Ultra-low Sulfur Non-oriented Electrical Steel Sheets for Highly Efficient Motors: NKB-CORE

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A new type of non-oriented electrical steel sheet, NKB-CORE, has been developed by NKK through the application of a unique ultra-low sulfur technology. This type of steel sheet shows: (1) low hysteresis loss; (2) high magnetic flux density; (3) excellent punching property, and (4) low production cost. The low core loss was obtained by reducing the sulfur content in steel and suppressing surface nitriding. The high magnetic flux density was obtained by reducing silicon and aluminum content. This paper describes the material design of NKB-CORE, and presents the application of this material to motors for electric power steering systems for automobiles.

1. Introduction

An electric motor is a device which converts electrical energy to mechanical energy, and is used extensively in daily life for driving air-conditioners, refrigerators, vacuum cleaners, CD-ROM drives, just to mention a few of an almost infinite number of applications. The efficiency in electric power consumption by these appliances is almost unilaterally determined by the electric motor's performance. Recently, in the automotive field, high-efficiency motors have been extensively employed for driving HEV (Hybrid Electric Vehicles) and electric power steering systems[1),2)].

Non-oriented electrical steel sheets are used as the core material for such high-efficiency motors. The non-oriented electrical steel sheet is a key material that transmits magnetic energy thus affecting the efficiency of electric motors, and is highly desirable in terms of achieving both low core loss and high magnetic flux density. The traditional method of achieving low core loss was to add Si and Al to the steel and reduce the eddy current loss in the electrical steel sheets that form the motor core. However, there are important drawbacks to this method. First, the magnetic flux density declines[3)]. Second, the hardness increases and consequently the punching property suffers. In contrast, lowering hysteresis loss by high purification technology does not lower magnetic flux density nor affects the hardness. This is the preferred method for achieving low core loss.

Conventionally, efforts have been made to reduce the contents of elements such as oxygen, nitrogen, and sulfur at the stage of steelmaking in order to produce purified steel[4),5)]. With regard to the sulfur content, recent remarkable advances in steelmaking technologies have made it easier to produce ultra-low sulfur steel that contains sulfur at less than 10 ppm, a level hitherto difficult to achieve. Against this background, detailed investigations were made on the magnetic properties of ultra-low sulfur steel (S<10 ppm). Based on the findings obtained through these investigations, a new type of ultra-low sulfur electrical steel sheet was developed for the manufacture of highly energy efficient motors.

2. Effect of sulfur content on magnetic properties of steel

2.1 Experimental method

In order to study the effect of extremely low sulfur content on the improvement of magnetic properties, steel samples with specific chemical compositions, shown in **Table 1**, were prepared by vacuum melting, and cast into ingots. These ingots were soaked at 1200℃ for one hour and hot-rolled into 2.3 mm thick sheets. After pickling, these hot-rolled sheets were annealed at 830℃ for three hours in a pure hydrogen atmosphere. Thereafter, these sheets were cold-rolled into 0.50 mm thick sheets, which were then subjected to final annealing at temperatures of 850-1050℃ for 2 min in an atmosphere of 10%H_2 - 90%

N_2. The magnetic properties of steel sheets processed in this manner were measured by a single-sheet tester at 50 Hz and 60 Hz. Loss separation was performed by applying the two-frequency method.

The cross-sectional microstructures of the steel sheets were observed under an optical microscope. The portions near the surfaces of these steel sheets were closely examined by a SEM (Scanning Electron Microscope). To determine the amount of nitrides contained in the surface portion, the content of N that was present as AlN was determined by electrolytic extraction at depth intervals of 30 μm from the sheet surface. Auger electron spectrometry was applied to investigate the segregation of elements in the surface portion.

Table 1 Chemical composition of sample steels

(Unit: mass %)

No.	Si	Mn	Al	S	N	Fe
1	2.63	0.18	0.27	0.0004	0.0020	bal.
2	2.75	0.22	0.30	0.0032	0.0019	bal.
3	2.73	0.22	0.30	0.0054	0.0019	bal.

