resistance test

Fig. 21 shows the results of a Sawin wear resistance test. The results indicate that NSJ2 has similar wear and seizure resistance to AISI 52100.

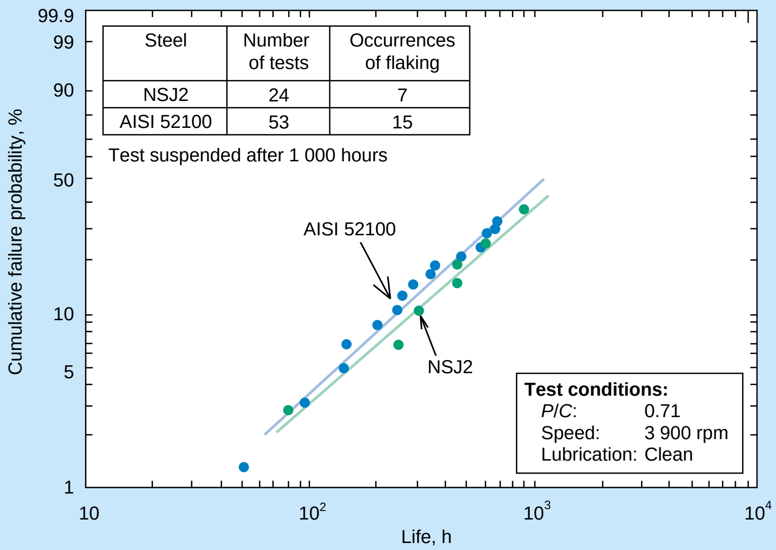


Fig. 17 Fatigue life under clean lubrication conditions of 6206 bearings made of NSJ2 and AISI 52100

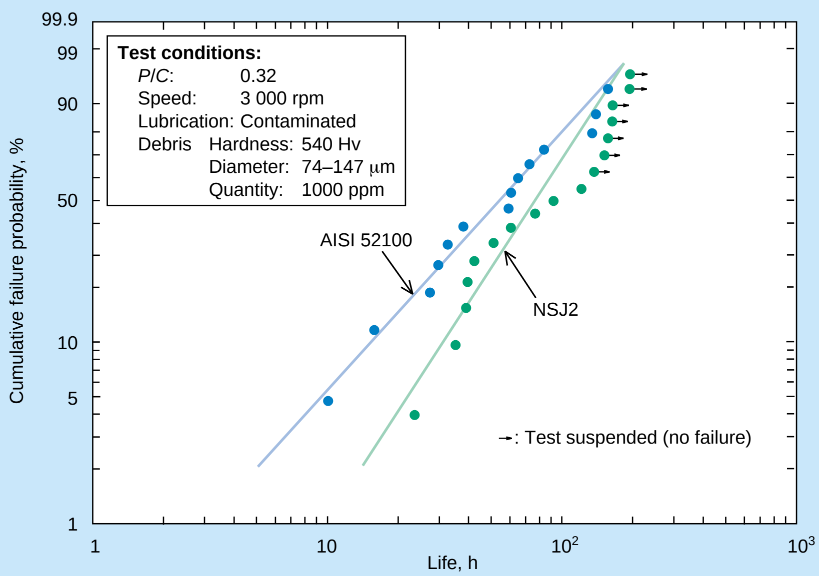


Fig. 18 Fatigue life under contaminated lubrication conditions of 6206 bearings made of NSJ2 and AISI 52100

