Abridged version

KAWASAKI STEEL TECHNICAL REPORT
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Automative Materials and Instrumentation
and Process Control

Core Materials for Motors in Automobiles and Evaluation Method

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The body can be viewed from the next page.

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1 Preface

Dozens of motors are used in a car to improve safety and comfort. Moreover, electric motors will come into greater use in response to environmental problems such as global warming, air pollution, and energy problems, and the development of motors for electric vehicles and hybrid cars has been progressing.[1)]

Since the performance of these motors directly affect fuel mileage and driving condition, brushless DC motors may be able to meet the strong demand for high performance and high efficiency.

The authors previously investigated the influence of the core material on motor efficiency and found that an optimum value exists for the amount of Si in the material, which varies depending on the number of rotations and the design flux densities for conventional induction motors.[2,3)]

On the other hand, the brushless DC motor using a permanent magnet has less copper loss than the induction motor because it does not have the second winding in the rotor, resulting in higher efficiency.[4)] Therefore, it is considered that a core material different from that in the induction motor is required in a brushless DC motor, whose ratio of iron loss is relatively high due to the lower copper loss.

In this report, the controlling factor of the properties of the non-oriented electrical steel used for the core material is described, and a new product of Kawasaki Steel is introduced. Next, the results of investigations on various non-oriented electrical steels to find a suitable core material for a brushless DC motor are reported.

Finally, this paper describes an introduction to the technology for evaluating the local magnetic properties of the motor which Kawasaki Steel has developed for the motor design, and the material it contains.

2 Non-oriented Electrical Steel

Non-oriented electrical steel is used as the core material of rotating machinery, mainly generators and motors, because its magnetic properties are not biased in any specific direction. One feature of non-oriented electrical steel is its wide range of applications, from large rotating machinery in which low iron loss is necessary, to small electrical devices in which high permeability is required. Because of the varied uses, non-oriented electrical steels are manufactured in many grades, from high grade non-oriented electrical steel strip with an Si content of approximately 3%, to low grade products containing no Si. These steels are required to provide a diverse range of properties, including magnetic properties, strict gauge accuracy punchability, electrical insulation by coating, corrosion resistance, mechanical properties, and weldability.

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The production of electrical steel at Kawasaki Steel began with hot rolled Si steel in the early 1930s. Since then, a stable supply system for both quality and quantity has been established for the wide range and grade of products. The present paper describes the controlling factors of the properties of these non-oriented electrical steels and recent progress at Kawasaki Steel.

2.1 Factor Influencing Magnetic Properties

To satisfy the many requirements such as low iron loss, high permeability, etc., sheets are produced with optimum control of the metallurgical factors which affect magnetic properties. These factors are presented below.

2.1.1 Si and Al contents and sheet thickness

Iron loss can be divided into hysteresis loss and eddy current loss, and the eddy current loss can be further divided into classical eddy current loss and anomalous eddy current loss in which the domain structure is taken into account. Classical eddy current loss, W_e, is expressed by Eq. (1).

$$W_e = k(tfB)^2/\rho \quad \cdots\cdots (1)$$

Where, k: constant, t: sheet thickness, f: frequency, B: magnetic flux density, and ρ: resistivity.

As the amount of added Si and Al increases, the resistivity, ρ, of the sheet increases, and iron loss decreases in accordance with the above equation. However, the addition of these elements reduces magnetic flux density. For this reason, the content of Si and Al is decided so as to satisfy the target magnetic properties. Generally, the amount of added material is larger in higher grade products, in which lower iron loss is required. Reducing the sheet thickness is also effective in reducing iron loss, as is clear from Eq. (1).

2.1.2 Grain size

Among the factors of iron loss in non-oriented electrical steel, eddy current loss increases and hysteresis loss decreases as the grain diameter increases.[5] This is because the domain width increases, resulting in greater anomalous eddy current loss as the grain diameter increases. In contrast, the larger the grain diameter, the smaller the area of the grain boundary, which impedes domain wall motion, and thereby reduce hysteresis loss. Thus, there is an optimum grain diameter for minimizing iron loss, which is the sum of eddy current loss and hysteresis loss. Hysteresis loss is also influenced by the presence of inclusions, the texture, and other factors, so it is also necessary to optimize these conditions. With high Si steel, the optimum grain diameter is relatively large, at around 150 μm, as shown in **Fig. 1**. Therefore, material control which adequately promotes grain growth in a relatively short time is necessary in industrial operations. It is particularly important to minimize the content of fine precipitates and inclusions, which impede grain growth.