2.2 Results of the experiment and discussion

Fig.1 shows the relationship between the sulfur content and ferrite grain size after final annealing. The grain size was measured based on the JIS G 0552 method by polishing the central portion of the thickness of the sheets. It is noted that the grain growth is markedly improved over that of conventional materials (S content 30 to 50 ppm) by lowering the sulfur content to 4 ppm. This is because the MnS content, which inhibits grain growth, is lowered by reducing the sulfur content.

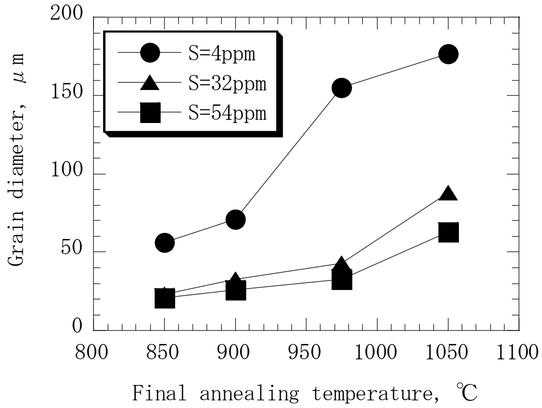

Fig.1 Relationship between sulfur content and ferrite grain size after final annealing

Fig.2 shows the total core loss at 50 Hz. In the final annealing temperature below 900℃, the core loss decreases with increasing final annealing temperature for both high-sulfur steel (S content of 32 or 54 ppm) and ultra-low sulfur steel (S content of 4 ppm). However, in terms of absolute values, the core loss of the ultra-low sulfur steel is much lower than that of high-sulfur steel. In the final annealing temperature above 900℃, the core loss of high-sulfur steel decreases with increasing final annealing temperature, but in contrast, the core loss of the ultra-low sulfur steel increases with increasing final annealing temperature. In the final annealing temperature zone above 1050℃, the core loss of the ultra-low sulfur steel becomes larger than that of high-sulfur steel.

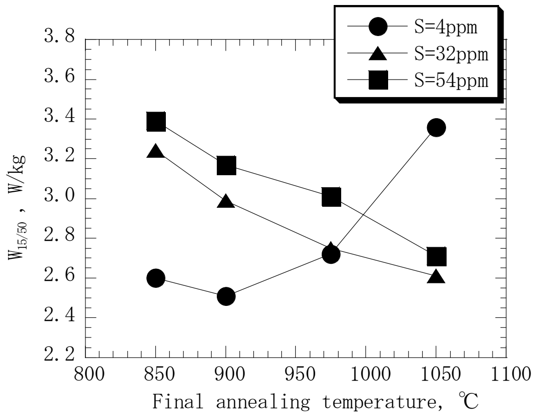

Fig.2 Effects of sulfur content on total core loss

To find the cause of such phenomena, loss separation was performed by the two-frequency method. The results are shown in **Fig.3**. Eddy current loss increases as the final annealing temperature increases for both high-sulfur and ultra-low sulfur steels. These behaviors are considered to be attributable to the fact that the grain diameter increases as the final annealing temperature increases. This increases the width of the magnetic domain, thereby increasing the eddy current loss. Eddy current loss is larger for ultra-low sulfur steel than for high-sulfur steel. This result is conceivably attributable to the same reason. The grain size is larger, hence the magnetic domain is wider for ultra-low sulfur steel than for high-sulfur steel.

On the other hand, hysteresis loss steadily decreases as the final annealing temperature increases for high-sulfur steel. Hysteresis loss also decreases for ultra-low sulfur steel as the final annealing temperature increases to 900℃, but once the final annealing temperature goes beyond 900℃, hysteresis loss increases as the temperature increases.

As above, the final annealing temperature dependence of hysteresis loss is markedly different for ultra-low sulfur steel and high-sulfur steel. This is considered to be the major factor that increases core loss for ultra-low sulfur steel when the final annealing temperature is high.

