In the 1970's, ladle furnace process and continuous casting process were established, and as a result, the oxygen content in steel was further reduced. The oxygen content continued to decrease and is now as low as 5 ppm. The effect of these technologies will be apparent from the result of rolling contact fatigue test with specimens plotted in Fig. 2 which shows correlation between the years of steel manufacture and rolling contact fatigue life.

The focus of this paper is the review of past, current, and future trends regarding steel used for rolling bearings, steel making, and heat treatment technologies. The improvement of steel purity and the development of new steels have been conducted mainly with steel manufacturers so far.

Considering the issues related to globalization, the environment, raw materials such as rare metals, and safety, the future focus will be on surface modification technologies and the coordination of each elemental technology.
Trends in Materials and Heat Treatments for Rolling Bearings

The lives of test steel specimens.

The lives of the present-day specimens are more than 10 times longer than those from 1964. However, no significantly novel steel-making technologies have been introduced since 2000, and the increase in rolling contact fatigue life of bearings has already leveled out. Incidentally, in 1964, the rolling contact fatigue life of carburizing steel (SCr420) was about twice as long as that of bearing steel (SUJ2). The fatigue life difference continued to decrease and by 1990 the carburizing grade material no longer had an advantage for fatigue life.

2.2 Advance in assessment technologies for effects of non-metallic inclusions

As mentioned above, the history of bearing steel has been a history of efforts for decreasing inclusions, and as a result, technologies for making highly clean steels have shown significant improvements. Now, let us think of assessment technologies for evaluating effects of non-metallic inclusions. The most common assessment techniques for non-metallic inclusions among conventional methods are the point count method per JIS (Japanese Industrial Standards) and ASTM-A method for indicating worst visual field. However, owing to dramatic advance in steel making technologies, these assessment techniques are no longer capable of accurately differentiating between steel materials. Since the latter half of the 1980’s, new assessment techniques have been introduced which focus into the numbers, sizes and distributions of inclusions. Typical examples of such techniques include extreme value statistics, electron beam melting process, ultrasonic method, and a method where material is electrolyzed, resultant solution is subjected to filtration and the filtration

![Fig. 1](image1.png) The trend of oxygen content in steel

![Fig. 2](image2.png) The trend of rolling contact fatigue life of 12mm in diameter specimen
residue is analyzed\(^6\). Despite these efforts, we are still not able to estimate the rolling contact fatigue life of a given steel material based on an assessment of the inclusions contained in it.

Utilizing its unique knowledge about image analysis, NTN has successfully developed a unique system that automatically determines the sizes and types of all the inclusions in a given steel material. By using this system, NTN has been developing technologies for quantifying the physical properties of inclusions contained in a given rolling bearing material and estimating the rolling contact fatigue life of this material\(^7\)\(^8\).

Typical examples of the interrelation between rolling contact fatigue lives estimated based on measured inclusion ratings and actual rolling contact fatigue lives is graphically plotted in Fig. 3. Thanks to these new assessment techniques, it is now possible to adopt a simplified rolling contact life test for a steel material and promptly assess the quality of the material in question.

Furthermore, there is a recent attempt\(^9\) to analyze inclusions occurring on the fisheye fracture appearance on specimens undergone test using an ultrasonic fatigue tester that is capable of high speed at 20 kHz (fatigue test is completed in a very short test run as short as about 10 minutes) in order to assess the quality of specimens. It is said that the volume of specimen possibly treated with this technique can be larger compared with that with microscopic examination and this technique is capable of examining much larger inclusions. However, owing to variation in the state of bonding between inclusions and the base surface, the inclusions detected with this technique somewhat differs from specimen to specimen. Also, for this technique, correlation between inclusions and rolling contact fatigue life of steel material will need to be clarified in the future.

2.3 Rolling contact fatigue life and chemical components

Various researches\(^10\)\(^11\) are so far available as to the effects of alloy elements onto rolling contact fatigue lives of steels. Efforts for these studies were very active in a period from the latter half of the 1980’s to 1990’s. This is because during this period it became possible to further clarify the effects of alloy elements in highly clean steels. At the same time, various manufacturers strenuously developed bearing materials each optimized for a particular application while bearing operating conditions were becoming more demanding.

The alloy elements possibly affecting rolling contact life of bearing include Si, Mn, Ni, Cr, Mo and V. However, for convenience, discussion here is made taking Si as an example because this elemental additive is relatively cheap and is very effective.

As summarized in Table 1, the rolling contact fatigue life is longer with a greater Si content. This is because addition of Si improves the resistance to temper softening for the steel material. Using this

<table>
<thead>
<tr>
<th>Steel</th>
<th>Chemical component (%)</th>
<th>10% life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>Suj 2</td>
<td>0.97</td>
<td>0.31</td>
</tr>
<tr>
<td>A</td>
<td>1.02</td>
<td>1.01</td>
</tr>
<tr>
<td>B</td>
<td>0.96</td>
<td>1.30</td>
</tr>
<tr>
<td>C</td>
<td>1.00</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Fig. 3 The comparison of rolling contact fatigue life and estimated life based on inclusion rating
advantage of Si, NTJ2 material as semi-high temperature material and STJ2 were developed. Other bearing manufacturers developed similar steel materials having a higher Si content; however, these materials have Mo additive which is an expensive alloy element.