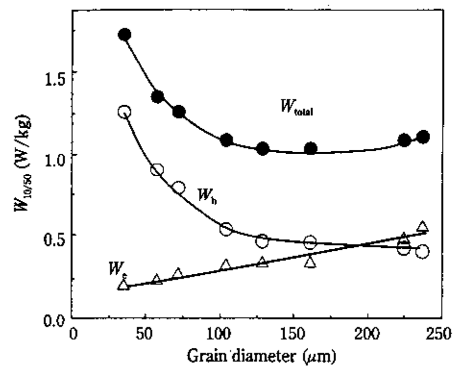

Fig. 1 Influence of grain diameter on hysteresis loss, eddy current loss and total iron loss

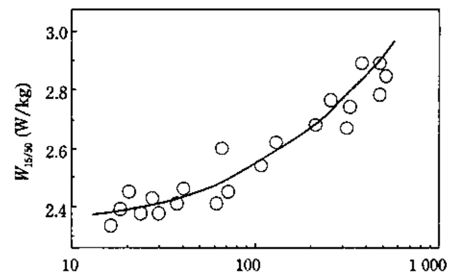

Fig. 2 Effect of inclusions on iron loss of 0.5 mm thick material

2.1.3 Inclusions

Sulfides, oxides, nitrides, precipitates and inclusions exist in steel. The diameter of inclusions ranges from approximately less than 0.1 μm to several tens of μm. While these inclusions increase hysteresis loss by impeding grain growth, they also directly degrade magnetic properties. This is because domain wall motion is hindered by the inclusions themselves or by the peripheral lancet domains which are formed when inclusions cause a reduction in magnetostatic energy. **Figure 2** shows an example of the reduction of iron loss when the number of inclusions in the steel was reduced.[6] Reducing the absolute amount of inclusions is extremely important. However, it is also important to control the size and distribution of inclusions to the adequate morphology, to minimize the negative effects. Assuming the absolute amount of inclusion is equal, the negative effect of such inclusions on grain growth and domain wall motion is minimized when the inclusion is made as coarse as possible.

2.1.4 Texture

The condition of having a so-called preferential orientation, in which grains are aligned in a particular direction, is called texture. The magnetic properties of

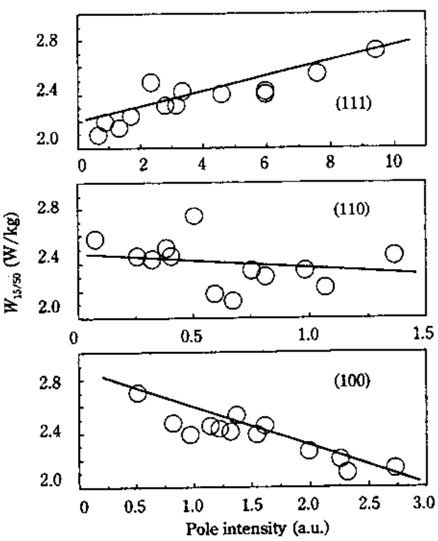

Fig. 3 Relationship between pole intensity and iron loss

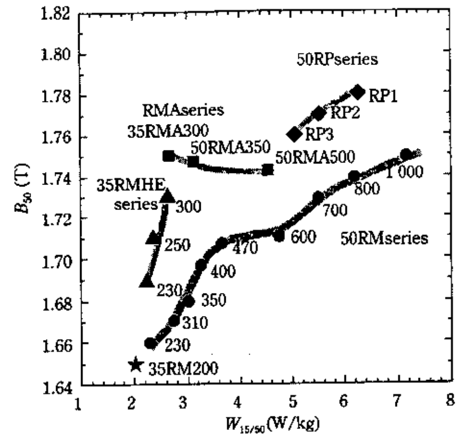

Fig. 4 Iron loss and fluxdensity of non-oriented electrical steel produced by Kawasaki Steel

electrical steels are strongly dependent on their textures. As shown in **Fig. 3**, iron loss decreases as the (100) pole intensity increases; conversely, iron loss increases as the (111) pole intensities become stronger.[6] This is due to the fact that electrical steels have strong magnetic anisotropy, being most easily magnetized in the direction of the [100] axis and most difficult to magnetize in the [111] direction, because two [100] axes exist in the (100) plane whereas there are no [100] axis in the (111) plane. Further, it has been found that texture can be improved remarkably by the addition of Sb, which can also improve magnetic properties.[7-9]

