Development of Medium Carbon Bearing Steel Achieving Life Improvement and Resource Saving

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In recent years, the growing interest in protecting the global environment has given rise to a demand for saving resources in bearing manufacturing. In particular, a large amount of rare metals are added to the NiCrMo steel used to manufacture rolling bearings for industrial machinery and the like. If less rare metals were used, resource-saving could be achieved. Furthermore, if the replacement frequency could be decreased by extending the life of the bearing, even greater resources-saving could be achieved. Increasing the amount of retained austenite on the surface is known to be an effective method of extending bearing life and, in this study, we concluded that life can be further improved by controlling the stability of retained austenite. We have developed a new rolling bearing steel which enables both reduced rare metal usage and longer bearing life by controlling the quantity and stability of retained austenite.

Key Words*: rolling bearing, rolling contact fatigue, retained austenite, precipitate, resource-saving*

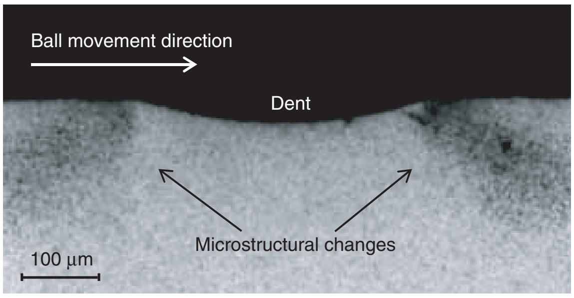
1. Introduction

High-strength steel is used for races and rolling elements that are major components of rolling bearings, as these are required to be capable of cyclic contact at a high surface pressure of several GPa. A steel typically used for races and rolling elements is high carbon chromium bearing steel subjected to a process of through hardening in order to harden the overall part. Meanwhile, regarding those applications which demand high impact resistance, case hardening steel is used to increase toughness, and this steel is subjected to surface-hardening processes such as carburized hardening or carbonitrized hardening, then used with the interior in a low-hardness state. If case hardening steel is to be used for large bearings, steel (nickel chromium molybdenum steel) containing many rare metals, such as nickel, chromium and molybdenum, is used in order to secure hardenability. In recent years, concern about protecting the global environment has been growing around the world, and there is lively action being taken by the steel industry to stop using so much rare metal in order to enhance steel properties through substitution with metals that can be easily refined and are available in an abundance on the planet. Even in regards to bearing steel, resource-saving could be achieved if it were possible to substitute nickel chromium molybdenum steel with a material containing minimal rare metals. Furthermore, if bearing life was extended, replacement frequency would be reduced, thus also contributing to resource-saving.

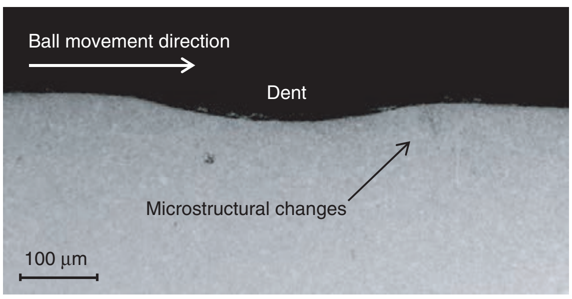
This report introduces the results of JTEKT's development of a bearing steel with reduced rare metal content and excellent life performance compared to conventional products, developed with the aim of shifting toward an environmentally-friendly society.