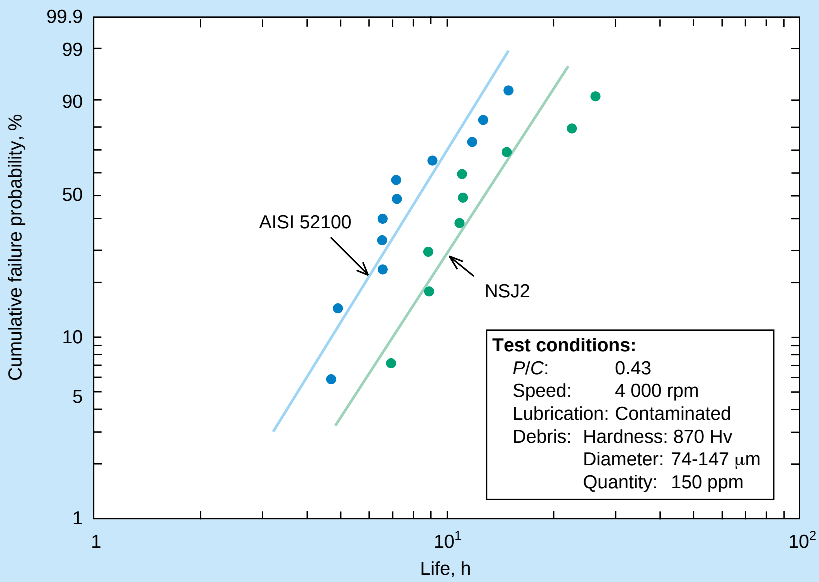


Fig. 19 Fatigue life under contaminated lubrication conditions of L44649/610 tapered roller bearings made of NSJ2 and AISI 52100

The results of the evaluation tests show that NSJ2 steel has greater resistance to surface-originated fatigue than existing AISI 52100 bearing steel. This is due to NSJ2's high level of retained austenite, which is achieved by careful control of its composition. This high level of retained austenite, however, compromises the dimensional stability of the bearing. Furthermore, the lower content of Cr, while necessary to ensure a high level of retained austenite, has an adverse effect on wear and seizure properties. To overcome these problems, silicon content is increased and Cr content is optimized. As a result, NSJ2 has similar dimensional stability and wear resistance to AISI 52100.

6. Conclusion

NSK has developed a new bearing steel, NSJ2, that improves the service life of bearings by minimizing premature failures. NSJ2 was developed based on the understanding that the majority of in-service premature bearing failures are due to surface-originated fatigue. The composition of NSJ2 is designed to promote higher retained austenite content, which improves bearing life under surface-originated fatigue. In testing, bearings made of NSJ2 demonstrated longer life than bearings made of AISI 52100 steel.

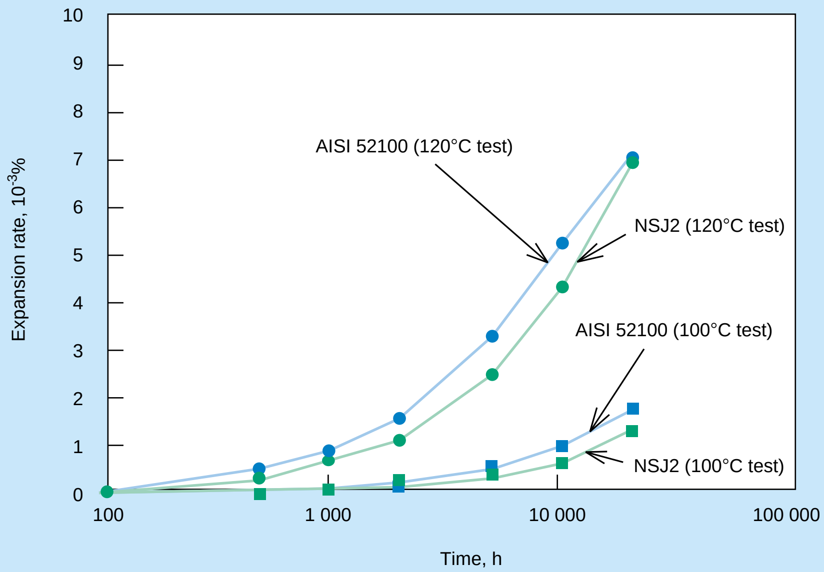


Fig. 20 Dimensional stability of outside diameter of 6206 bearings made of NSJ2 and AISI 52100

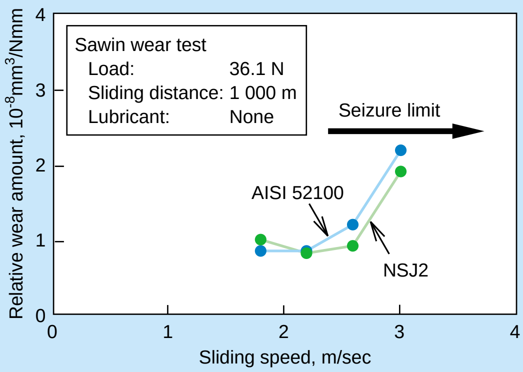


Fig. 21 Comparison of wear resistance of NSJ2 and AISI 52100l

References:

1) K. Furumura, S. Shirota and K. Hirakawa, "The Surface-initiated and Subsurface-initiated Rolling Contact Fatigue," NSK Bearing Journal No. 636 (1977) 1-10.
2) K. Furumura, Y. Murakami and T. Abe, "The Development of Bearing Steels for Long Life Rolling Bearings under Clean Lubrication and Contaminated Condition," NSK Technical Journal No. 656 (1993) 15-21.
3) T. Abe, H. Narai and K. Furumura, "EP Steel (A Superlong-Life, High Reliability Bearing Steel)," NSK Technical Journal No. 652 (1992) 1-8.
4) K. Furumura, S. Shirota and A. Fujii, "Fatigue Analysis of Rolling Bearings (Part 1) - Analysis of Surface Fatigue Damage (1) -," NSK Bearing Journal No.643 (1982) 1-10.
5) K. Furumura, S. Shirota and A. Fujii, "Fatigue Analysis of Rolling Bearings (Part 2) - Analysis of Surface Fatigue Damage (2) -," NSK Bearing Journal No.644 (1984) 1-6.
6) K. Furumura, S. Shirota and A. Fujii, "Fatigue Analysis of Rolling Bearings (Part 3) - Analysis of Subsurface-Fatigue Damage (1) -," NSK Technical Journal No.646 (1986) 18-25.
7) Y. Murakami, N. Mitamura and K. Furumura, "Long Life Super TF & Hi-TF Bearings under Severe Lubrication Conditions," NSK Technical Journal No. 652 (1992) 9-16.

Nobuaki Mitamura

Yasuo Murakami

NSK Linear Guides for High-Temperature Environments

The NSK linear guide has a history dating back more than 17 years. During this period, NSK has introduced many different products to meet the varied and expanding needs of the market. Examples of these include: the LY Series for machine tools, which require high accuracy and rigidity; the LA Series with enhanced capability of the LY Series; the LH Series with high load capacity and self-aligning performance for a wide range of applications; the compact and low-profile LS Series; the wide-rail LW Series; and the miniature LU, LE and LL Series.

Today, linear guides are often used in high-temperature environments such as in semiconductor and LCD manufacturing, glassware production, and welding machines on automobile assembly lines. To meet the particular challenges of these applications, NSK developed heat-resistant specifications for its linear guides and optional heat-resistant bellows to protect the linear guide rails (Photo 1).

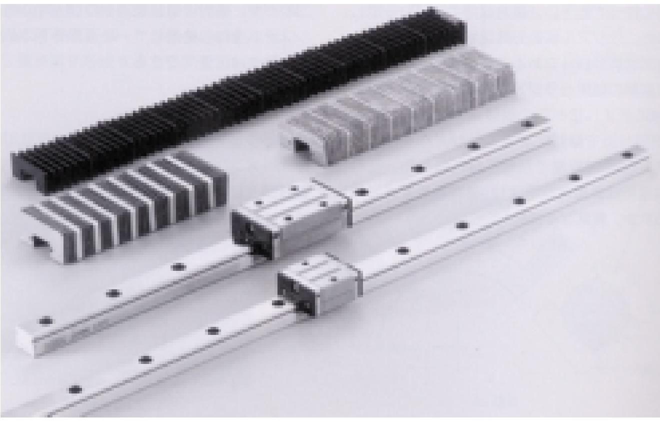


Photo 1 NSK Linear Guides and their bellows for high temperature

Features

■ Heat resistance

While standard NSK linear guides can be used at 80°C for continuous operation and 100°C for short periods, the new heat-resistant linear guides are serviceable at 150°C and 200°C for short periods.

■ Stainless steel material

Stainless steel not only provides high heat resistance, but also corrosion and chemical resistance and excellent performance in vacuum environments.

■ Optional heat-resistant bellows

With heat-resistant bellows, linear guides can be used in applications like welding equipment where high-temperature substances are spattered.

■ Variety of standard products available

A wide variety of standard products ensures broad applicability, short delivery times and low prices.