2.1.5 Strain induced by punching

Electrical steel is generally sheared when it is used. A considerable strain induced by shearing causes deterioration of magnetic properties. Therefore it is necessary to use the proper shearing condition such as setting clearance so that the induced strain can be suppressed. It is also preferable to carry out stress relief annealing.

2.2 Development of New Products

Precise control of the process conditions based on the principles discussed above has made it possible to develop a variety of non-oriented electrical steel products, as shown in **Fig. 4**.

(1) Highest Grade Non-Oriented Electrical Steel 35RM200

High purity in molten steel is extremely important for the development of the highest grade of steel sheet. In addition, the elements, Si and Al, which increase resistivity, are added within the range allowed by cold rolling technologies. The application of high purification technology, inclusion dispersion control, texture control, and other techniques, has made it possible to develop and supply 35RM200 ($W_{15/50} \leqq 2.0$ W/kg), which is presently the world's best steel in its class.

(2) High Flux Density RP Series[10]

The high induction RP series was developed in response to the heightened demand for reduced size and improved efficiency in equipment in recent years. The Si content decreases in the order RP1, RP2, RP3. These steel sheets are produced using advanced texture control technology.

(3) RMA Series with Low Iron Loss after Strain Relief Annealing[11,12]

The RMA series, which shows particularly excellent grain growth during annealing, was developed as a series of steel sheets with effectively reduced iron loss after stress relief annealing by the customer while maintaining magnetic flux density. Grain growth can be improved by inclusion morphology control. A variety of products have been developed in this series, from RMA600 ($W_{15/50} \leqq 6.0$ W/kg) to 35RMA300 ($W_{15/50} \leqq 3.0$ W/kg).

(4) RMHE Series with Low Iron Loss and High Permeability

Low iron loss and high flux density were achieved without a large increase in hardness. This series improves the grain growth by inclusion morphology control and provides highly developed texture. The highest quality steel of the series is 35RMHE230 (HV $\leqq 200$, $W_{15/50} \leqq 2.3$ W/kg, $B_{50} \geqq 1.67$ T).

(5) RMHF Series for High Frequency

This series is suitable for the high-speed rotation of small motors etc., and has an excellent magnetic properties at high frequencies. The top of the line is 20RMHF1200 ($W_{10/400} \leqq 12.0$ W/kg).

(6) Bonding Type B Coating[13,14]

Because electrical steel is laminated after punching or shearing into various shapes, a variety of characteristics are required for the coating which is applied to

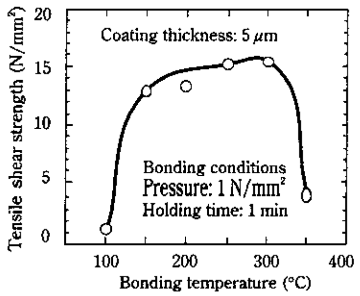

Fig. 5 Effect of bonding temperature on tensile shear strength at a room temperature

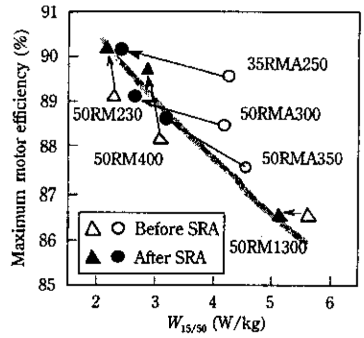

Fig. 6 Relationship between maximum motor efficiency and material iron loss before and after stress relief annealing (SRA)

the sheet surface, depending on the processing method and application. The semi-organic A1 Coat, which is a general purpose coating, has excellent overall characteristics, and is presently used both in the greatest quantity and widest range of applications. B Coat, which is an organic adhesive resin capable of heat bonding, was developed and commercialized for applications in which clamping, welding, and other methods of joining cannot be applied, and for applications which require airtightness between stacked sheets. **Figure 5** shows the effect of bonding temperature on tensile shear strength of 5 μm thick B Coat at room temperature.