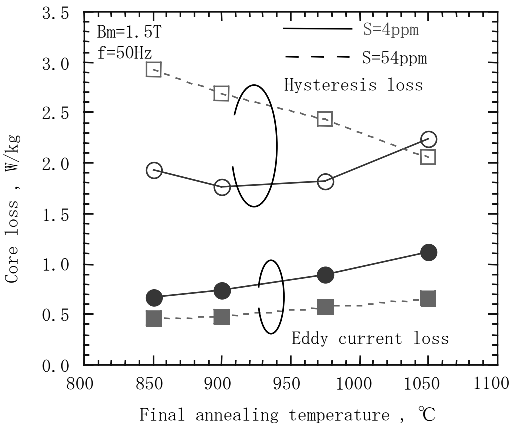

Fig.3 Effect of sulfur content on hysteresis loss and eddy current loss (Bm = 1.5T, f = 50Hz)

In order to study why hysteresis loss of ultra-low sulfur steel increases when it is annealed at high temperatures, cross-sectional microstructures of high-sulfur steel and ultra-low sulfur steel were compared under optical microscope (**Photo 1**). The ferrite grain size of the ultra-low sulfur steel near the center of the thickness is about 1.5 times as large as that of high-sulfur steel. Nevertheless, a small ferrite grain layer is noticeable near the surface of ultra-low sulfur steel. The cross-sectional microstructures at the depth of 10 μm from the surface which is part of the small ferrite grain layer, was observed using SEM. Fine AlN particles measuring 0.1 to 0.5 μm across were noticed, see **Photo 2**. This observation suggests that the small ferrite grain surface layer was formed due to the pinning effect on grain boundaries caused by surface nitriding.

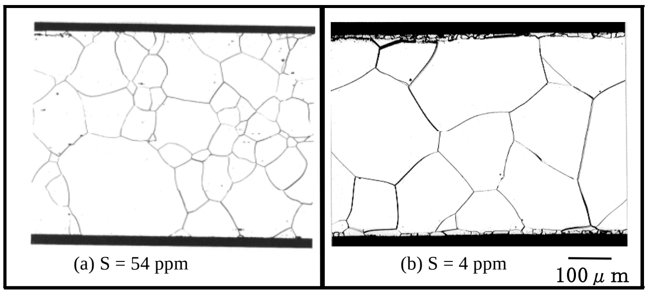

Photo 1 Optical micrograph of the steel
(final annealing temperature: 1050℃)

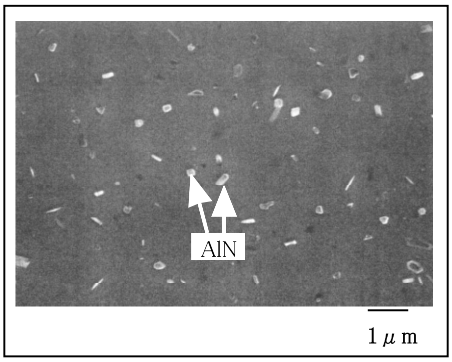

Photo 2 SEM micrograph at the depth of 10 μm from the surface (S = 4 ppm, annealed at 975℃ for 2 min)

In order to quantify the amount of AlN in the surface layer, electrolyte extraction was conducted at intervals, 30 μm from the surface. The measured results obtained for the nitride that is present as AlN are shown in **Figs.4** and **5**. The ultra-low sulfur steel exhibits pronounced nitriding to the depth of about 60 μm when annealed at 1050℃, see **Fig.4**. The degree of nitriding on the surface increases as the final annealing temperature rises for both types of steel, see **Fig.5**. However, the degree of nitriding with ultra-low sulfur steel (S = 4 ppm) is 9 times as high as that with high-sulfur steel (S = 54 ppm) when annealed at 1050℃.