Specifications

Table 1 lists the types of heat-resistant NSK linear guides available. As indicated in the table, the products are made of either a combination of stainless steel and standard material or all stainless steel (excluding the seals) and are available in five series. As with the standard series, products suited to medium, high, and super-high loads are available. The dimensions of the heat-resistant linear guides are the same as the standard products. Please refer to the catalog, “NSK Precision Machine Components,” for more information. Models other than those in Table 1 are available upon request; contact NSK for details.

Table 2 and Fig. 1 show the special materials and components used in the heat-resistant linear guides. For the rail, ball slide and balls, either special high-carbon steel with high rolling contact fatigue strength or high-purity martensitic stainless steel is used. Fluororubber with high heat and chemical resistance is used for the seals while highly corrosion-resistant austenitic stainless steel is used for other parts. The lubricant is a high-temperature grease with a urea thickener and a synthetic base oil that has excellent oxidation stability and lubricity at high temperatures. For vacuum environments, all-stainless steel linear guides lubricated with special vacuum grease are available.

Table 1 NSK Linear Guide series and model numbers for high temperatures

Series	Model number	
	Standard specification	All-stainless steel specification (excluding seals)
LH (High load capacity, self-aligning type)	20, 25, 30, 35, 45, 55	20, 25, 30
LS (Compact, low height)	15, 20, 25, 30	15, 20, 25, 30
LW (Wide type)	17, 21, 27	
LU (Miniature)	09, 12, 15	09, 12, 15
LE (Miniature, wide type)		12, 15

Table 2 Material for specific components of NSK Linear Guides for high temperatures

Components	Standard specification	Stainless steel specification
Rail and ball slide	Special high-carbon steel	Martensitic stainless steel
Balls	AISI 52100	AISI 440C
End cap, components for ball re-circulation, and screws	Austenitic stainless steel	
Seals	Fluororubber	