2. Approach to Improving Life

Failure of bearings caused by rolling contact fatigue (RCF) can be broadly divided into two types; sub-surface initiated spalling caused by non-metallic inclusions present in steel and surface initiated spalling caused by lubricant becoming contaminated with foreign matter or poor lubrication. Bearings made from nickel chromium molybdenum steel which has undergone surface-hardening are often used in industrial machinery such as construction machinery and steelmaking equipment. As such, improving a bearing's durability against not only sub-surface initiated spalling but also surface initiated spalling (dent initiated spalling) which originates from dents created when wear debris becomes trapped, would be effective in extending bearing life. Dent initiated spalling is caused by a mechanism of a dent forming in the race surface, stress becoming concentrated around the edges of this dent when the rolling element passes by and the microstructure becoming fatigued. Therefore, in order to improve bearing life by addressing dent initiated spalling, there is a need to increase microstructural fatigue strength, and one effective means of doing so is to increase the volume fraction of retained austenite (γ) of the surface[1]). **Figure 1** shows the cross-section microstructures of two ball bearing inner rings with equivalent hardness and different volume fraction of retained γ manufactured by adjusting materials and heat treatment, then artificially given dents and rolled for a certain period of time under identical conditions. For the inner ring with a high volume of retained γ in the surface, in the portion where stress is concentrated around the edge of the dent, microstructural fatigue is suppressed by the retained γ transforming into martensite through a process of strain-induced martensitic transformation. In this way, by increasing the volume fraction of retained γ, it is possible to increase bearing life relating to dent initiated spalling (**Fig. 2**). Furthermore, this technique is being applied to improve bearing life relating to sub-surface initiated spalling[2]). **Figure 3** shows the evaluation results for sub-surface initiated spalling life using a specimen in which the volume fraction of retained γ has been intentionally changed by adjusting materials and heat treatment. In this way, by increasing the volume fraction of retained γ of the zone affected by shear stress located directly under the rolling contact surface, which is where cracks initiate from, it is possible to promote strain-induced martensitic transformation during rolling, and improve bearing life. Bearing steel unavoidably contains non-metallic inclusions which cause sub-surface initiated spalling therefore in order to further improve the sub-surface initiated spalling life of high-cleanliness steel, utilizing retained γ is believed to be an effective method.



(a) Hardness 65HRC, retained γ=14%, 20 hours of operation



(b) Hardness 64HRC, retained γ=46%, 20 hours of operation

Fig. 1 Microstructural changes in the vicinity of the dent (Nital etching)[1])

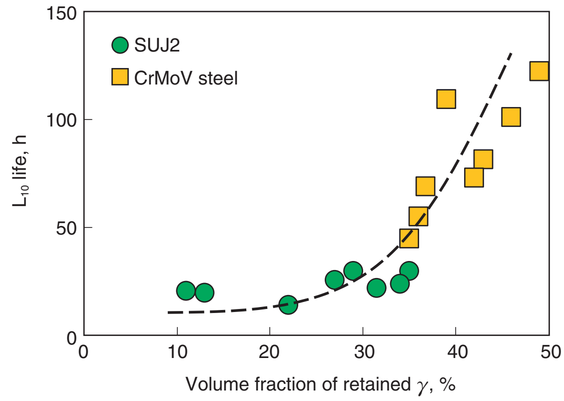


Fig. 2 Relationship between volume fraction of retained γ and dent-initiated spalling life[1])

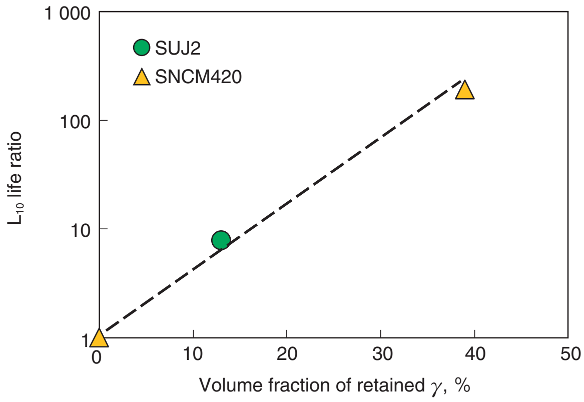


Fig. 3 Relationship between volume fraction of retained γ and sub-surface initiated spalling life[2])

As described above, it is possible to improve bearing life by utilizing the strain-induced martensitic transformation of retained γ, and this is the perspective which we applied to this steel development project. In this development, in order to achieve a life performance better than conventional products, we focused not only on the volume of retained γ, but also its stability, clarified the alloy components which are more likely to undergo the process of strain-induced martensitic transformation during rolling contact, and adjusted the components of the developed steel. Furthermore, increasing the volume of low hardness retained γ leads to reduced bearing hardness, therefore we incorporated a strengthening mechanism through nanoscale carbonitrides to achieve both a higher volume of retained γ and high hardness. Through these efforts, we succeeded in developing a steel that uses less rare metals overall than the typical nickel chromium molybdenum steel, which conforms to JIS-SNCM420.