3 Evaluating Actual Machine Characteristics

Non-oriented electrical steel is usually evaluated by the Epstein test of JIS2550 standard. However, if the characteristics of a machine which actually uses the product can be evaluated, more detailed information can be provided to the customer and applied to the core material development.

Kawasaki Steel has developed devices for evaluating 600 W single phase motors,[2] 400 W 3 phase 6 pole induction motors,[3] and 300 W 3 phase 8 pole brushless DC motors,[15] and a localized iron loss measurement device for induction motors.[16] The experimental results for devices to evalute brushless DC motors and measure localized iron loss are introduced here.

3.1 Influence of Core Material on Brushless DC Motor Characteristics

In brushless DC motors, the copper loss is smaller than that of widely used induction motors because the former do not have the second winding in the rotor in which a permanent magnet is set, and the efficiency is rather high as described earlier. As Japan has superior technologies specifically in magnet manufacturing, brushless DC mortors are commonly employed for highly-efficiect uses.

3.1.1 Core material and measurement method

A commercial brushless DC motor and its drive system were used throughout the experiment. The rated power output was 300 W. The rotor was a permanent surface magnet type with eight poles. The stator had 12 slots. Five kinds of material, 50RM230, 50RM400, 50RM1300, 35RMA250, and 50RMA300, were used as stator core material. The stacked core was wound with enamel wire with a star connection before and after being annealed at 750°C for 2 h in an N_2 atmosphere.

The driving voltage was fixed by PWM pulse width adjustment and the rotating speed was kept in the range of 2 000 to about 1 200 rpm by applying torque load with a brake motor.

3.1.2 Relation between maximum efficiency and material iron loss

The influence of the material iron loss $W_{15/50}$ (iron loss at 1.5 T, 50 Hz) on maximum motor efficiency over the rotating speed range is shown in **Fig. 6**. The efficiency tended to increase as $W_{15/50}$ decreased. The correlation was much better for annealed cores, where efficiency increased by 1.3% for each decrease of 1 W/kg in $W_{15/50}$. Non-annealed materials showed somewhat different behavior. The maximum motor efficiency was lower for the RM series and higher for the RMA series than values expected from the maximum efficiency-$W_{15/50}$ curve for annealed materials. This apparent discrepancy disappears when the efficiency is plotted against higher frequency iron loss $W_{10/400}$ (iron loss at 1.0 T, 400 Hz) as shown in **Fig. 7**.

It can be understood that the maximum efficiency was determined by material high-efficiency iron loss, irrespective of the core being annealed or not. In order to understand the fact that the 400 Hz iron loss determined the motor efficiency, the flux voltage waveform was measured in stator tooth and yoke portions. Typical results are shown in **Fig. 8**. Although the synchronous frequency when the efficiency was maximum varied between 100 and 150 Hz, a storong 6th harmonics palse was superposed on the fundamental, and this is considered to have exerted a strong influence on the motor efficiency.

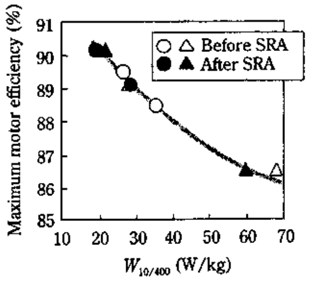

Fig. 7 Relationship between maximum motor efficiency and material iron loss at high frequency before and after stress relief annealing (SRA)

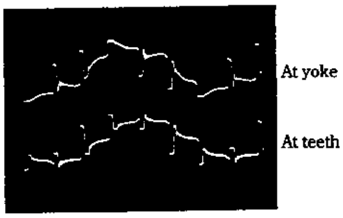

Fig. 8 Differential wave form of fluxdensity in stator core

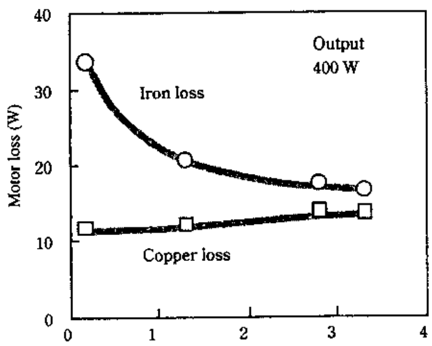

Fig. 9 Effect of Si content of core materials on iron loss and copper loss in a brushless DC motor