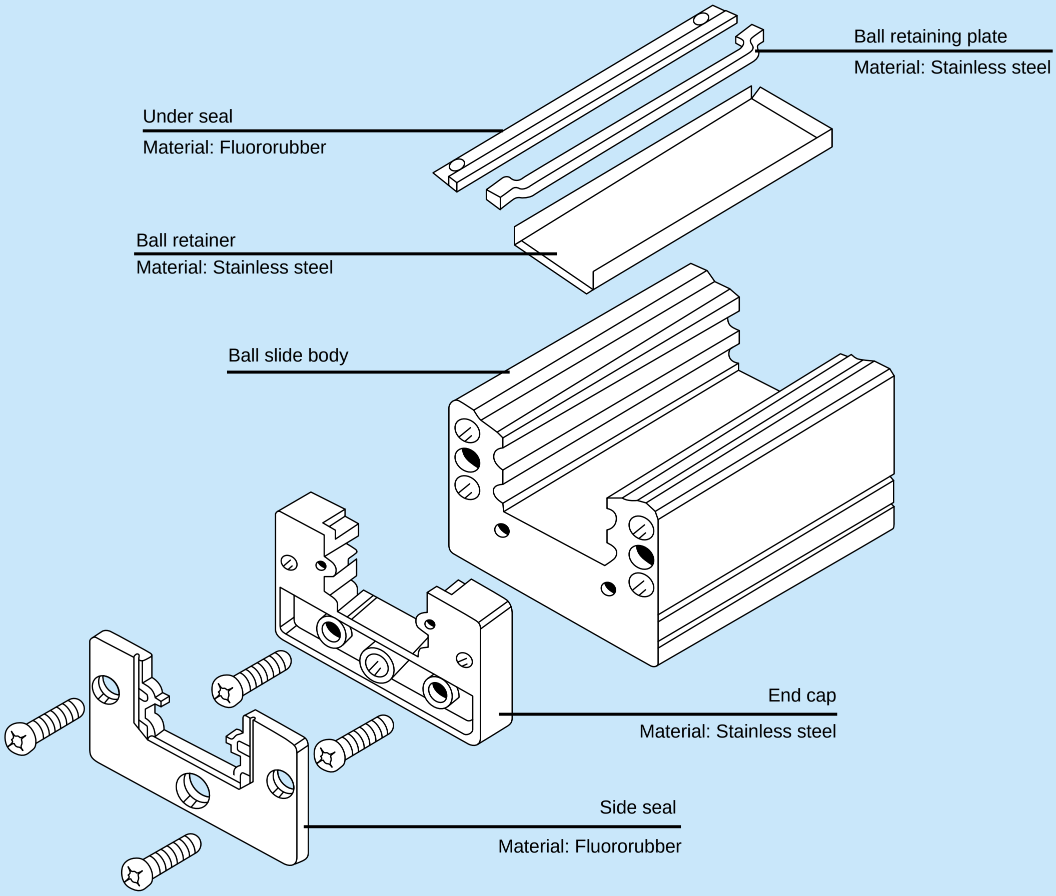


Fig. 1 Parts of NSK Linear Guide for high temperature

Applications

NSK's new heat-resistant linear guides are most suitable for high-temperature applications such as in the diffusion process of semiconductor manufacturing, and in welding machines, glass production equipment and steel mills. They can also be used in food and chemical processing where heat and corrosion resistance are required. The all-stainless steel products available have extremely low out-gassing and thus are ideal for vacuum environments.

Following are two examples of applications for heat-resistant NSK linear guides:

(1) Wire bonder (Fig. 2)

This machine connects lead frames and silicon chips with gold wires about 30 μm in diameter. An NSK linear guide is used to guide the heat block in this system. The standard heat-resistant series can be used continuously at a maximum of 150°C.

(2) SP Ring-8 (A synchrotron radiation facility located in Hyogo Prefecture, Japan; Fig. 3)

SP Ring-8 is an abbreviation of Super Photon Ring 8 GeV; it refers to the high-energy photons generated by this facility's 8-billion electron volt (8 GeV) storage ring. The facility is the world's most powerful third-generation