3. Controlling the Stability of Retained γ Through Alloying Element Adjustment

3. 1 Concept

The stability of retained γ is closely related to alloying element content and an evaluation indicator of this is Ms temperature (martensite start temperature). If the content of each alloying element is expressed as a mass percentage (%), for example the experimental equation shown in Equation (1) below is proposed as the relationship between Ms temperature and the alloying element[3).]

$$Ms=550-361\times(\%C)-39\times(\%Mn)-35\times(\%V)-20\times(\%Cr)-17\times(\%Ni)-10\times(\%Cu)-5\times(\%Mo+\%W)+15\times(\%Co)+30\times(\%Al) \quad (1)$$

Higher Ms temperature means lower stability of the retained γ, making it more likely to transform into martensite. Most alloying elements in steel material have the effect of lowering Ms temperature. Therefore, in order to lower the stability of retained γ and promote the process of strain-induced martensitic transformation during rolling contact, it is preferable to add the barest minimal alloying element necessary to secure sufficient volume fraction of retained γ and prevent Ms temperature from dropping as much as possible.

3. 2 Evaluated Steels

In order to clarify the effect of alloying elements on the stability of retained γ, we prepared the five types of evaluated steels shown in **Table 1**. For the evaluation, we selected the typical alloying elements of bearing steel; namely Si, Cr, Mo, and V, which is formed from nanoscale carbonitrides, and adjusted the content of these in the evaluated steels. The types and amounts of alloying elements not written in the table are the same for all of the evaluated steels.

Table 1 Nominal composition of evaluated steel (mass %)

	Si	Cr	Mo	V
A	0.1	1.2	0	add.
B	0.1	1.2	add.	add.
C	0.1	1.2	0	much
D	0.1	1.5	0	add.
E	0.3	1.2	add.	add.

3. 3 Evaluation Method

We performed a twin-disc test to evaluate the stability of retained γ in relation to load. The test discs were made by turning each evaluated steel, subjecting these to heat treatment, then grinding to ultimately create a disc shape with an O.D. of 30mm and width of 8mm. The heat treatment adopted was carbonitrized hardening and tempering which involves distribution of a high amount of nanoscale carbonitrides and each of the test discs were given a volume fraction of retained γ of around 30% in order not to affect the stability of retained γ. **Table 2** shows the volume fraction of retained γ for the surface of each test disc measured using X-Ray Diffraction (XRD). As **Fig. 4** shows, each test disc was put in contact with a drive cylinder made by through hardening and tempering high carbon chromium bearing steel (JIS-SUJ2) (surface hardness: 750 HV) and rolled under the conditions shown in **Table 3**. The post-rolling volume fraction of retained γ of the surface was measured, and the stability of retained γ evaluated by calculating the reduction rate of retained γ using Equation (2).

$$\text{Retained } \gamma \text{ reduction rate} = \left(1-\frac{\text{Post-rolling volume fraction of retained } \gamma}{\text{Pre-rolling volume fraction of retained } \gamma}\right)\times 100,\ \% \quad (2)$$