Novel longer life application specific bearing materials have been developed. At the same time, novel materials featuring optimal machinability have also been developed. Consequently, NTN has successfully commercialized NKJ65 material based on medium carbon steel and utilizing the above-mentioned advantage of utilizing Si.

Global demand for raw materials has been accelerating since the beginning of the 21st century resulting in skyrocketing prices and reduced availability of resources including coke and rare metals.

3. Life-extending efforts through improvement in heat-treatment techniques

The basic requirements for bearing materials are longer lives, good wear resistance and higher dimensional stability. Various heat-treatment techniques have been developed to obtain bearing materials that satisfy these requirements.

3.1 Effects of retained austenite

A quenched high-carbon chromium bearing steel contains retained austenite in a range of several % to 15%, though this percentage can vary depending on the heating temperature before quenching. Because retained austenite is essentially a soft, unstable structure, it has been believed that too much retained austenite in a bearing steel material will cause the material to be less hard and more wear-prone as well as lead to greater deformation from aging (in other words, poorer dimensional stability). Therefore, people believed that a lower retained austenite content is favorable.

In contrast, ever since it was learned that retained austenite can help extend rolling contact fatigue lives of bearing steel materials, heat-treatment techniques positively utilizing retained austenite have been adopted in applications aiming at longer bearing life, in particular, applications intended to extend bearing lives in a contaminated oil-lubrication environment, thereby NTN has developed the TMB bearing products by utilizing these techniques.

As discussed earlier, the rolling contact fatigue life with highly inclusion-free carburizing steel is roughly equivalent to that with highly inclusion-free bearing steel (Fig. 2), and, therefore, the effect of retained austenite is less apparent. Nevertheless, if bearings are used under contaminated oil lubrication, the effect of retained austenite is still apparent as shown in Fig. 4. To summarize, retained austenite is an important material factor for longer bearing life.

3.2 Carbonitriding process

In carbonitriding process, propane or butane is fired to generate reformed carburizing gas into which 5-15% of ammonia gas is added, thereby in the so-formed atmosphere, C and N are allowed to simultaneously enter and get diffused in a bearing steel material.

Nitrogen diffused in the surface layer stabilizes retained austenite. Consequently, the amount of retained austenite is greater after quenching, and, at the same time, the solution of nitrogen helps enhance resistance to temper softening, thereby the rolling contact fatigue life of bearing steel is extended. This process is identical to the multi-stressing process Fig. 4

![Fig. 4 Relationship between retained austenite and rolling contact fatigue life](image)
disclosed in USA in 1964, and has been positively employed as a special heat treatment technique by various Japanese bearing manufacturers since the beginning of the 1990’s.

In Fig. 5, rolling contact fatigue lives of various bearing materials, to which this process was applied, are graphically plotted, wherein each steel species exhibits extended life owing to carbonitriding process. NTN calls this process the AS (Austenite Strengthening) treatment, and has been adopted for long-life bearings. NTN believes that a carbonitriding process will remain used to extend bearing life.

3.3 Crystal grain refinement process

As described above, the technologies for longer bearing life so far attempted use effects of either retained austenite or nitrogen-derived enhanced resistance to temper softening. In addition to these longer bearing life-endowing material factors, a new technology has been developed since the year 2000, wherein the new technology features adoption of a novel longer bearing life-endowing factor that is based on crystal grain refining technique. This new technique is the NTN’s unique FA treatment (Fine AS treatment). Though researches for obtaining higher-strength structural steel materials through enhanced crystal grain refinement were encouraged by the Japan’s national super steel material research project, NTN is the very first bearing manufacturer who positively adopted increased crystal grain refinement for bearings that are highly hard mechanical members. This FA treatment is a complex heat-treatment technique comprising grain refinement featuring crystal grain size less than 1/2 (see Fig. 6) compared with that obtained from conventional quenching technique as well as a carbonitriding process.

By combining two techniques, NTN has attempted
to further extend rolling contact fatigue life of its bearing (see Fig. 2). This heat-treatment technique is suitable for attaining longer rolling contact fatigue life with general-purpose bearing steel. Such a heat-treatment technique will be more commonly used.

4. Future challenges

4.1 Development of novel materials

As a material assessing technique develops, the performance of subject materials will further improve. This is also true in the field of bearing technology. Much progress has been made in the various assessment and analysis techniques related to bearings. Typical examples of such techniques include microspace assessment technology, surface analysis technology, analysis technique, and simulation technique. NTN expects that these novel tools help us attain new knowledge and technologies such that we can now view nano-structures where in the past the minimum-possible were micro-structures. In the field of steel-making, the oxygen content in steel has already reached lowest practical level, and further bearing life extension in this aspect seems to be virtually impossible.