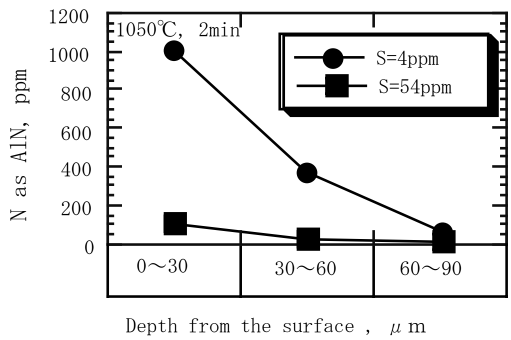

Fig.4 The amount of AlN close to the surface

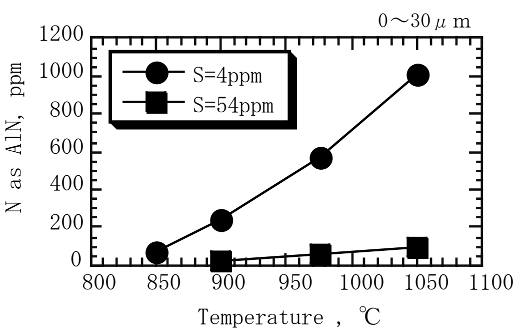

Fig.5 Relationship between final annealing temperature and the amount of AlN

These results suggest that the increase in hysteresis loss in ultra-low sulfur steel noticeable in **Fig.3** is attributable to the magnetic domain walls being prevented from moving by the small ferrite grain layer and AlN that are present near the surface.

Auger electron spectrometry was applied to the steel sheet surfaces to clarify the causes of increased surface nitriding of the ultra-low sulfur steel. First, in order to clean the surfaces of cold-rolled steel sheet specimens, their surfaces were subjected to Ar ion spattering in an Auger chamber. The specimens were then kept at the elevated temperature for 30 minutes, then cooled to room temperature, and an elemental analysis was performed on the surfaces of the specimens. The temperature inside the chamber was raised to only 850℃, since it was difficult to keep the specimens in the chamber at higher temperatures. A prominent sulfur peak was noticed for high-sulfur steel as shown in **Fig.6**. This specimen was subjected to Ar ion spattering for 30 seconds to remove the surface layer, then analyzed again. The sulfur peak had disappeared. This indicates that segregation of sulfur occurs near the surface of high-sulfur steel during the annealing. In contrast, the sulfur peak is very weak in ultra-low sulfur steel, and the segregation of sulfur near the surface is hardly detectable. Driscoll has pointed out that surface segregation of sulfur affects the ability of the steel sheet surface to absorb atmospheric oxygen[6]. From this, it is also conceivable that the segregated sulfur near the surface may interfere with the process of nitrogen absorption. In other words, sulfur in high-sulfur steel conceivably segregates near the surface during the annealing process after hot-rolling and also during the initial period of the final annealing. The sulfur segregated near the surface inhibits nitrogen absorption on the surface during the high-temperature annealing. In the case of ultra-low sulfur steel, sulfur is virtually absent near the surface. Therefore, nitrogen in the atmosphere is easily absorbed though the steel surface during the final annealing, and absorbed nitrogen further diffuses into the interior of the steel. It then combines with Al to form AlN, which in turn precipitates near the steel surface and increases the core loss.