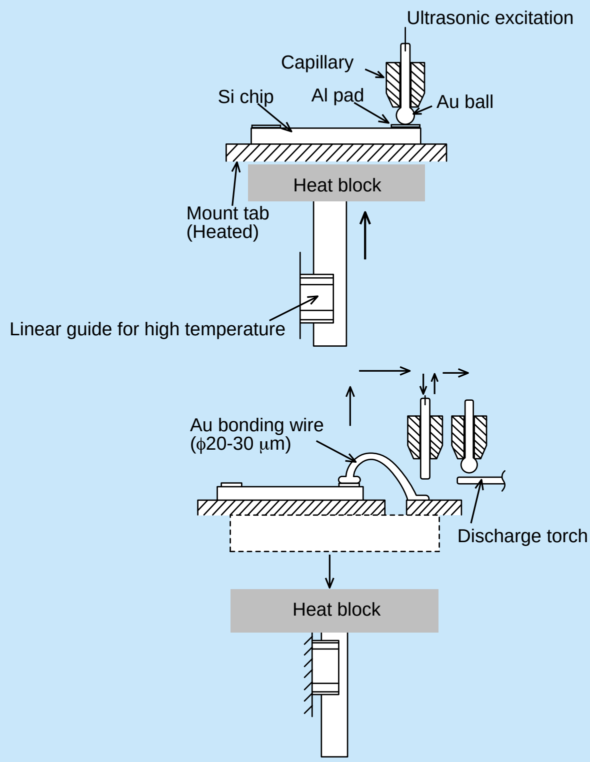


Fig. 2 Wire bonder

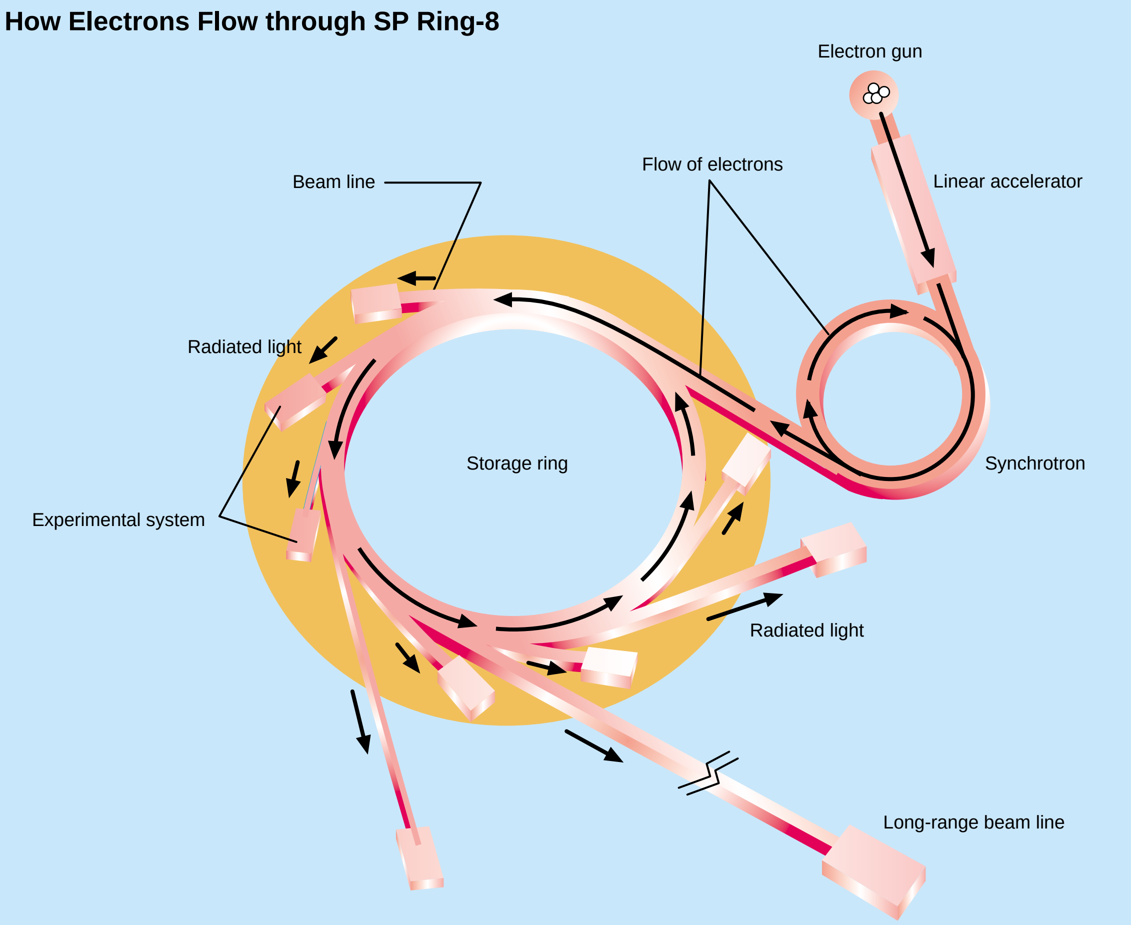


Fig. 3 SP Ring-8 (From: "SCLAS," October 1997, copyright Asahi Shimbun)

synchrotron radiation facility. It generates extremely intense ultraviolet and X-rays that are invaluable in basic and applied research in materials science and medicine. Electrons are first accelerated to 1 GeV (a unit of energy equal to that acquired by an electron when it is accelerated by one billion volts) by a linear accelerator, and then further accelerated to 8 GeV with a synchrotron that has a circumference of 396 m. Next, the electrons are stored in the storage ring (a circular accelerator with a circumference of 1 436 m) until their use in various experiments and research. All-stainless steel NSK linear guides are used as positioning mechanisms and mirror adjusting axes in the experimental and measuring systems that use the radiated light from the storage ring to the beam line whose end is connected to a particular experimental system. The linear guides operate in a vacuum environment of 1.33×10^{-4} Pa $\{10^{-6}$ Torr$\}$ or more.

Addendum

In addition to the new heat-resistant series, NSK produces linear guides for special environments including linear guides with special surface treatments to enhance corrosion resistance, and linear guides with NSK K1™ lubrication units for low maintenance and high resistance to foreign particle contamination. Also, we have recently developed the NSK S1 Series™. These new linear guides have a special resin retainer that separates the balls, thus significantly reducing operating noise and helping to ensure smooth, trouble-free performance. To keep pace with the constantly evolving needs of the market, research and development on linear guides is ongoing at NSK.

Press-Fitted Bearing Units for Swing Arms

In hard disk drives (HDDs), a pivot unit is used to support the swing arm on which the magnetic head is mounted. In order to facilitate the development of HDDs with higher speed, greater density and reduced size, pivot units must have higher stiffness and generate as little contamination as possible inside the disk drive. To meet these requirements, NSK has recently developed and begun mass-producing bearing units for which press fitting, rather than an adhesive, is used to fix miniature ball bearings to the shaft and housing. Photo 1 shows the new bearing units.