3.1.3 Loss analysis of motors

Figure 9 shows the influence of the amount of Si in material on motor iron loss and copper loss. Because the output and the number of rotations vary the maximum efficiency condition of each material, the driving condition was fixed at an output of 400 W to obtain the data. Iron losses were larger than copper loss and the material dependence was stronger in the high output power of 400 W. It can be concluded that the material high frequency iron loss had the greatest effect on the motor efficiency, judging from the motor iron loss in the brushless DC motor tested here. The brushless DC motor tend to have a smaller copper loss in equal output and rotation number region when this result is compared with that of the induction motor shown in **Fig. 10.**

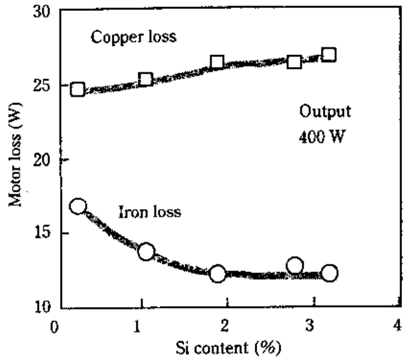

Fig. 10 Effect of Si content of core materials on iron loss and copper loss in an induction motor

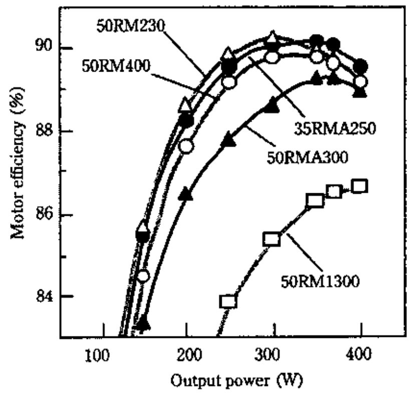

Fig. 11 Relationship between motor efficiency and output power

3.1.4 Output dependence of motor efficiency

Figure 11 shows the effect of motor output on motor efficiency. The motor using high B_{50} material shows higher efficiency in the high output region. The efficiency of the motor using 35RMA250 became higher than 50RM230, especially in the output of about 330 W or more. The high B_{50} material may have been advantageous because of an increase in the copper loss ratio in the high power region.

3.1.5 Influence of material on torque

The torque measured at 1 500 rpm during a process starting from a no-load rotation speed of 2 100 rpm and increasing the loaded torque is plotted against material flux density B_{50} in **Fig. 12**. Higher material flux density resulted in higher torque as shown in the figure.

3.2 Magnetic Properties Distribution in Motor Core

In order to design motors efficiently, it is necessary to

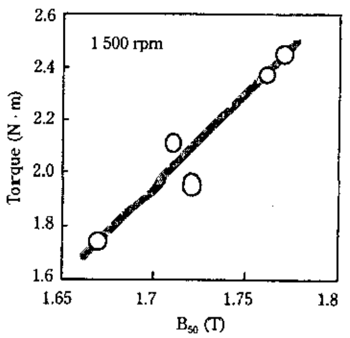

Fig. 12 Effect of B_{50} of core material on motor torque

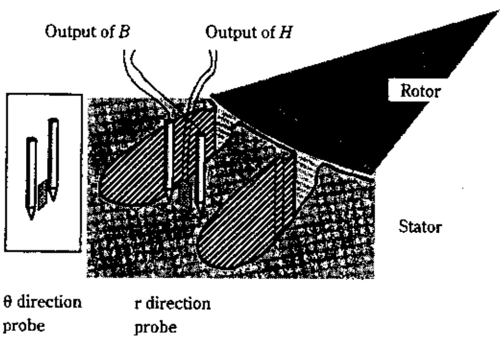

Fig. 13 Schematic diagram of measuring method of B and H

develop simulation technology which takes into consideration the nonlinar, anisotropic, and hysteresis characteristics of the magnetic material. At the same time, demand has risen for both macroscopic and local data for the basic measurements of motor loss. To meet this demand, Kawasaki Steel has developed the local analysing method of magnetic properties method for rotating motors in conjunction with the stylus probe method.[17,18)]