Despite this, we hope that further improvement in bearing life is realized through researches into bonding between inclusions and base surface and into techniques to turn inclusions harmless by modification of inclusions.

In the aspect of bearing material development, there will remain two long-lasting approaches: one approach is an attempt to seek highly functional materials and the other approach is placement of heaviest importance onto cost-performance. NTN believes that the latter approach in particular requires more strenuous utilization of surface modification technology. More specifically, in an extreme case, it is important with a rolling bearing to modify the surface area in a depth of 1 to 2 mm (can vary depending on the bearing size) where Hertzian contact pressure is applied, and it is not necessary to enhance the hole bulk of the bearing.

Though details are not presented in this report owing to space limitation, flaking (brittle flaking) accompanying a white etching structure such as one shown in Fig. 7 can still occur in limited situations. Previously this brittle flaking was explained by the stress field theory, hydrogen embrittlement theory or vibration theory. However, recently, the most widely accepted explanation is tribochemical reaction-derived hydrogen embrittlement. These flaking modes previously occurred only under operating conditions associated with severe lubricating conditions such as those in alternator bearing applications. Bearing operating conditions are becoming increasingly severe, and at the same time, the requirements for lubrication become more demanding. There are also new examples of brittle flaking occurring in less demanding applications where low viscosity oils are used for reduced torque.

Therefore, though attempts have been so far made to prevent this problem by using improved lubricants, we will implement comprehensive countermeasures against this problem, and such countermeasures will include improvements in heat-treatment technique, surface modification technique and bearing design.

4.2 About heat-treatment technologies

Commonly applied heat-treatment technologies for bearing steel are atmospheric heat hardening, gas carburizing hardening and induction hardening. Recently, the price of crude oil has been soaring and, at the same time, environmental issues (such as reduction in CO2 emission to help prevent global warming) as well as problems associated with work environment and labor safety have been increasingly highlighted. These issues are important challenges closely related with heat-treatment process.

In this context, we expect particular carburizing process will be more commonly utilized. Examples of such process include carburizing process based on nitrogen gas, where reforming gas generated from propane or butane and used for atmospheric heating and carburizing is not used; vacuum carburizing process; plasma carbo-nitriding; high-temperature carburizing for reducing process time. Table 2, presented for providing additional information, summarizes features of various carburizing processes.

Incidentally, use of quenching oil (coolant) is disadvantageous in terms of safety and work environment of hardening operation. NTN believes that a positive attempt will be made to supersede oil
hardening, which is currently employed, with air hardening, cooling with pressurized gas or water-soluble coolant.

Induction heating technique is said to be advantageous in reducing CO2 emission, and an ultra-rapid short-time induction hardening technique has been sometimes used on a commercial basis in manufacturing gears. Induction hardening techniques are very often used in manufacturing automotive bearing components, and this trend will be more common. Simulation techniques for induction hardening have shown much progress. In addition, a unique control technique for induction hardening process, known as feedback control-based induction hardening technique has been developed.

According to this technique, a product is heated while its temperature is being monitored; the austenitic state of the material in quenching is calculated, thereby the quenching timing as well as the tempering hardness are calculated, estimated and controlled by the computer. These new techniques will be eventually adopted.

Furthermore, dramatic advancements in sensor technologies, analysis techniques and simulation techniques applicable to heat-treatment process have recently developed. NTN believes that a heat-treatment process, more positively utilizing these techniques and capable of more active control, will show much more advance.

### Table. 2 The comparison of various carburizing process

<table>
<thead>
<tr>
<th>Item</th>
<th>Plasma carburizing</th>
<th>Vacuum carburizing</th>
<th>Gas carburizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presence/absence of abnormal layer</td>
<td>Absent</td>
<td>Absent</td>
<td>Present</td>
</tr>
<tr>
<td>Cleanliness of surface</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Surface hardness</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Carburizing on porous area</td>
<td>Good</td>
<td>Good</td>
<td>Difficult</td>
</tr>
<tr>
<td>Operating environment</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Medium</td>
</tr>
<tr>
<td>Working energy</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Amount of gas consumed</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

5. Conclusion

The achievements so far attained in the field of materials for rolling bearing and associated heat-treatment techniques have been described above. These achievements are primarily contributable to developments in material engineering and material assessment techniques supported by steel manufacturers. Typical results of the efforts by steel manufacturers include development of highly clean steel materials containing minimal non-metallic inclusions as well as development of special steel material with varying alloy components. The future challenges in our research and development efforts will fall in two fields: development of ultimate material and research R&D efforts thoroughly centered onto cost-performance. In particular, in the cost-performance aspect, material engineers at any bearing manufacturer will need to fulfill required bearing functions even when using a general-purpose material. To this end, it will be increasingly more important, not only to develop more sophisticated elemental technologies including materials, heat-treatment techniques, surface modification techniques (by heat treatment as well as by processing, powder technology and surface coating) and lubrication techniques but also to attempt to realize integration and collaboration with individual technologies.
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