Photo 1 Press-fitted bearing units

Press Fitting vs. Fitting with Adhesive

Fig. 1 compares the new press-fitted design with the conventional design using an adhesive. With the conventional design, an adhesive is used to fix the miniature ball bearings to the shaft and housing, and preload is controlled by a deadweight or spring. This design presents three problems: potential variations in the bearing unit's resonance frequency (rigidity), the possible contamination of the disk drive by the adhesive, and limitations on developing compact designs. In contrast, press fitting is performed by a special machine, as shown in Fig. 1. The resonance frequency of the new press-fitted bearing units is controlled during assembly. Both the inner ring and the shaft are oscillated as the inner ring is inserted slowly onto the shaft until the resonance frequency, monitored by a sensor attached to an end of the housing, reaches a desired level. The insertion force can be controlled for each bearing on the shaft by means of a load cell attached to the shaft.

Features

■ Improved rigidity

For an HDD to have greater density and be capable of faster disk rotation, greater accuracy is required in the positioning performance of the pivot unit. To meet this requirement, the rigidity (resonance frequency) of the pivot for the swing arm is required to be constant. For the new press-fitted bearing units, the variation in resonance frequency (rigidity) is reduced because resonance frequency is controlled during assembly. Resonance frequency distributions of press-fitted bearing units and adhesive-bonded bearing units are compared in Fig. 2.

■ No contamination from adhesive

Because no adhesive is used, there is no risk of contamination from the adhesive causing the magnetic head to crash into the hard disk. This contributes to the overall reliability of the drive.

■ Miniature units also available

The smaller bearing units in Photo 1 are used for swing arms in HDDs with one-inch disks. In addition to personal computers, these HDDs are beginning to be used in high-definition, high-capacity digital cameras.