3.2.1 Core material and measurement method

Evaluation was carried out on a single phase 600 W induction motor using non-oriented electrical steel 50RM400 for the core material. To insert the probe in the teeth the winding was installed with a gap of width of the teeth × height, about 20 mm. The flux density and magnetic field strength on the stator core were measured by the probe and a small hall element, respectively. **Figure 13** shows their arrangement. The distance between two probes was set at 2 mm, and two pairs were used for the measurement in the radial and circumferential directions.

For each point, the measurements in the direction of radius (r) and circumference (θ) were taken separately. The values were defermined averaging of 100 measurements. Each measurement was carried out for two cycles of which the sampling points were 1 000 per cycle.

The iron loss in each measurement point was obtained by the next expression. Two-dimensional iron loss value W_{2d} was derived as a summation of iron loss in r direction W_r and in θ direction W_θ.

$$W_{2d} = (f/r)\oint H \cdot dB = W_r + W_\theta \cdots\cdots\cdots\cdots (2)$$

$$W_{r,\theta} = (f/r)\oint H_{r,\theta}\, dB_{r,\theta} \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

here, f is the synchronous frequency and r is the density of the electrical steel. One synchronous cycle is integrated. The measurements were taken under a rotating condition with 100 V of single phase voltage.

3.2.2 Distribution of local magnetic characteristics

Figure 14 shows W_r and W_θ elements and two-dimensional iron loss W_{2d} at a stator under no-load condition. The distribution of W_r is in good agreement with that of the magnetic field strength, and is large in the teeth. The distribution of W_{2d} is similar to that of W_r and also tends to be large in the teeth. However, the overall distribution has smoothed because the distributions of W_r and W_θ are complementary.

It seems that in addition to no load loss, the large output was included in the above-described iron loss value because it was not in complete synchronization, and generated some torque in the motor. Actually, there was a tendency toward large iron loss value in the teeth regardless of the state of distribution of the flux density. This was probably because some work to the rotor was received from the current of the armature through the teeth.

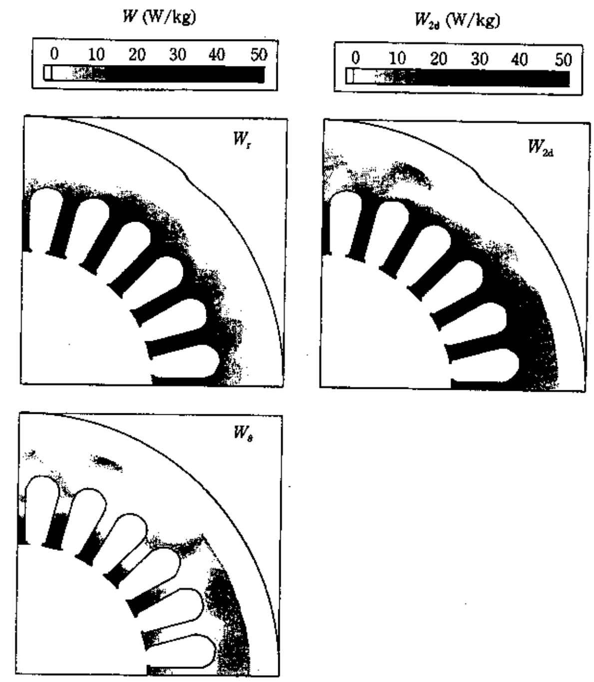

Fig. 14 Local iron loss distribution

4 Conclusions

Kawasaki Steel has been developing new products suitable for motor cores, such as the highest grade non-oriented electrical steel, 35RM200; the high permeability RP series; the low iron loss, high permeability RMHE series; the RMHF series with excellent high frequency properties; and bonding type B coating materials.

To improve brushless DC motor efficiency, it was found that decreasing the high frequency iron loss of the core material was effective. However, the flux density of the material must be increased to obtain high torque.

Moreover, measurements of localized magnetic characteristic of the rotating induction motor using the probe method clarified that there was much iron loss in the teeth.

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