Table 2 Volume fraction of retained γ in each steel type

A	37%
B	32%
C	30%
D	27%
E	27%

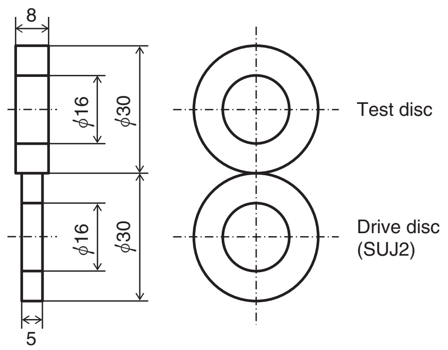


Fig. 4 Schematic of twin-disc test

Table 3 Twin-disc test conditions

Contact stress	1.5 GPa
Rotational speed	100 min^{-1} (drive disc)
Slip ratio	9.1%
Lubricant	ISO-VG8
Lubrication method	Dripped (2 mL/min)
Test duration	8 hours

3. 4 Evaluation Results

Figure 5 shows the reduction rate of retained γ in each steel type obtained through the experiment. For Steels A and B, even though there is no distinct different in reduction rate, there is a difference in the reduction rates with the other steels, therefore it is clear that the type of alloying element has an effect on the stability of retained γ. Here, if we sort out the effects of the alloying elements, we observe what is shown in **Table 4**. "↑" represents elements which increase the stability of retained γ, "↓" represents elements which decrease the stability of retained γ and "–" represents elements which have no effect. By comparing Steels A and B, we see that Mo has no effect on the stability of retained γ, by comparing Steels A, C and D, we see that V and Cr increase the stability of retained γ, and by comparing Steels B and E, we see that Si decreases the stability of retained γ.

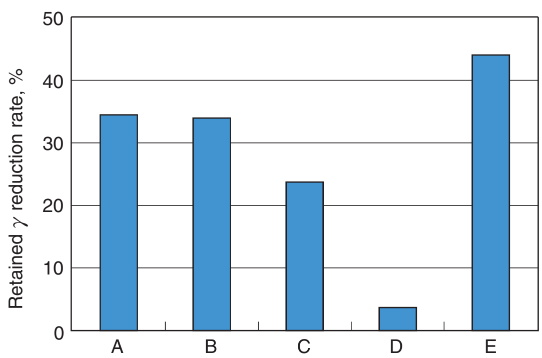


Fig. 5 Reduction rate of retained γ in each steel type

Table 4 Influence of alloy elements on retained γ stability

	Evaluation steel used for comparison	Effect on the stability of retained γ
Si	Steels B and E	↓
Cr	Steels A and D	↑
Mo	Steels A and B	–
V	Steels A and C	↑

The effects of Cr, Mo and V can be explained by the Ms temperature equation shown in Equation (1). In other words, Cr and V are the elements which majorly reduce Ms temperature therefore, by adding these, it is believed that retained γ is made more stable. Although the coefficient of V is larger than that of Cr, the stability of Steel C, which has an increased amount of V, is lower than that of Steel D, which has an increased amount of Cr, and this is believed to be due to carbonitrides forming easily through the carbonitrization of V, therefore reducing the content in retained γ. Furthermore, from Equation (1), it is believed that Mo slightly lowers Ms temperature therefore there was no obvious effect on the stability of retained γ.

Si is not included in Equation (1), therefore its effect on Ms temperature is unknown. However, unlike Cr, Mo and V, Si is known to be an element that increases carbon activity[4], therefore it is believed that when permeating the steel with carbon through the process of carbonitrization, compared to the other evaluated steels, there is less carbon content in the matrix. In other words, while the effect of Si itself is unknown, by adding Si, it is possible to reduce the post-carbonitrization carbon content compared to the other evaluated steels and this suppresses reduction of the Ms temperature, which is therefore believed to reduce the stability of retained γ.

From the above results, we understood that increasing the amount of Si, which reduces the stability of retained γ is an effective approach to encouraging the strain-induced martensitic transformation of retained γ during rolling contact and, ultimately, improving life.