■ Removal force for inner ring totally controllable

In view of the relation between insertion and removal

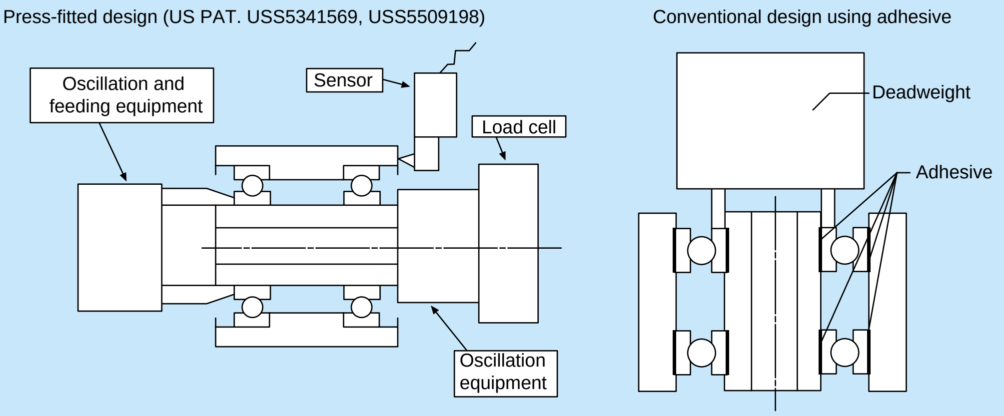


Fig. 1 Comparison of press-fitted and conventional designs

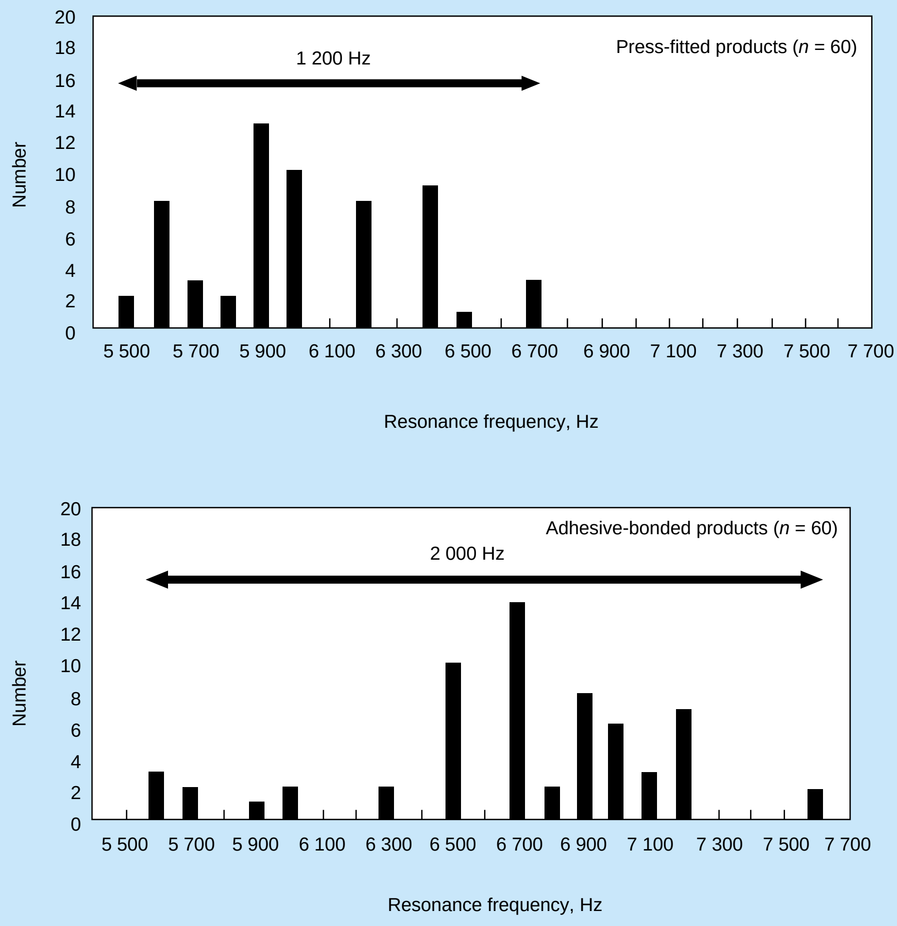


Fig. 2 Comparison of resonance frequency distributions

force of press-fitted bearings (Fig. 3), the control of the removal force for every bearing, while difficult for adhesive-bonded bearing units, is possible for press-fitted bearing units because inserting force is controlled during mounting.

Durability

■ Heat cycle endurance test

In a heat cycle endurance test in which test bearing units were exposed to six heat cycles (one cycle consisted of 24 hours at 70°C followed by 24 hours at 0°C), little change was observed in the resonance frequency of the press-fitted product (Fig. 4).

■ Oscillation endurance test

After 20 000 000 oscillations, the new bearing unit showed no change in resonance frequency.

Conclusion

In response to the need for higher-performance HDDs, we have developed press-fitted bearing units that are adhesive-free. Compared with adhesive-bonded bearing units, the new bearing units provide greater reliability and facilitate the development of faster, smaller HDDs with higher density. We expect them to be used extensively as pivot units for swing arms in HDDs.

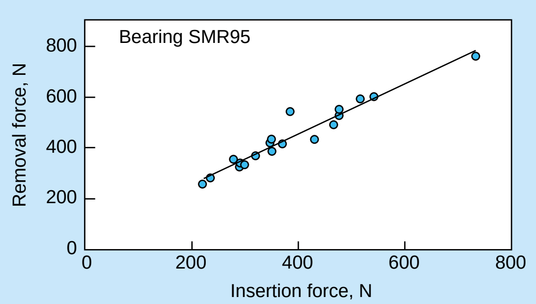


Fig. 3 Insertion force vs. removal force

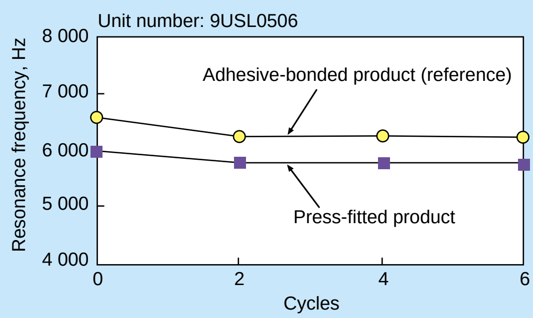


Fig. 4 Effect of heat cycles on resonance frequency