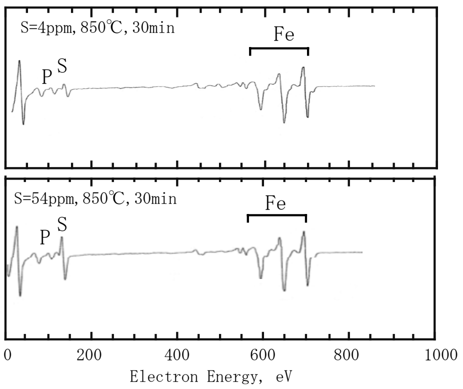

Fig.6 Auger spectra of steel surface following annealing

3. Development of an electrical steel sheet for energy efficient motor

3.1 Material design concept

The results of these investigations indicate the following possibilities. Ultra-low sulfur steel is apt to suffer from prominent surface nitriding, but has excellent property in terms of interior grain growth. If the surface nitriding of ultra-low sulfur steel is effectively prevented, core loss will possibly be substantially reduced. Two approaches appeared possible to achieve this objective: (1) to increase hydrogen partial pressure in the annealing atmosphere, and (2) to add elements such as P, Sb, Sn which, like S, tend to cause surface segregation but do not form precipitates that inhibit grain growth. Taking the second option, an element that causes surface segregation was added to ultra-low sulfur steel to prevent surface nitriding and obtain large uniform grains throughout the steel sheet thickness. **Fig.7** shows the degree of nitriding at the depth of 30 μ m from the surface when 40 ppm of Sb was added to ultra-low sulfur steel. Addition of Sb substantially inhibits surface nitriding of ultra-low sulfur steel. A similar effect of inhibiting surface segregation was also confirmed with the addition of Sn and P.

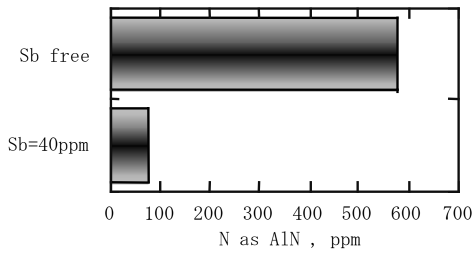

Fig.7 Effects of Sb on surface nitriding of ultra-low sulfur steel (final annealing temperature: 975℃)

A new type of electrical steel sheet was developed by adding a surface-nitriding inhibitor to ultra-low sulfur steel. **Fig.8** compares eddy current loss and hysteresis loss of 0.35 mm thick conventional 35A300 grade steel, purified steel (ultra-low sulfur steel) and newly developed steel. Hysteresis loss, hence the total core loss as well, was significantly reduced by adding a surface-nitriding inhibitor to ultra-low sulfur steel.

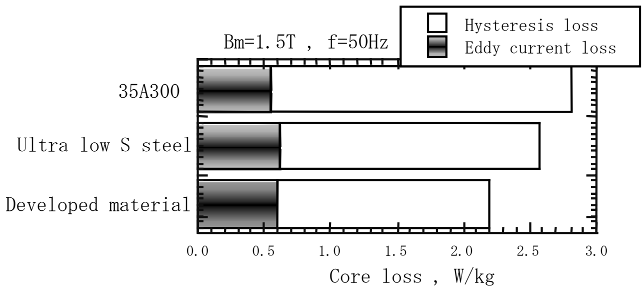

Fig.8 Comparison of core loss of 35A300, ultra-low sulfur steel, and newly developed material

Fig.9 shows the features and key technologies of the newly developed steel. The newly developed steel achieves low core loss by distributing large grains uniformly in the thickness direction. With a lower Si and Al content than in conventional materials, the newly developed steel achieves higher magnetic flux density than that of conventional materials. The lower Si and Al content soften the material, thus making punching operations easier and extending the life of punching dies. Furthermore the lower Si and Al content make the material easier to cold-roll, this in turn has led to higher production yields and cost reductions.