4. Developed Steel for Long-life, Resource-saving Bearings

4. 1 Features of the Developed Steel

We determined the components of the developed steel based on the results of the preceding section. **Figure 6** shows the main alloying elements added to the developed steel and their respective roles. If the developed steel is used to make bearings, it undergoes a process of carbonitrized hardening and tempering in order to precipitate nanoscale carbonitrides. **Figure 7** shows the results of observing precipitates by using Transmission Electron Microscope (TEM). Primarily, the carbonitrides created from V and Cr are distributed evenly, and the size of these particles are around several tens of nm. Through the distribution of these fine precipitates, precipitation strengthening is achieved, and both a higher volume of retained γ and high hardness are achieved. Furthermore, the existing SNCM420 contains not only chromium and molybdenum, but also a high amount of nickel in order to secure the hardenability required for large bearings. In the case of the developed steel, however, rather than adding nickel, hardenability was compensated by using other elements, thus reducing the overall rare metal content by more than 20% and achieving resource-saving. By increasing the base material carbon content more than SNCM420 to the extent not to reduce impact resistance to create a medium carbon bearing steel, the time taken for the carbonitrization is reduced and less energy is required for heat treatment.

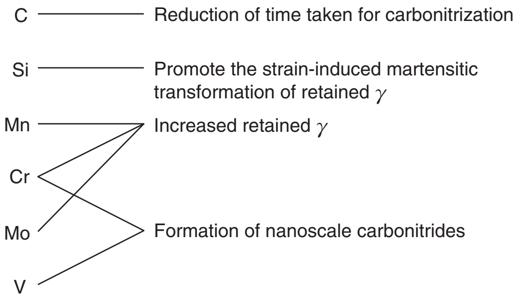
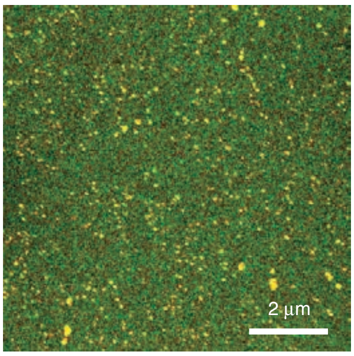
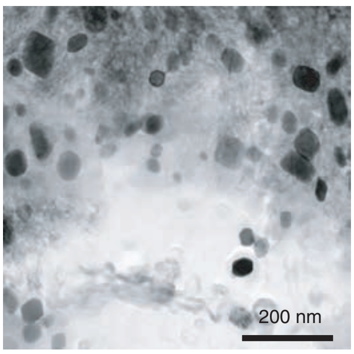


Fig. 6 Effects of alloy elements in the developed steel



Red : V
Green : Cr
Yellow : V+Cr

(a) Element analysis results using Energy Dispersive X-Ray Spectroscopy (EDS)



(b) Observation results using the extraction replica method

Fig. 7 Precipitate observation results

4.2 Life Performance of Bearings Made from Developed Steel

The dent initiated spalling life of a bearing made from the developed steel was evaluated under the conditions shown in **Table 5**. **Figure 8** shows the results of this evaluation. This bearing has a life over two times longer than a bearing made from SNCM420 that has undergone carburized hardening. This was accomplished by not only balancing an increased amount of retained γ and high hardness, but also by controlling the stability of retained γ.

Table 5 Life test conditions

Test bearing	30306D (O.D. 72mm, I.D. 30mm, assembled width 20.75mm)
Axial load	25.9 kN
Rotational speed	2 000min^{-1} (inner ring rotation)
Lubricant	85W-90 gear oil
Lubrication method	Oil bath
Contaminants	High-speed steel atomized powder (730 HV, 100 to 150 µm)
Consentration of contaminants	0.02 mass% (0.1g/500 mL)