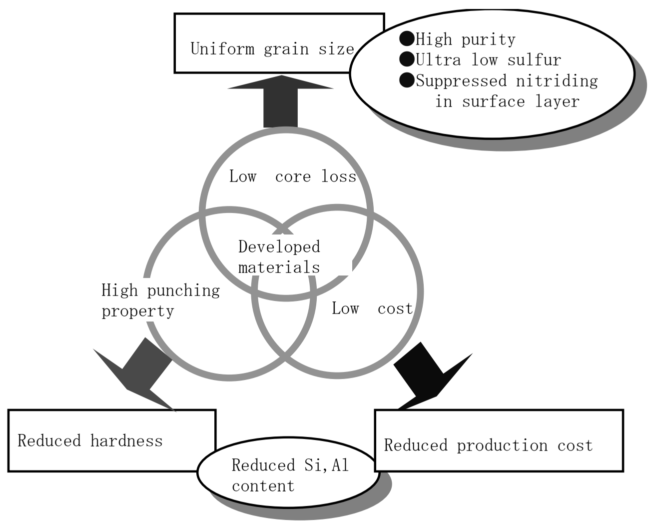

Fig.9 Characteristics of newly developed materials

3.2 Features of the newly developed materials

Figs.10 and **11** show the magnetic properties and Vickers hardness of the 0.50 mm thick newly developed steel sheets. These newly developed steel sheets show higher magnetic flux density than conventional steel sheets that have nearly the same level of core loss. The newly developed steel sheets exhibit 20 to 30 points lower Vickers hardness than the JIS grade materials with comparable core loss. These improvements make cold-rolling easier, thus improving steel maker productivity, and also making the punching operation easier, thus reducing the wear on the customer's dies.

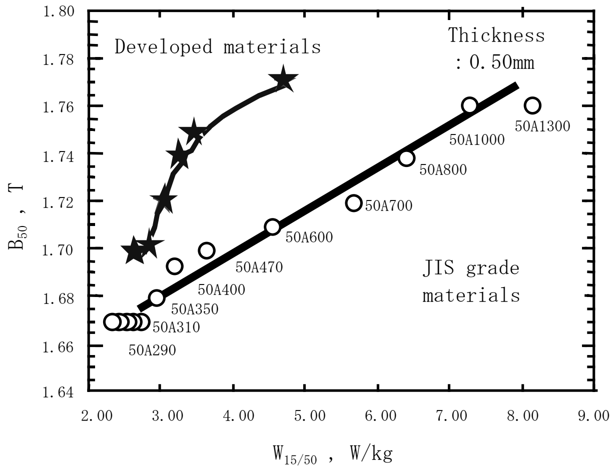

Fig.10 Magnetic properties of newly developed materials

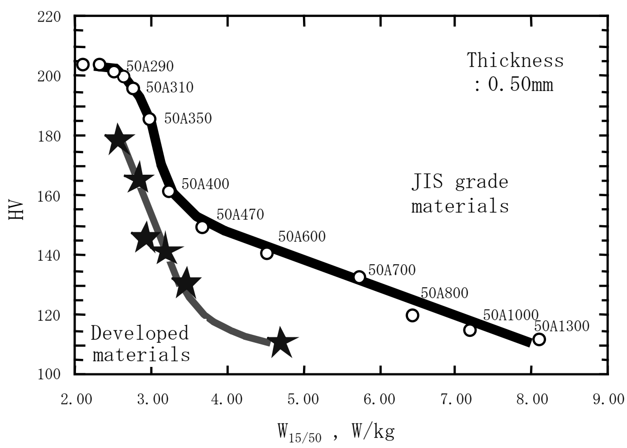

Fig.11 Vickers hardness of newly developed materials
(Load : 500g)

Fig.12 shows a magnetization in high strength magnetic fields of the newly developed steel sheet and a conventional material (35A230) that has comparable core loss. The newly developed material shows a saturation magnetization of 2.00T as compared with 1.95T for the conventional material, an improvement of 0.05T. The newly developed technology makes it possible to reduce the need to add non-magnetic elements such as Si and Al. Energy efficient motors for automobiles are sometimes designed in such a way as to make the magnetic flux density reach 2.0T in order to increase their torque. In such applications newly developed steel sheet with high levels of magnetic saturation can reduce flux leakage.

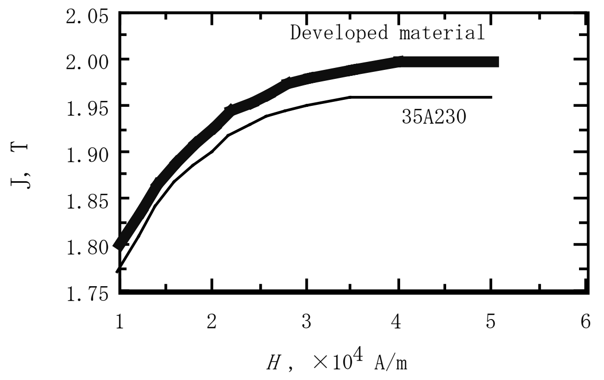

Fig.12 Magnetic properties in high strength magnetic fields

4. Applying newly developed steel sheet to electric power steering

EPS (Electric Power Steering) systems are being increasingly used as a means of achieving fuel economy. Applying the newly developed steel sheet to the EPS system is worth mentioning. The EPS system is said to reduce fuel consumption by 3 to 5% when compared with the conventional hydraulic power steering system. This reduction is due to the fact that the hydraulic pump in the conventional hydraulic power steering system operates continuously even when the automobile is driving in a straight line and the steering wheel is not being turned. This means that conventional hydraulic power steering systems waste energy when the automobile is driving fast and in a straight line on the high way. In contrast, the motor in the EPS system is put into operation only when the driver turns the steering wheel, thus does not consume energy when the automobile is driving in a straight line. As a result of this advantage in terms of fuel consumption, about 30% of passenger cars are expected to be equipped with EPS systems by 2006.

However, there is a drawback to the EPS system. Its steering response is inferior to the hydraulic power steering system. This is due to loss torque generated when the motor is idling. Loss torque is attributable to the bearings, brushes, and other mechanical parts, as well as hysteresis loss originating in the motor core material. As a result it is necessary that the motor core material for the EPS system should exhibit low hysteresis loss. The newly developed material provides lower hysteresis loss than the JIS grade materials of comparable core loss, and is considered the best kind for use as EPS motor core material.

Brush DC motors were fabricated experimentally using electrical steel sheets of various grades, and their loss torque was analyzed. The result is shown in **Fig.13**. The loss torque is expressed as a ratio with that of the conventional 50A1000 grade material being unity. The newly developed material exhibits a loss torque of about 60% that of the conventional material. Lowering the loss torque improves the steering response of the EPS system. For this reason, several new model automobiles have already adopted this material in their EPS motors.

Furthermore, the newly developed material has already been used in hybrid electric vehicle motors, high-efficiency induction motors, and other motors that need to be highly energy efficient. It is expected that its applications in various motors will further expand in future.

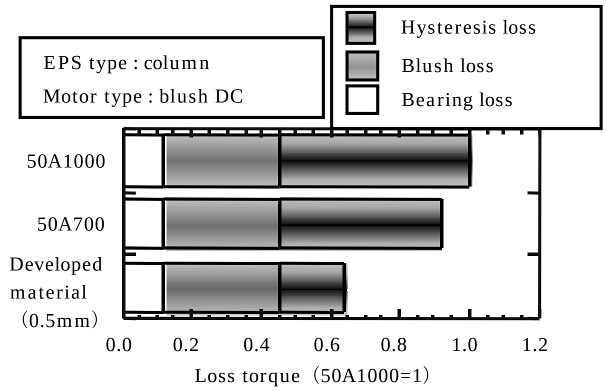

Fig.13 Effect of hysteresis loss on loss torque of the EPS motor

5. Conclusion

NKK carried out extensive investigations on the effect of sulfur on the magnetic properties of electrical steel sheets, and obtained the following findings. The hysteresis loss of the ultra-low sulfur steel sheet containing sulfur at less than 10 ppm increases with increased temperatures in high-temperature annealing. This is because AlN precipitates in the surface layer, prevents the move of the magnetic domain wall. Ultra-low sulfur steel exhibits pronounced surface nitriding due to the decreased levels of surface segregation of sulfur.

On the basis of the above findings, NKK developed a new type of electrical steel sheet for energy efficient motors. This was achieved by reducing the sulfur content to an extremely low level while inhibiting surface nitriding. The newly developed material has lower hysteresis loss, higher magnetic flux density, and better punching property when compared with conventional materials. The newly developed material is also easy to produce, and very promising as a core material for highly energy efficient motors.

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