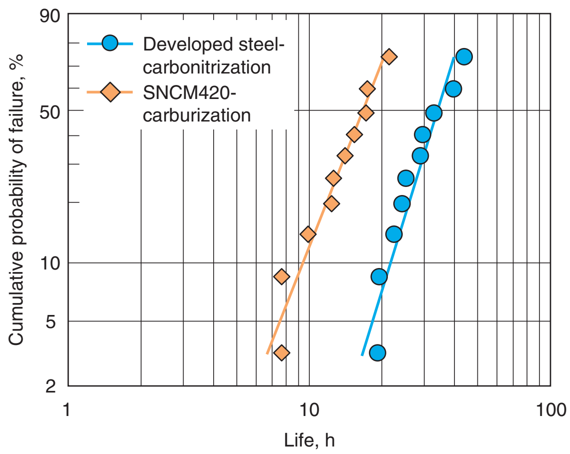


Fig. 8 Dent-initiated spalling life

4. 3 Basic Performances of Bearings Made from Developed Steel

In order to apply the developed steel to bearings, there are certain performance requirements other than life which must be satisfied. In particular, we evaluated the anti-brinelling and dimensional stability, as there was a concern these could be reduced with an increased volume of retained γ in the surface.

Anti-brinelling performance was evaluated by pressing a 3/8 inch steel ball into a flat plate at a predetermined load and measuring the depth of the resulting dent. The evaluation results are shown in **Fig. 9**. The developed steel has a greater amount of retained γ due to undergoing a process of carbonitrized hardening, however at the same time it achieves precipitation strengthening through nanoscale carbonitrides therefore it is apparent that the developed steel is capable of anti-brinelling performance equivalent to conventional steel that has undergone carburized hardening.

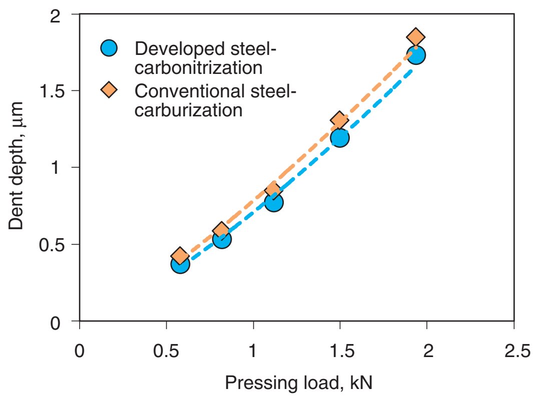


Fig. 9 Anti-brinelling test results

Dimensional stability was evaluated by press-fitting a round bar with dimensions that make hoop stress equal 90 MPa into the bearing's inner ring then holding for a set period of time at an ambient temperature of 120℃, removing the round bar and measuring the dimensional change rate of the inner diameter compared to the start. The evaluation results are shown in **Fig. 10**. The surface of the developed steel subjected to carbonitrized hardening has a high amount of thermally-unstable retained γ, however by turning it into medium carbon bearing steel, the internal volume fraction of retained γ is reduced and a dimensional stability equivalent to the carburized hardening of conventional steel is obtained.

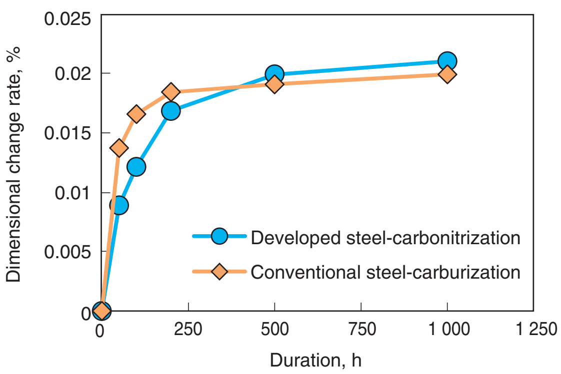


Fig. 10 Dimensional stability test results

5. Conclusion

Through precipitation strengthening with nanoscale carbonitrides and incorporating the new method of controlling the stability of retained γ, we succeeded at developing a bearing steel with superior life performance compared to conventional products. This developed steel, in terms of properties other than life performance also, has performance equivalent to standard carburized bearings, therefore can be applied to any application, however can contribute to resource-saving particularly when used in bearings for industrial machinery as an alternative to SNCM420 and other nickel chromium molybdenum steel.

6. Special Thanks

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